PRELIMINARY DESIGN AND PERFORMANCES OF THE SKIM KA-BAND CONICAL SCANNING RADAR

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Abstract — This paper provides an overview of the Ka-band conical scanning Doppler scatterometer designed for the Sea surface KInematics Multiscale (SKIM) monitoring mission. SKIM will demonstrate the maturity of Doppler oceanography to obtain ocean surface currents at a global scale by direct measurements. This mission has been proposed for ESA Explorer 9, with a launch date in 2025. Mission objectives and concept are also presented.

Index terms — Spaceborne Doppler Scatterometer, radar Ka-band, Ocean remote sensing, sea surface waves, currents and waves.

INTRODUCTION

On-going operationnal sea surface current estimations from satellite rely on the combination of geostrophic current anomalies obtained from radar altimetry, mean dynamic topography obtained from gravimetry or drifters [1] and Ekman currents derived from ocean surface wind scatterometers. This approach misses many features of the real currents whereas in-situ measurements like drifting buoys and HF coastal radar provide insufficient or local data.

Instead of ocean topography, one can measure velocities directly. The feasibility of such measurements was demonstrated at global scales by Chapron et al. [2] with Envisat ASAR: the Doppler centroid provides a measurement of a mean ocean surface velocity, in the line of sight, as detected by a radar. This Doppler information then contains a "Doppler wave bias" (U_{WB}) that is proportional to the surface Stokes drift velocity U_S along the look direction [2,3]. An accurate correction for U_{WB} requires a the measurement of ocean wave properties that can be derived from the directional wave spectrum. The design of SKIM builds on this strategy: measuring both the full vector current and the full directional wave spectrum, down to wavelengths of 20 m or less.

SKIM combines in a single Ka-band instrument an accurate state of the art Nadir looking altimeter (sea level, wave height, ice freeboard, …) and a novel current + wave scatterometer using 5 to 7 rotating beam around Nadir at 6° and 12° of incidence (measurement of the current vectors and directional surface spectrum using slopes and orbital velocities).

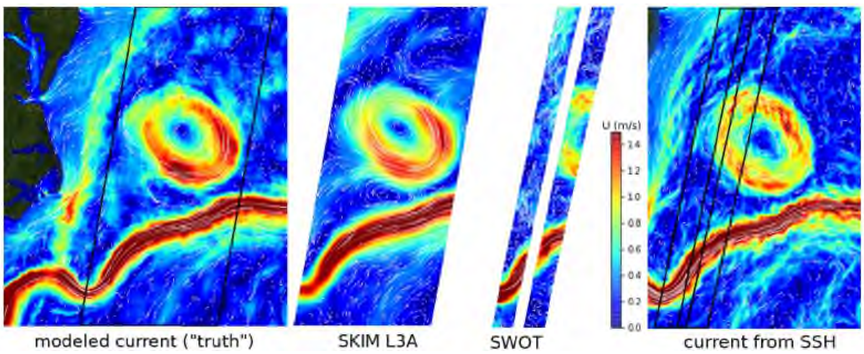


Fig. 1: Simulated ocean currents over the Gulf Stream and associated SKIM and SWOT simulated observations for a single satellite pass. The SWOT simulated current assumes that the current is in geostrophic equilibrium with the sea surface height (SSH), which introduces small scale noise associated to ageostrophic motions (reproduced from Ardhuin et al. 2017).

MEASUREMENT CONCEPT

Retrieval algorithm

The radar estimates line of sight Doppler velocities from the phase difference within pulse pairs [5] thanks to a high PRF (32 kHz). The radial geophysical Doppler velocity U_{GD} represents the Doppler anomaly after substracting the contribution of the non moving surface (U_{NG}), see Eq. 1. The wave bias is removed from backscattering and Doppler modulation spectra obtained from the instrument data [6].

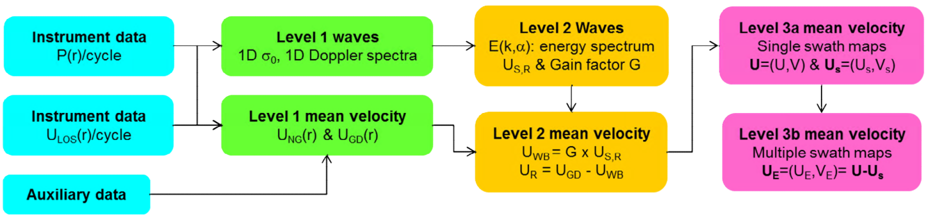
$$U_{LOS\ radar}(r,\alpha,pso) = \underbrace{U_{sat}(r,\alpha,pso)}_{\substack{\text{Non Geophysical Doppler } (U_{NG}) \\ \text{Satellite movement} \\ \text{Earth Rotation} \\ \text{Orbit diving}}} + \underbrace{\left[U_{current}(r,\alpha) + U_{wave\ bias}(r,\alpha)\right]}_{\substack{\text{Geophysical Doppler } (U_{GD}) \\ \text{Total Surface Current Velocity} \\ \text{Sea wave bias}}} x \sin(\theta_i(r)) \qquad \text{(Eq. 1)}$$

r	range
α	azimuth
θi	incidence
pso	satellite orbital position

The correct estimation of U_{NG} requires a very accurate knowledge (<1 arcsec) of the observation geometry (platform attitude, antenna pointing). The retrieval algorithm for U_{NG} uses the data acquired by the instrument during the rotation of the beams over 360°, over which any error in pointing gives a very particular signature on U_{LOS} (see Eq. 2). Perturbators are the current, the velocity bias induced by waves (U_{WB}). Preliminary simulations have shown that the instrument noise contribution is weak (<1 cm/s) and the effect of the current and wave acceptable (1 cm/s). This requires a satellite pointing stability of 10^{-4}°/s over 20 s (one antenna scan used), feasible with standard AOCS equipments (star trackers, reaction wheel, magnetorquer bar). Earth rotation (yellow in Eq. 2) and orbit diving (green in Eq. 2) contributions can be retrieved with pointing knowledge of the system.

$$\begin{aligned} U_{NG}(r,\alpha) = & \boxed{V_{sat}.\sin\gamma(r,\alpha)\cos\alpha} && \pm 1400 \text{ m/s} \\ & \boxed{-V_{earth}.\sin\gamma(r,\alpha)(\varepsilon.\cos\beta.\sin\Psi.\sin\alpha + \cos\psi.\cos\alpha)} && \pm 90 \text{ m/s} \\ & \boxed{+e.V_{sat}.\cos\gamma(r,\alpha)\frac{\sin(\beta - p)}{\sqrt{1+e^2+2e.\cos(\beta-p)}}} && \pm 7 \text{ m/s} \end{aligned} \qquad \text{(Eq. 2)}$$

The end to end retrieval schematic of TSCV (U_E) is depicted on Fig. 2. Level 3 products corresponds to current vector maps obtained by optimal interpolation of surface radial velocity sampled by the radar. The density of radar beams and the angle of radial components at crossing point of the beams drives the accuracy and the spatial resolution of the current vector retrieval (0.1 to 0.2 m/s at a wavelength of 70 km, as demonstrated by several simulations [3]).



U_{LOS} = $U_{NG} + U_{GD}$ x $\sin(\theta_i)$

U_{LOS} = Line Of Sight (LOS) Doppler Velocity
U_{NG} = Non moving surface LOS Doppler Velocity
U_{GD} = Surface Doppler Velocity

U_R (radial) : Total Surface Current Velocity
U_{WB} : Wave velocity bias
$U_{S,R}$: Radial Stokes drift
$G(mss,\theta_i,f_{radar})$: Gain factor

Fig. 2: Interface between main instrument data and waves/current products.

Observation technique

The dense sampling of the swath is obtained thanks to a rotating system of the antenna feeds developped by Thales Alenia Space for SWIM [4]. The complete azimuth spread is covered by the conical scanning and an equivalent 280 km swath is obtained. The maximal configuration envisaged 8 beams with the following incidence angles: Nadir, 2 beams at 6° and 5 beams at 12° equally spaced in azimuth (Fig. 4). The number of beams is linked to the rotation speed and has been optimised with respect to current retrieval simulations. The instrument chronogram is sequential, the pulses being transmitted and received on one beam before switching to the next one (Fig. 3). A cycle is a succession of pulses on the same beam (1024 pulses in open burst mode) and 145 pulses in closed burst mode. The number of pulses and then the cycle length is programmable on-board. A macro-cycle is a succession of cycles on all consecutive beams (1 to 8), with a duration from 80 ms (closed burst) to 300 ms.

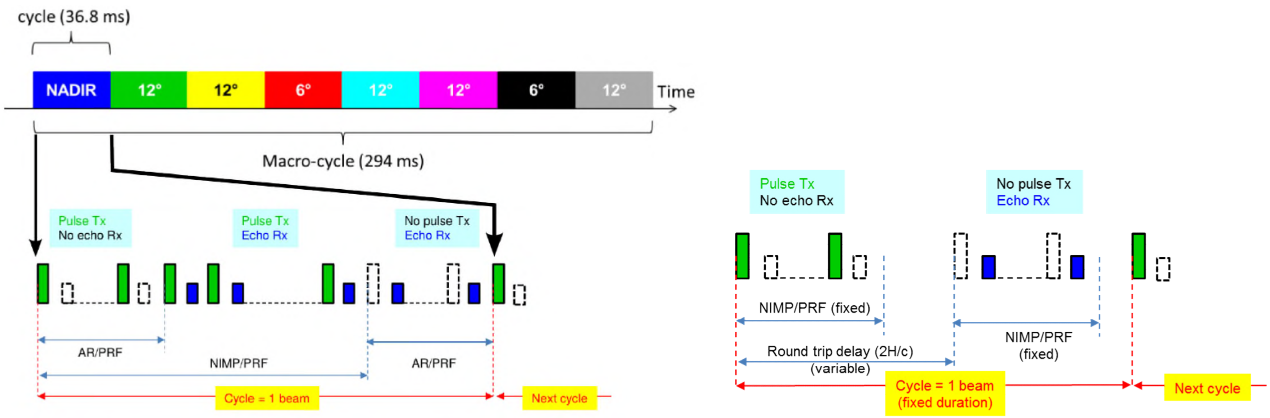


Fig. 3: Instrument chronogram.
(Left: open burst mode – Right : closed burst mode).

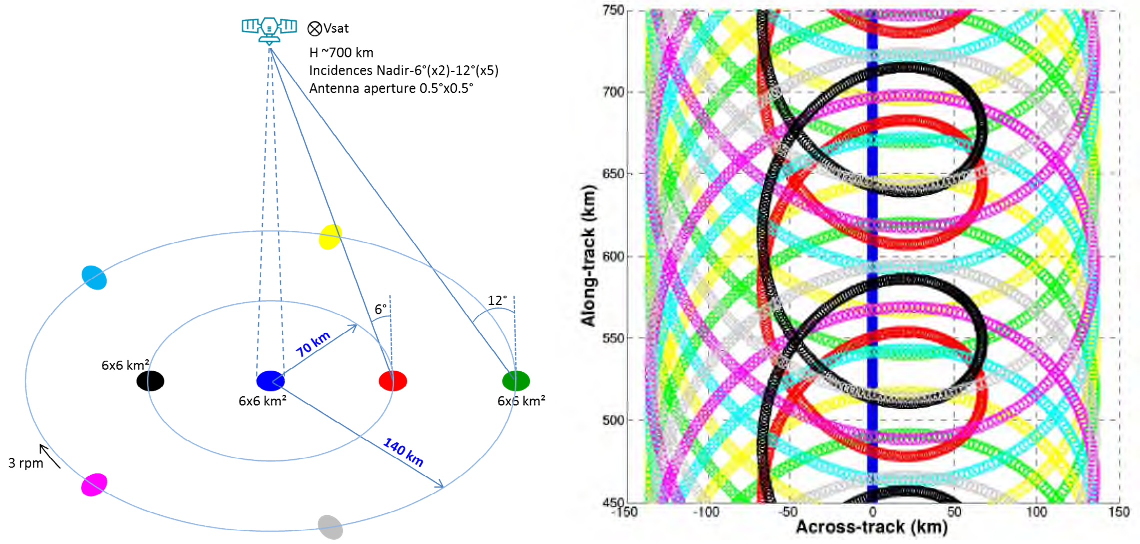


Fig. 4: Instrument observation geometry and ground footprints (for open burst operation).

SPACE SEGMENT DEFINITION

The space segment requires a single small satellite in LEO near-polar Sun Synchronous Orbit with Local Time at Descending node between 6h and 7h in the morning. The satellite and payload performances are compatible with orbit altitude range between 500 km to 700 km. Because SKIM can complement Sentinel-1 (S1), the S1 orbit (700 km SSO, 12 days cycle) with a +4° shift in longitude has been considered (maximize overlap on ascending tracks, given the different incidence angles). The satellite track is controlled at all latitudes with an accuracy of +/- 1 km (similar to Jason and Sentinel 3 satellites).

The instrumentation relies on the Ka-band low incidence Doppler scatterometer (SKaR) using a mechanical low rate conical scanning around the Nadir direction. The concept is based on the heritage of SWIM on CFOSAT [4], translated to Ka-band and optimising the re-use of equipment of the Thales Alenia Space altimeter product line. This includes qualified Ka-band key technologies (HPA, ferrite switches from SWOT) and provides innovative Doppler measurements not available on SWIM. A GNSS system for Precise Orbit Determination (associated with a Laser Retro-reflector array) and for monitoring of the SKaR reference clock (USO 10 MHz) is also used. An X-Band Payload Data Handling Transmitter is considered to download the instrument telemetry.

Satellite overview

The overall configuration of the S/C is dictated by the implementation of the antenna while reusing a recurring, low-cost, type Proteus150 platform from Thales Alenia Space. A reinforced structure and the addition of a third solar array wing are adapted for the mission.

Mechanical and Thermal Design

The S/C is composed of two modules, hosting separately the PF units and the PL units. All the dissipative units have a dedicated thermal surface. The thermal control is based on passive cooling using classical flight-proven technologies (processes and hardware). A preliminary mechanical modal analysis has shown compatibility of the design with launcher (VEGA-C dual launch) stiffness requirements.

Attitude and Orbit Control System

The momentum induced by the rotating part of the instrument is very low(< 0.4Nms) so the disturbance torque will be directly handled by the four Reaction Wheels (RWs) on-board the platform. With star trackers directly mounted on the instrument antenna structure and using advanced filtering techniques enable to ensure accurate and stable Nadir pointing.

Satellite Budgets

The overall maximum satellite mass including system margin is lower than 580 kg. The total consumed power including system margin during data telemetry transmission is lower than 750 W. This is easily handled thanks to the 3 Solar Array wings (2m x 1m each) providing 1050 W EOL.

Fig. 5: SKIM satellite in flight configuration (Xsat axis is the flight direction).

INSTRUMENT TECHNICAL SOLUTION

The SKaR is able to operate both in Real Aperture Radar (RAR) and un-focussed Synthetic Aperture Radar (SAR) modes. The unconventional conical scanning geometry of the radar provides radial range sampled echoes at low incidence angles (6° and 12°) processed on-board to obtain radar cross-section profiles with respect to incidence, radial 1D amplitude and Doppler spatial wave spectrum and integrated Doppler measurements over each beams. A nadir beam, that is an along-track sampling SAR altimeter, is implemented and designed to obtain accurate altimeter measurements (range noise <8 mm @ 1 Hz, $H_{1/3}$=2m).

Operating parameters selection

The Doppler spectrum mean frequency estimation with the pulse pair processor requires the selection of the Ka-band (accuracy proportional to radar wavelength) and a high Pulse Repetition Frequency (power spectral density width weaker than the unambiguous range), see Fig. 6. For an antenna diameter of 1.2 m, optimal performances are obtained for PRF around 30 kHz and SNR in the range 5 to 10 dB (performance driven by geometric decorrelation). Increasing PRF will reduce significantly SNR (Tx/Rx chronogram constraint) and then performances.

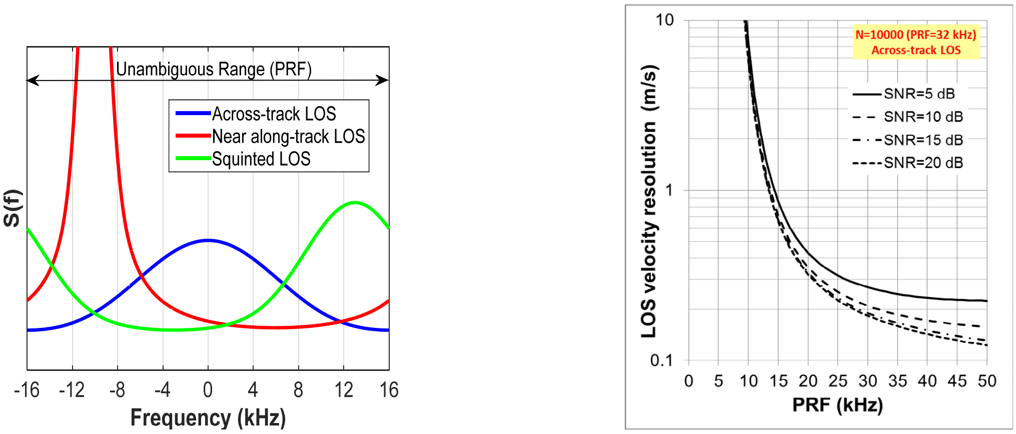


Fig. 6: Range sample Doppler spectrum and Line Of Sight velocity resolution noise.

Parameter	Value
Frequency	35.75 GHz
Antenna diameter	1.2 m
Polarization	Radial
Bandwidth	200 MHz
PRF	32 kHz

Observation geometry	Conical scan
Incidence angles	Nadir – 6° - 12°
Number of beams	8 beams
Number of pulse / beam	145 to 1024 (programmable)
Rotation rate	3 to 5.6 rpm (fixed)
Beam aperture (3-dB)	0.5°
Peak Power	1.5 kW
Pulse length	1.6 to 3.2 µs
Data rate	20 Mbits/s (nom.) – 50 Mbits/s (max)

Table 1: Summary of main instrument parameters.

Instrument description

The SKaR architecture is based on a Core instrument Electronics Unit (CEU) build with Poseïdon-4 DPU slices (Jason-CS/Sentinel-6). Ka-band functions benefit of the SARAL Altika (Ku/Ka module, duplexer, reflector) and SWOT KaRIn (EIK, duplexer) heritages. Critical parts of the antenna (RMA) are herited from SWIM instrument. In the antenna concept, only the plateau supporting the feeds is rotating (reflector fixed) as for SWIM (Fig. 5). The kinetic momentum produced by the concept is weak (< 0.4 Nms) and stable (< 0.0005 Nms) and does not affect platform AOCS.

The on-board processing of received echoes (pulse compression, unfocussed SAR, averaging, …) is conventionnaly (SWIM, Poseïdon 4) implemented in European ASIC technology. For the SKaR, existing ASICs cannot be used, and we envisage the use of and recent advances of European FPGA technology capabilities (NanoXplore).

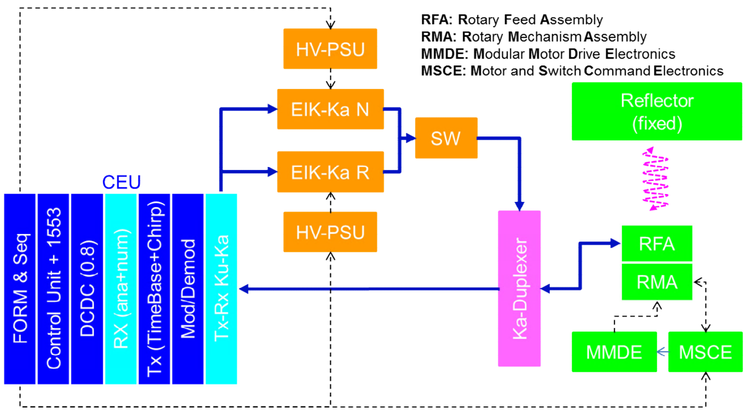


Fig. 2: SKaR functional block diagram.

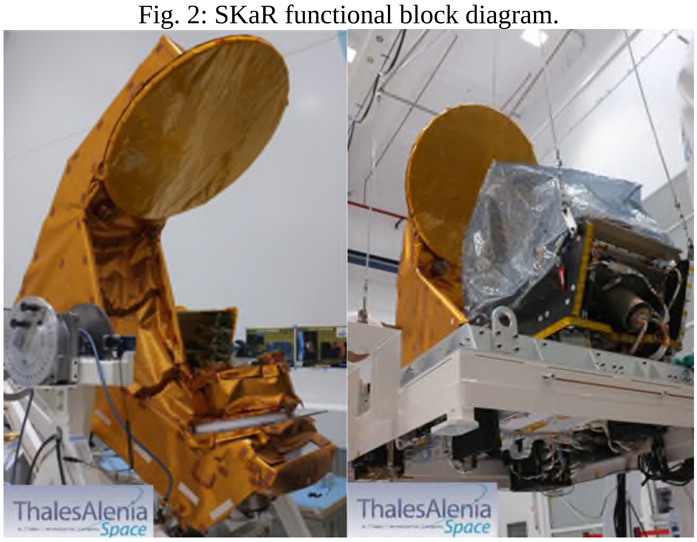


Figure 5: SWIM antenna PFM (left) after tests (left) and during mounting on the flight panel (right). All SWIM electronic equipments are installed in the interior side of the flight pannel supporting the antenna.

Instrument performances

Single shot SNR are obtained with a mean transmitted power at antenna feed of 50 W and an instrument receiver noise of 1045°K.

Parameter	Value
SNR (single shot)	>30 dB Nadir >10 dB (6°) >7 dB (12°)
Altimetric performances - range noise - range bias/drift	 1cm @1Hz (2m) 1 mm/an
Radiometric performances - Absolute accuracy - Relative Beam Accuracy - Resolution (Kp)	 ± 0.5 dB ± 0.1 dB 0.1 dB
Pointing restitution accuracy (Data re-tracking)	0.2 arcsec (incidence) 1 arcsec (azimuth)
Pulse pair phase estimator resolution (LOS over beam)	2 cm/s (12°) 2.6 cm/s (6°)
Effective resolution (range resolution+range migration correction)	<6 m (12°) <8 m (6°)

Table 2: Single shot Signal to Noise Ratio in the Line of Sight.

Instrument budgets

Power consumption of the instrument in measurement mode is estimated to 400 W (250 W for the HPA). Mass of the instrument is lower than 120 kg (around 50% for the antenna).

CONCLUSION

Doppler oceanography from space has the unique capability to reveal the complex structures of the ocean (equatorial upwellings and dynamics of marginal ice zones for instance). The innovative radar instrument presented in this paper has been designed for the "Sea surface KInematics Multiscale monitoring" mission SKIM. It is the combination of an improved altimeter design (high pulse repetitionfrequency, SAR mode, Ka-band) with a proven rotating beam system to sample a 280 km swath inherited from the SWIM instrument built by Thales Alenia Space for the CFOSAT mission and the use of Doppler measurements for both currents (Doppler centroid) and waves (Doppler modulation in range).

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