THE HARMONY MISSION: END OF PHASE-0 SCIENCE OVERVIEW

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ABSTRACT

Using a combination of multi-directional SAR and TIR measurements, the Harmony Earth Explorer 10 mission candidate will provide high resolution simultaneous measurements of surface stress, surface currents SST and wave spectra over oceans, 3-D deformation vectors over solid Earth, and time-series of surface elevation changes over volcanic areas and land ice masses. This will serve a series of science objectives aimed at better understating multi-scale processed and feedbacks in the Earth System.

***Index Terms*—** bistatic, companion missions, Synthetic Aperture Radar

1. INTRODUCTION

Harmony[1] is one of the three ESA Earth Explorer 10 mission candidates. This paper gives an overview of the mission reflecting its status at the end of the Phase-0 studies, which were completed towards the end of 2020.

The Earth is a highly dynamic system where transport and exchanges of energy and matter are regulated by a multitude of processes. The non-linear nature of the governing physics results in couplings between processes happening at a wide range of spatial and temporal scales, with cascades of energy flowing from the larger to the smaller scales and vice-versa.

The Earth System cannot be understood or modeled without adequately accounting for small-scale processes. Indeed, the parameterisation of the unresolved, sub-grid physical processes in global or regional models remains one of the main sources of uncertainty in climate projections, in particular with respect to air-sea coupling, cryosphere and clouds [2, 3].

2. MISSION OVERVIEW

Addressing these needs, Harmony is dedicated to the observation and quantification of small-scale motion and deformation fields, primarily, at the air-sea interface (winds, waves, and surface currents), of the solid Earth (tectonic strain), and in the cryosphere (glacier flows and surface height changes).

The retrieval of kilometre and sub-kilometre scale motion vectors requires concurrent observations of its components. As illustrated in Fig. 1, this will be achieved by flying two relatively light-weight satellites as companions to a Sentinel-1 mission [4] spacecraft, with a receive-only radar as main payload. The resulting line-of-sight diversity will be exploited in combination with repeat-pass SAR interferometry to estimate tiny deformation rates in the solid Earth, and for land ice processes. It will also be used in combination with Doppler estimation techniques for the retrieval of instantaneous ocean and sea ice surface velocities. Over oceans, geometry-diverse measurements of the radar backscatter will further allow the retrieval of surface (wind) stress and wave-spectra. The Harmony spacecraft will also carry a multi-beam thermal-infrared payload, which in the presence of clouds will allow the retrieval of height-resolved motion vectors. The combination of surface currents, surface wind-stress, along with TIR derived cloud-top height and cloud-top motion vectors will provide an unprecedented view of the MABL. In absence of clouds, the TIR payload will provide simultaneous observations of the sea surface thermal differences, providing a unique window to look at upper-ocean processes and air-sea interactions on the small ocean scales.

The formation flying architecture of Harmony enables the unique capability to reconfigure its flight formation so that instead of being optimised for the measurement of motion vectors, it is optimised for the measurement of time-series of surface topography. This will, among other outcomes, result in a globally consistent and highly resolved view of multi-annual glacier volume changes between well defined epochs, needed to better quantify the climatic response of glaciers. At the same time, Harmony will allow studying the seasonal and sub-seasonal processes from space that play a role in such responses, for instance by measuring variations in lateral ice flow and associated elevation changes simultaneously over large areas for the first time.

3. SCIENCE OBJECTIVES

3.1. Oceans, atmosphere, and air-sea interactions

Harmony will provide kilometer-scale surface roughness, root mean squared slopes, and surface kinematics, in different viewing perspectives, reflecting the imprint of Marine Atmospheric Boundary Layer (MABL) eddies on the ocean surface. This provides information about both the surface wind vector, as well as surface current vectors and swell, and, importantly, the thermal disequilibrium between air and ocean.

This will lead to a more precise understanding of small-scale (submesoscale) impacts on air–sea fluxes, especially CO_2 fluxes, momentum, ocean heat uptake and overall energy pathways, to reduce uncertainties for lateral dispersion of pollutants and tracers, vertical transport and nutrient pumping. Specifically, Harmony's very high-resolution capabilities aim at:

- Extend the knowledge of the 2D co-spectra of surface stress and wind, surface currents, and SST from scatterometric scales (25km) down to O(1km) scales.
- Quantify the contribution of small scale processes (down to O(1 km) scales) to the air-sea fluxes of gas (CO_2), momentum, and heat.
- Quantify the vertical fluxes within the MABL at 1km horizontal scale.
- Measure surface stress equivalent wind vectors at 1 km scale in extreme wind conditions.
- Retrieve directional wave spectra and simultaneous near inertial currents at 5-10km resolution, during all phases (ahead, during, and in the wake) of the passage of the extreme weather event.
- Extend the knowledge of the ocean surface motion power spectrum from currently resolved mesoscales (O(50km)) down to submesoscales (O(1-10km)), capturing regional and seasonal variabilities.
- Quantify the vorticity and flow divergence in the upper ocean at O(1km) horizontal scale, to estimate vertical fluxes across the ocean boundary layer.

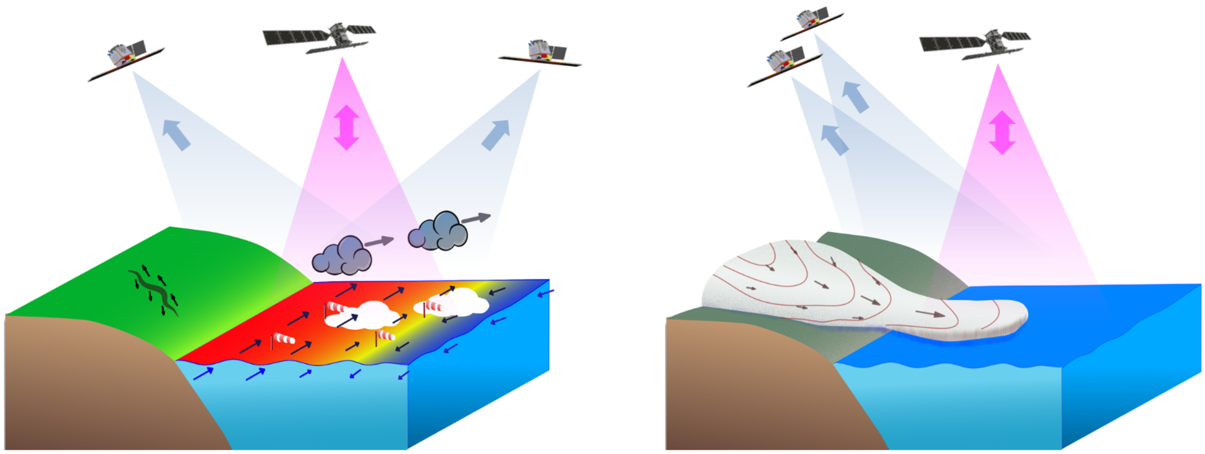

Fig. 1: The left cartoon illustres Harmony flying in StereoSAR configuration. High resolution measurements of surface roughness are used to retrieve high resolution surface stress-equivalent winds, while short-baseline ATI Doppler measurements allow the simultaneous retrieval of surface currents. Simultaneously, the multi-directional TIR payload provides observagions of sea-surface temperature and/or cloud-top heights and motion vectors. Over land surfaces, line-of-sight diverse repeat pass InSAR allows the retrieval of 3D surface motions. The cartoon on the right shows Harmony in a XTI formation, which will allow the retrieval of dense time series of surface elevation models while retaining 3-D DInSAR capabilities.

3.2. Dynamical changes in the Cryosphere

The scientific goal of Harmony for the cryosphere is to bridge existing observational gaps in order to improve our understanding of the physical processes causing the widespread shrinkage of the cryosphere. These conceptually new observations will push back the existing limits by refining the reconstructions of past and ongoing glacier changes, by improving the representation of the driving mechanisms in regional and global models of ice flow dynamics and mass balance, by describing the unresolved complex processes allowing calibration and validation of sea ice models with more realistic rheology or by improving our understanding of the permafrost dynamics.

Harmony aims at providing, for the first time, worldwide integrated measurements of elevation changes and ice flow on glaciers and ice-sheet coastal areas, as well as localised elevation measurements of icebergs and ice shelves. A particular strength of the interferometric capabilities of Harmony that the mission is able to measure large topographic changes and lateral displacements (scale of metres and tens of metres) through repeat XTI-mode elevation models and SAR offset tracking, and, at the same time, small changes (cm-scale) thanks to the diversity of SAR lines-of-sight.

Specifically, the cryosphere-related mission objectives are:

- Quantify multi-year average elevation change for most glaciers and ice sheet outlets, with a high spatial resolution of at least 100m, and sub-meter accuracy.

- Providing (i) elevation change, at high spatial resolution of at least 100 m, at sub-seasonal time-scale, and with vertical accuracy of 5m or better, together with (ii) simultaneously-acquired SAR data from which horizontal displacements can be derived.

- Monitor 3-D surface motion and deformation of glaciers and ice streams.

Parameter	Accuracy	Spatial resolution
Relative Ocean Surface motion	$15\,\mathrm{cm/s}$	$4\,\mathrm{km}^2$
Surface wind	$7.5\,\%$	$1\,\mathrm{km}^2$
Relative SST	$0.1\,\mathrm{K}$	$1\,\mathrm{km}^2$
Surface Elevation Change (Ice)	$1\,\mathrm{m}$	$100 \times 100\mathrm{m}^2$
Surface Elevation Change (Land)	$1.5\,\mathrm{m}$	$30 \times 30\mathrm{m}^2$
3D surface deformation rate	$1\,\mathrm{mm\,yr^{-1}}$	$100 \times 100\,\mathrm{m}^2$

Table 1: Main Harmony sensitivity requirements.

3.3. Solid Earth

Harmony aims to provide an integrated view of the dynamic processes that shape the Earth's surface. For the Solid Earth, the scientific goals are to improve our understanding of tectonic and magmatic processes by bridging existing observational gaps with regard to strain rates, which are currently hindered by the lack of sensitivity to the North-South deformation component, and with regard to rapid elevation changes. Filling these gaps leads to the following mission objectives:

- Measure 3-D surface motions in tectonic regions with an uncertainty lower than 1 mm/yr over a distance of 100 km.
- Quantify N-S surface motions associated with earthquakes, volcanoes and landslides at a spatial resolution of 100 x 100 m^2.
- Quantify topographic change at erupting volcanoes with a spatial resolution of 20 x 20 m^2.

3.4. Mission requirements & performance

Table 1 provides an overview of some key observation requirements, which are satisfied by the system concepts developed during the Phase-0 industrial.

4. OUTLOOK

At time of writing, Harmony is firmly expected to go into Phase-A, during which the system concept and the science will be consolidated. The information rich multi-modal measurements that Harmonty will provide, together with the proposed mission phasing, allows providing high quality data to service a number of science goals. This is a key strength of the mission. At the same time, adequately addressing the different goals in order to achieve the required levels of technological and scientific maturity at the end of Phase A (summer 2022) represents a significant challenge. If selected for implementation, Harmony could be launched around 2028-2029.

5. REFERENCES

[1] Paco López-Dekker, Helmut Rott, Pau Prats-Iraola, Bertrand Chapron, Klaus Scipal, and Erik De Witte, "Harmony: an Earth Explorer 10 Mission Candidate to Observe Land, Ice, and Ocean Surface Dynamics," in *IGARSS 2019 - 2019 IEEE International Geoscience and Remote Sensing Symposium*, July 2019, pp. 8381–8384, ISSN: 2153-6996.

[2] Tapio Schneider, Shiwei Lan, Andrew Stuart, and João Teixeira, "Earth System Modeling 2.0: A Blueprint for Models That Learn From Observations and Targeted High-Resolution Simulations," *Geophysical Research Letters*, vol. 44, no. 24, pp. 12,396–12,417, 2017.

[3] Tim Palmer and Bjorn Stevens, "The scientific challenge of understanding and estimating climate change," *Proceedings of the National Academy of Sciences*, vol. 116, no. 49, pp. 24390–24395, Dec. 2019.

[4] R. Torres, P. Snoeij, D. Geudtner, D. Bibby, M. Davidson, E. Attema, P. Potin, B. Rommen, N. Floury, M. Brown, I. Navas Traver, P. Deghaye, B. Duesmann, B. Rosich, N. Miranda, C. Bruno, M. L'Abbate, R. Croci, A. Pietropaolo, M. Huchler, and F. Rostan, "GMES Sentinel-1 mission," *Remote Sensing of Environment*, vol. 120, pp. 9–24, May 2012.