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GEOSYNCHRONOUS CONTINENTAL LAND-ATMOSPHERE SENSING SYSTEM (G-CLASS): PERSISTENT RADAR IMAGING FOR EARTH SCIENCE

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ABSTRACT

More frequent imaging of Earth system processes is recognised as one of the emerging needs in Earth observation. Conventional low Earth orbit satellites are limited in their ability to provide this, whereas satellites in geosynchronous orbit can in principle provide continuous imaging. A new mission design has been developed from studies for a previous geosynchronous radar mission concept (GeoSTARe) to improve its technical feasibility and geographical coverage, and to reinforce its science focus. This new mission (Geosynchronous - Continental Land Atmosphere Sensing System (G-CLASS)) is presented. G-CLASS is in fact a family of missions: we present a version focussed on the diurnal water cycle - G-CLASS:H2O - for which geosynchronous radar has great potential. G-CLASS:H2O is being developed as a proposal for ESA's Earth Explorer programme.

***Index Terms*—** GeoSTARe, radar, geosynchronous, water, G-CLASS

1. INTRODUCTION

Space provides a wide range of data for monitoring Earth system processes and is practically essential for such studies. One of the emerging requirements however is for improved temporal sampling, so that processes on timescales of a day or less can be observed directly. At the same time, radar mission proposals for geosynchronous orbit (GeoSAR) have been developed in the US, China and Europe. China is expected to launch the first GeoSAR mission in the early 2020s, and researchers in Europe have developed a family of mission proposals of increasing maturity (e.g. [1, 2]). These two trends converge in that radars in geosynchronous orbit could in principle provide some of the frequent images needed to observe processes with timescales of only a few hours - these are far beyond the capability of low Earth orbit missions. This article presents a mission concept which addresses important science questions related to the diurnal water cycle, and which is the latest version of the GeoSAR concept being developed by a team of European researchers from Italy, Spain and the UK.

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Earth observation (EO) is not a new concept. It is already provides visible and infrared images used operationally in meteorology, with imagers such as AGRI, INSAT and SEVIRI from China, India and Europe respectively [3]. However, radar imaging from geosynchronous orbit has not yet been demonstrated even though it is widely used from low Earth orbit and provides many valuable services.

The next two sections present the science motivation and an outline of the current mission design. The article concludes with a brief discussion of the concept.

2. SCIENCE OBJECTIVES

The water cycle is fundamental to Earth system science and impacts hugely on human society. It has therefore, unsurprisingly, been the focus of much study, however there still remain significant gaps. Recent surveys of scientific challenges in Earth system science (e.g. by ESA [4]) include many references to the water cycle, and identify a range of related measurement needs or science questions. ESA's science strategy is framed around broad challenges relating to the main Earth system themes of atmosphere, cryosphere, land surface, ocean and solid Earth. Challenges linked to the water cycle include:

- A1 (processes linking water vapour and the hydrological cycle with radiation),
- A2 (surface-atmosphere processes, including water, although with a focus on climate timescales),
- A4 (weather and climate interactions, including lower atmosphere measurements for regional weather and hydrology),
- C3 (seasonal snow and inland ice, and their link to climate, energy and water cycles),
- L2 (a broad set of processes involving global change drivers, and including the water cycle and hydrology),
- L5 (the effects of limiting factors such as water availability on land surface processes).

Reinforcing ESA's priorities, the survey of Societal Benefit Areas by the Group on Earth Observation [5] identifies specific measurement needs, and lists precipitation and soil moisture as the highest ranked observation needs. Other water cycle aspects such as surface humidity, river flow and snow cover are also ranked highly.

Further development of these science aims is provided by the World Climate Research Programme (WCRP) and its Global Energy and Water cycle EXchanges (GEWEX) core project. They suggest measurement needs to improve knowledge of land surface atmosphere interactions. A coherent set of water cycle measurement needs which relate to ESA's Earth science challenges (above) and which map onto aspects of the WCRP and GEWEX are:

- Fine-scale weather processes (e.g. 3 km or less, [6]),
- Improved temporal sampling, ideally to several per day or even hourly images [7] such as would be enabled using a satellite constellation or geosynchronous imaging [8]. Trenberth and Asrar also note the difficulty of modelling the diurnal cycle for understanding "water extremes" (flood, drought, etc.).

Another aspect of the measurement needs is the geographical coverage. We have relatively good data for much of Europe, but some regions of the world such as Africa have very little ground infrastructure for in situ observations and so satellite measurements which can substitute for these could have great value.

Observations which fill the measurement gaps noted above could have a real impact in improving our understanding of fine-scale weather, of within-catchment variability of surface moisture, and of the hourly to daily variability of these processes. The proposed science objectives for G-CLASS:H2O are therefore:

1. Improve the prediction capability of intense rainfall and related impacts such as flooding and landslides.
2. Improve understanding of the diurnal water cycle, especially of soil moisture in hot, dry regions and snow melt / re-freeze.

2.1. Secondary Objective

The measurements identified above also enable other science challenges to be tackled. In particular a range of weather extremes and ground motion related geohazards are served by practically the same datasets required for the primary objectives. With minimal impact on the primary objectives we can also tackle Earth science challenge G1 (volcanoes, earthquakes, landslides; [4]). This adds value without deflecting from the primary science goals.

3. Enable practically real-time monitoring of ground motion and response management for landslides, earthquakes and volcanoes.

3. IMPLEMENTATION

Observing the daily water cycle requires a mission able to persistently view the land surface and overlying atmosphere. This requires a *radar* (for all weather, day-night imaging, and sensitivity to the atmosphere and land surface properties) in *geosynchronous* orbit (persistent viewing). A single satellite in geosynchronous orbit (GEO) is proposed, with orbit inclination and eccentricity chosen to avoid the geostationary protected region used by commercial communication satellites. Motion of the satellite relative to Earth enables synthetic aperture imaging (azimuth resolution of about 1 km typically achieved in less than a minute, or 100 m within 10 min) for around 85% of the day.

3.1. Payload

C-band imaging provides a good compromise between high surface coherence (favoured by long wavelengths), sensitivity to atmospheric humidity and good spatial resolution (favoured by short wavelengths), and compatibility with many current radar missions in low Earth orbit. Polarimetric imaging with several spot beams maximises the information available and provides good geographical coverage. Figure 1 shows the coverage possible using an array of spot beams which is swept by slewing the whole satellite slowly. During the mission the beams will be steered frequently, and may cover almost any area within the local incidence angle limits of approximately 20–70°: the coverage can be commanded at short notice and requires no additional propellant, making the mission highly flexible. Using geosynchronous orbit can give much better coverage of low latitude areas than is available using conventional low Earth orbit radars (e.g. Sentinel-1A and -1B combined only provide 12 day repeats over Africa).

The mission uses a standard small GEO satellite bus which is compatible with the Vega-C launcher. Electric propulsion will be used to raise the orbit to GEO and for station-keeping. A large deployable reflector illuminated by an array of feedhorns provides the spot beams. Total power consumption of the satellite and its payload will be several kW. The ground segment supports the mission by tracking the satellite and providing calibration targets, as well as processing the payload data (in addition to standard functions of data archiving and dissemination).

Relative to the previous mission concept (GeoSTARe [2]) from which G-CLASS is derived, the main differences are (a) the relative orbit has a much larger amplitude, and (b) the antenna is larger. These are related: the larger amplitude implies a higher relative velocity, therefore shorter integration times, and thus a larger antenna diameter to achieve sufficient signal-to-noise ratio. The main benefits of these changes are avoiding the need to use the protected and tightly regulated geostationary region, increased geographical coverage, and improved interference rejection ([9], due to the smaller spot

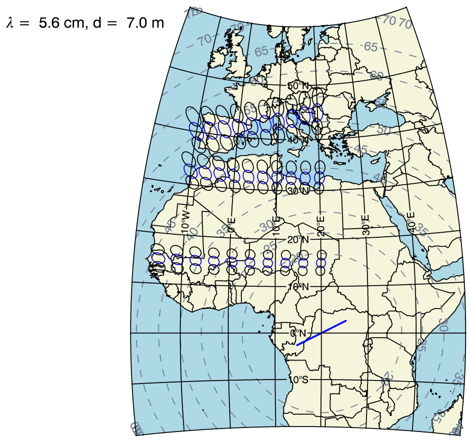

Fig. 1. Example C-band spot beam coverage, steerable over Europe and Africa by slewing the whole satellite (blue diagonal line is a representative relative orbit projected onto Earth; the dashed contours show local incidence angle).

beams).

3.2. Expected performance

Table 1 lists the geophysical variables required to address the science objectives and the corresponding measurement requirements for typical surface properties and viewing geometry (45°incidence angle). The quantitative requirements are provided by Earth scientists in the mission team or from databases such as the World Meteorological Organisation's OSCAR [10]. The baseline design assumes C-band, antenna diameter of 7 m and transmitted RF power of 300 W, and the resulting performance estimates using standard expressions based on the radar equation show that all the measurement requirements can be met, apart from the fine spatial resolution surface motion data (example results are shown in Table 2). Surface motion of the required rate uncertainty can be provided at coarser resolution (100–200 m) only.

4. DISCUSSION

G-CLASS:H2O is summarised as "A mission to observe and understand processes of the daily water cycle over land". This identifies its primary science focus and enables clear design of the mission. However, the G-CLASS mission concept is poly-valent, and the data obtained to study the water cycle can readily be applied to other areas, such as ground motion (earthquakes, landslides, subsidence, volcanoes), the cryosphere (e.g. snow cover and depth, glacier motion), and emergency response (floods, etc.). Thus missions such as G-CLASS:ground, G-CLASS:cryo, and G-CLASS:respond can also be envisaged at minimal additional cost. GeoSAR missions also scale easily for greater geographical coverage, simply by adding further satellites. Multiple satellites in principle also enable more sophisticated imaging modes such as MIMO.

The implementation challenges are not trivial, but neither do they seem insurmountable. As proposed here, G-CLASS:H2O reuses much existing technology and so the TRL is generally high. There are uncertainties for topics such as phase compensation (correcting perturbations due to clock drift, orbit uncertainty, and atmospheric refractive index changes) and the antenna design (multiple spot beams, full polarisation, agile beam steering), however we believe that these risks concern the extent to which we can maximise operational capability rather than the fundamental feasibility of the concept.

G-CLASS:H2O is being developed as a proposal for ESA's Earth Explorer programme. It addresses a significant science question, has the potential to make an important contribution, and, although challenging is some aspects, can be implemented with relatively low risk for its fundamental feasibility. Members of the development team are planning technology demonstrations and studies to retire the main technical risks, and working to develop the underlying science to enable the wide range of applications we envisage for the mission.

We believe that geosynchronous radar has significant potential. It tends to complement the capabilities of low Earth orbit satellites, and thus should become a valuable addition to the "system of systems" now underpinning our knowledge and understanding of planet Earth.

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Table 1. G-CLASS geophysical measurements related to science objectives and the corresponding Level 1 radar data products (IWV = Integrated Water Vapour, SM = soil moisture, SWE = Snow Water Equivalent; ■and □are primary and secondary requirements, ♦and ◊are corresponding primary and secondary measurements).

Science objective 1	2	3	Measurand	Level 2 data Resolution Space (m)	time (hr)	Quality	Level 1 data Measurement σ^0 HH	σ^0 VV	ϕ	$\|\gamma\|$	Quality
■	□	□	IWV	500	0.25	1 kg m^{-2}			♦	◊	$\delta\phi_z$ = 1.46 rad
■			SM (coarse)	1000	0.25	0.05 m^3 m^{-3}	♦	♦			-19.4 dB (100L)
	■	□	SM (fine)	200	3	0.03 m^3 m^{-3}	♦	♦			-19.4 dB (280L)
	■		Snowmelt area	100	3	100 m	◊	♦			-23.9 dB (1L)
	□		SWE	100	3	5 mm			♦	◊	$\delta\phi_z$ = 1.00 rad
□		■	Surface motion	20	6	2 mm d^{-1}			♦	♦	$\delta\phi_z$ = 0.25 rad
□		■	Flood extent	20	6	20 m	♦	◊		◊	-19.0 dB (1L)

Table 2. G-CLASS baseline mission design radar backscatter performance results (for incidence angles of 25°, 45°and 60°-Near, Mid and Far beam positions respectively; yellow shading shows marginally (<1 dB) missed requirements)

Objective 1	2	3	Measurand	Resolutions	Required NE σ^0 (dB) Near	Mid	Far	Achieved NE σ^0 (dB) Near	Mid	Far
■			SM (coarse)	1 km, 0.25 hr	-15.5	-19.4	-23.0	-41.0	-39.0	-36.4
	■	□	SM (fine)	200m, 3 hr	-15.5	-19.4	-23.0	-34.1	-32.1	-29.4
	■		Snowmelt area	100 m, 3 hr	-20.6	-23.9	-27.2	-31.0	-29.0	-26.4
□		■	Flood extent	20 m, 6 hr	-15.1	-19.0	-20.2	-24.1	-22.1	-19.4

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