THE NEXT GENERATION OF L BAND RADIOMETRY: USER'S REQUIREMENTS AND TECHNICAL SOLUTIONS

Yann H. Kerr[1], Nemesio Rodriguez-Fernandez[1], Eric Anterrieu[1], Maria-Jose Escorihuela[2], Matthias Drusch[3], Josep Closa[4], Alberto Zurita[4], François Cabot[1], Thierry Amiot[5], Rajat Bindlish[6], Peggy O'Neill[6]

[1]Centre d'Etudes Spatiales de la Biosphère, Toulouse, France.
[2]isardSat, Barcelona Spain.
[3]ESA ESTEC Noordwijck The Netherlands.
[4]ADS Spain, Madrid, Spain.
[5]CNES, Toulouse France.
[6]NASA GSFC, Greenbelt, Maryland USA.

ABSTRACT

After almost 10 years in operation (SMOS- Aquarius - SMAP) the very high potential of L band radiometry is clearly demonstrated. Several applications are already operational (assimilation at ECMWF, for hurricanes, for sea ice etc.) so it is crucial to maintain such measurements. To do so while satisfying the current missions specifications is also of prime importance. Degrading spatial resolution is thus a significant step back which will impact science and applications).

These missions are now getting older and the goal of the study presented in this paper is to assess which planned mission could fulfill the requirements to ensure data continuity. For this purpose, an extensive users' requirements study was performed in 2018-2019 assessing what would be required in the near future as well as when L band radiometry was absolutely necessary to satisfy the requirements. From the gathered results a cluster analysis was performed and the only

Index Terms—L band radiometry, SMOS, SMAP, Future systems, users' requirements

1. INTRODUCTION

L band radiometry is unique in many respects and has such as a role to play in any Earth observing system [1-2]. Nevertheless, as with any instrument it is not self-sufficient for some aspects and many complementarities were identified. They can be sorted in several categories.

For resolution improvement optical and thermal bands (i.e., S3 or S2 and LSTM) are used to disaggregate SMOS data to finer resolutions. Radar (typically S1 or RadarSat) have been also used for the same purpose, with less efficiency but a very appreciable all weather capability.

Over sea ice it was also demonstrated that if CryoSat type of systems could infer sea ice thickness for thick sea ice SMOS could do the same for thin sea ice, giving very complementary information. Using both systems enables to monitor all se ice thicknesses.

Using Thermal infra-red (S3 or later maybe LSTM) with L band offers also ways to infer ET over large areas.

L band radiometry and scatterometers are also used in synergy to infer wind speed over the oceans (radiometry taking over for very high speed winds).

Over land, precipitation satellite retrievals (GPM) are greatly enhanced by assimilating L Band radiometry data.

Finally, and most obviously, if there are many other examples of synergisms, one must also mention the synergies with radiometers operating at higher frequencies. It is very useful for snow retrievals as well known, but also to enhance retrievals over dense vegetation.

Other general requirements are to be fully polarimetric and to have a good RFI filtering approach (as demonstrated by SMAP)

For weather and climate, it is necessary to ensure global coverage, while for some operational uses (NWP, flood forecasts, high winds, …) a near real time acquisition is absolutely necessary.

The remaining factors to assess were the actual spatial resolution requirements together with revisit and accuracy. The cluster analysis aims at assessing the requirements weighted by uses.

2. EXPRESSION OF NEEDS

Once the original requirements have been converted to system requirements, they have been grouped to narrow down the design. Figure 1, shows the percentage of the requirements met for the different applications vs the spatial, temporal and radiometric accuracy of the system, for the three levels (Threshold, Breakthrough and Goal). The target of the system is to cover as many requirements as possible.

In order to combine the results above, a weighted metric has been created to evaluate the value added by the different stages (Threshold, Breakthrough, Goal), and the different levels of SRL and ARL. The number of points given when a particular level is reached is as follows:

- Threshold: 7
- Breakthrough: 9 (Threshold + 2)
- Goal: 10 (Breakthrough + 1)

The resulting number of points for each requirement is weighted by a factor that depends on the ARL (Application Readiness Level) and another factor that depends on the SRL (Science Readiness Level). This gives less importance to the applications with the lower maturity levels:

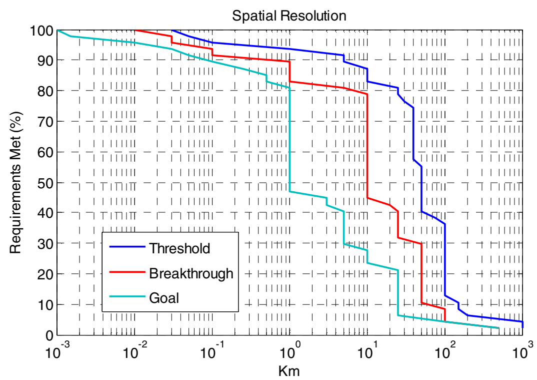

Figure 1: Percentage of requirements fulfilled vs spatial resolution of the system

The result of the weighted metrics for the three parameters is shown in the following Figure 2

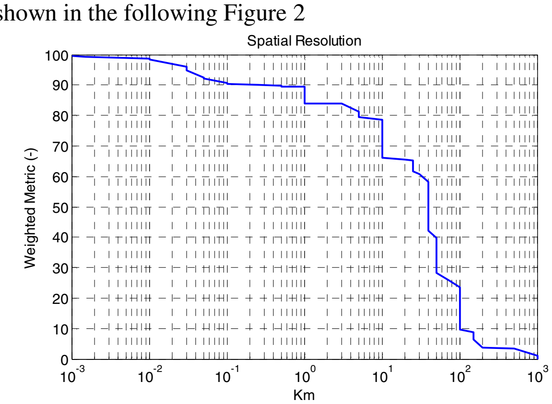

Figure 2: Value of the weighted metric achieved vs spatial resolution of the system

Obviously, the weighing carried out here is very subjective and prone different interpretations or could give different results if carried out differently (with for example elimination criteria below threshold). It is never the less a means to grasp the complex issue. It simply has to be considered with caution.

3. SYSTEM REQUIREMENTS

From the results obtained in the previous section, some key high-level system requirements are derived below.

3.1 Spatial Resolution

First, for the spatial resolution (Figure 1), it can be seen that 1 km fulfills around 95% of the applications' requirement, of which more than 90% is at the Breakthrough level, and 80% is at the Goal level. This is indeed the desired resolution. However, given the low frequency of 1413 MHz, this would require a huge antenna. A more realistic resolution would be in the range from 10 km (85% of applications' requirement, of which 80% are at the Breakthrough level) to 25 km (80% of applications' requirement met and 40 at Breakthrough level). The 60 km fulfils 40% of the applications' requirement with 10% at the breakthrough level.

Taking into account the weighted metric (*Figure 2*) for the spatial resolution, it is clear again that 1 km has a metric of 90, while for 10 km it is 80. The resolution of 25 km achieves a value of 65 and 60 km 25 in the weighted metric.

Considering the abrupt changes at 1 and 10 km in the weighted metric and the current technological and financial constraints, one can safely say 10 km should be the design driver.

3.2Temporal Resolution

The achieved temporal resolution depends on the position on the Earth. The worst case (lowest temporal resolution) happens on the Equator, but at higher latitudes, the temporal resolution improves.

The analysis in [4] showed that there is a clear step at the temporal resolution of 1 day, fulfilling 90% of the applications' requirement, with a value of the weighted metric of 82. A more conservative value would be a temporal resolution of 3 days (worst case, on the equator), which would fulfill 75% of the applications' requirement, achieving a weighted metric of 62.

3.3 Radiometric Accuracy

It was found [4] that there are three points of interest, 0.1K, 0.5K and 1K. The desired accuracy would be 0.1K, achieving almost 90% of the applications' requirement (70% at the Breakthrough level). However, this can be challenging. The value of 0.5K fulfills 60% of the applications' requirement at the Breakthrough level. An accuracy of 1K fulfills 63% resolution only at the threshold level.

For the weighted metric the desired resolution would be 0.1 K, achieving a value of 85. An accuracy of 0.5 K gives 65, and 1K achieves 60.

This value is assumed to reflect the residual accuracy achieved after in-flight calibration (e.g. bias removal after cold sky calibration, ocean target calibration, etc). Note that for some systems, (interferometers) data aggregation (multi angular viewing system) enables to improve the sensitivity.

3.4 Minimum System Requirements

According to the discussion in the previous sections, the optimum requirements for the system would be:

- Spatial Resolution: 10 km

- Temporal Resolution: 1 days on the Equator (would be better at higher latitudes)
- Radiometric Accuracy: 0.5 K

And the minimum requirements for the system would be:

- Spatial Resolution: 25 km
- Temporal Resolution: 3 days on the Equator (would be better at higher latitudes)
- Radiometric Accuracy: 1 K

4.ANALYSIS OF CANDIDATE MISSIONS

In this presentation we are discussing four mission concepts with respect to the requirements consolidation established in the analyses above:

1. SMOS / SMAP types of satellites as a baseline featuring technologies that were developed ten to twenty years ago;
2. An evolution of the SMOS concept with a hexagonal shape (Hexagon);
3. A SMOS High-Resolution (HR) concept based on an improved SMOS concept (patented [5]) enabling to achieve a 10 km spatial resolution, which should be in phase A Q1 2020 after a trade-off study between a cross and a square structure (ADS study for CNES) currently underway.
4. The Copernicus Imaging Microwave Radiometer (CIMR) that is currently being designed as a high priority Copernicus mission addressing sea ice and sea surface temperature.

In this presentation we will concentrate on potential missions and how they fit the users' requirements.

Considering that the "Threshold" requirements are something, which can be considered as currently performed with either SMOS or SMAP we will consider that a future system must comply with the "Breakthrough" limits as much as possible and possibly pave the way for the "Goal" requirements

Table 1 depicts the different mission (with SMOS SMAP as a kind of yardstick) and how they fulfil the users' requirements as depicted in Figure 1 and *Figure 2*. For each category the first column corresponds to the expected actual values and the following three the Threshold (T), breakthrough (B) and goal (G) degree of satisfaction.

The colour code is red below 33%, orange between 33 and 50% and green above 50%.

Table 1: description of how the different mission fulfil the users' requirements

Mission	Spatial resolution				Revisit				Radiometric accuracy			
	km	% req satisfied			*days*	% req satisfied			*K*	% req satisfied		
		T	**B**	**G**		**T**	**B**	**G**		**T**	**B**	**G**
SMOS/SMAP	*40*	**75**	**31**	**6**	*3*	**78**	**53**	**28**	*1*	**62**	**43**	**32**
CIMR	*65*	**38**	**10**	**5**	*1*	**95**	**85**	**70**	*0.1*	**90**	**69**	**66**
Hexagon	*25*	**81**	**35**	**20**	*3*	**78**	**53**	**28**	*0.5*	**71**	**60**	**38**
SMOS-HR	*10*	**87**	**80**	**25**	*3*	**78**	**53**	**28**	*0.5*	**71**	**60**	**38**

All the missions but for CIMR are systematically above threshold, and for future mission if all are adequate for breakthrough in terms of revisit and radiometric accuracy we can note that spatial resolution is the discriminating factor. It has to be noted that the CIMR design has not been derived from requirements for L-band but is tailored to applications using measurements taken at higher microwave frequencies.

It is also important to note that this study encompasses many domains from operational to climate science and from ocean to land including cryosphere (see [3]). Obviously, if one is only interested in a restricted and specific science and / or application domain, key requirements will differ and the metric established here may not be applicable. But in general terms and with the exception of agriculture maybe, there are many similarities between the different disciplines.

5. CANDIDATE SYSTEMS

Taking into account the requirements and the different design possibilities, two radiometric systems are proposed: a scanning radiometer and an interferometric system.

5.1 Conical Scanning Radiometer Design

The scanning radiometer option is considering similar orbital parameter as SMOS', with an orbit height of 740 km. The corresponding swath width is 1070 km, which accomplishes the 1-day worst case median revisit time, with a maximum value of 4 days - worst case - at the Equator.

A spatial resolution of 25 km at 40º incidence angle (with forward and aft looking) results in a reflector antenna of a projected diameter of 13.1 m (1.33° beam width). This is already in the order of the Biomass reflector size and achievable with the current capabilities of the American technology, likely as well for the European one in a 10-year time-frame. It is important to limit the rotation speed of the instrument to avoid undesired mechanical inertia concerns. Resulting from this, 3 across-scan channels are needed to cope with roughly 6 rpm rotation speed, considering a 20% overlap. The integration time results in 65 ms, yet at least 3-4 samples will be acquired at each integration time to increase the along-scan overlap. The corresponding radiometric sensitivity for a 210 K receiver seeing a 150 K scene is expected to be 0.33 K. Radiometric accuracy needs to consider a proper thermal and RF characterization especially of the large antenna and the calibration sources, and is expected to be in the order of 0.5 K.

5.2 Hexagonal Interferometric Radiometer Designs

An equivalent interferometric radiometer solution for the same orbital assumptions as before may be achieved with a 9.6 m instrument. This allows constraining the size of the overall instrument to 9.6 m, just 1.6 m above the SMOS size. The number of receivers to fill in the array with such a design is 192, fully polarimetric. An equivalent Y-shape array with the SMOS scheme would require 120 receivers with a larger diameter of 12 m. This achieves a similar boresight resolution of 19.2 km and 30.7 km at 40º incidence angle. However, the benefits of the hexagonal array shape in terms of side-lobes and redundancy have been already proven in previous studies.

Regarding radiometric accuracy, assuming similar errors as in SMOS in terms of thermo-elastic deformations, antenna position errors, phase errors, pointing errors, mismatch and linearity errors among other terms, a value of roughly 1.5 K could be achieved. This is to be largely improved depending on the application with temporal/spatial averaging and the incidence angle range use. In this case, the instrument design will also need to consider RFI on-board filtering and the smart deployment of the array antenna. The solutions related to these topics are currently under study.

5.3 Square interferometric design

Very similarly to the previous concept, the square (or cross) concept is based upon a Cartesian grid system which enable to use a new design [5] giving way to reduced aliasing and improved spatial resolution. The system would –with a larger size – enable reaching the 10km spatial resolution goal with an improved sensitivity as elementary antenna apertures can be made larger. All the other SMOS characteristics (revisit and sensitivity would be slightly improved. The concept has just finished phase 0 and is now starting phase A.

5.4 Way forward

As described above the most challenging issue is to achieve a better spatial resolution, ideally 1 km or less. With classical antennas this seems totally out order as the antenna size and number of receivers grows to an unachievable limit. The solution is with interferometry as demonstrated by radio astronomers.

SMOS –HR can achieve a resolution of 10 km or so it is also the limit – at least for some time. The idea is thus to go towards a hybrid system with a SMOS-HR like structure surrounded by a swarm of elementary (nanosat) units (an antenna which is the ULID concept (now in phase A at CNES). The ULID (Unconnected L-band Interferometric Demonstrator) demonstrator will thus address this point.

Coupled with disaggregation technique, such systems could provide data at 10 to 100 m spatial resolution with still a reasonable accuracy (around 6-8 %), largely superior to anything achievable with active systems.

6. CONCLUSION

In this presentation, the scientific requirements have been analyzed and the system level requirements have been defined after clustering and weighting the requirements for each application.

Considering the threshold values, all proposed future systems would meet the requirements and are technically feasible but for CIMR on the spatial resolution point of view.

Considering the Breakthrough values the interferometric approaches satisfies most of the requirements for the hexagon while the SMOS-HR concept is fulfilling 80 % of the requirements for spatial resolution.

Requirement	**Value**	**% Requirements met**
Spatial Resolution	10km	80 % (breakthrough)
Temporal Resolution	3 day	53 % (breakthrough)
Radiometric Accuracy	0.5 K	60 % (breakthrough)

As mentioned earlier, CIMR has not been designed to meet the requirements posed by the applications benefitting the most from L-band measurements. However, this Copernicus CIMR mission will be extremely valuable for what it was designed for albeit of limited interest for several applications fulfilled by SMOS/SMAP. All these prospective L band instruments are also important elements helping to keep L-band as a protected band.

The large number and variety of applications that heavily rely on L-band measurements justify a dedicated L-band mission meeting the requirements collected within the framework of this activity. With SMOS being operational for more than ten years, a follow-on mission is urgently needed and technically feasible.

7. ACKNOWLEDGEMENT

This study has been conducted within the framework of the ESA study 4000119610/16/NL/IA. The authors are also indebted to CNES and the TOSCA program which funded part of this study. The authors wish to thank all the science and technical contributors to this study who provided the science requirements and technical solutions

8. REFERENCES

[1] Y. H. Kerr *et al.*, "The SMOS Mission: New Tool for Monitoring Key Elements ofthe Global Water Cycle," *Proceedings of the IEEE,* vol. 98, no. 5, pp. 666-687, 2010.

[2] D. Entekhabi *et al.*, "The soil moisture active passive (SMAP) mission," *Proceedings of the IEEE,* vol. 98, no. 5, pp. 704-716, 2010.

[3] Kerr Y et al 2019, Low Frequency Passive Microwave User Requirement Consolidation Study, Issue 2, 09/09/2019, technical note SO-TN-CB-GS-0075, CESBIO, Toulouse.

[4] Yann Kerr et al , 2019 , Cluster Analysis Report, Technical note SO-TN-CB-GS-0082, Cesbio, Toulouse.

[5] Kerr et al., 2017, Système d'imagerie radiométrique, Nouvelle géométrie de la structure d'antennes, patent 2017, pat B1661