Ocean Monitoring using GNSS-R Techniques and Microwave Radiometry: the PAU Instrument Concept

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***Abstract*— Lack of frequent and global observations from space is currently a limiting factor in many Earth Observation (EO) missions. Two potential techniques that today have been proposed are: 1) the use of satellite constellations, and 2) the use of Global Navigation Satellite Signals (GNSS) as signals of opportunity (no transmitter required).**

GNSS-R was originally proposed in 1993 by M. Martin-Neira (ESA-ESTEC) for altimetry applications, but it has been proposed to use it to perform the sea state correction required in sea surface salinity retrievals by means of L-band microwave radiometry (T_B). At present, two space-borne missions are currently planned to be launched in the near future with this purpose: 1) ESA's SMOS mission, using a Y-shaped synthetic aperture radiometer, launch date November 2nd, 2009, and 2) NASA-CONAE AQUARIUS/SAC-D mission, using a tree beam push-broom radiometer.

In the SMOS mission, the multi-angle observation capabilities allow to simultaneously retrieve not only the surface salinity, but also the surface temperature and an "effective" wind speed that minimizes these errors. In AQUARIUS an L-band scatterometer measuring the radar backscatter (σ_0) will be used to perform the necessary sea state corrections. However, none of these approaches are fully satisfactory, since the effective wind speed captures some sea surface roughness effects, at the expense of introducing another variable to be retrieved, and on the other hand the plots (TB-σ0) present a large scattering.

In 2003, the *PAU* project was proposed to the European Science Foundation to test the feasibility of the use of GNSS signals of opportunity reflected over the sea surface to make sea state measurements and perform the correction of the L-band brightness temperature. This paper describes: the Physics of the L-band radiometric and GNSS reflectometric observations over the ocean, the ground-based measurements and their interpretation, and proposed satellite payloads to gather these type observations and how they can help future SMOS follow-on missions.

***Keywords*— microwave radiometry, GNSS-R, L-band, ocean, salinity, sea state, satellite payload.**

I. L-BAND RADIOMETRY AND GNSS-R PRINCIPLES

The Sea Surface Salinity (SSS) is a key climatologic and oceanographic parameter since it has a significant influence on the ocean currents, it is related to the evaporation minus precipitation… Sea surface salinity can be determined by means of L-band radiometry (1.400 – 1.427 MHz) where the sensitivity to salinity is relatively "high" (~0.5 K/psu at 15ºC), and a quiet band exists. However, the sea emission at L-band depends on other parameters, such as the Sea Surface Temperature (SST) and mainly, the sea state (surface roughness) [1]. However, the relationship between the brightness temperature changes and the sea state is complex, since the sea emission is not dominated neither by capillary waves, nor by the long waves, and even swell effects have an influence.

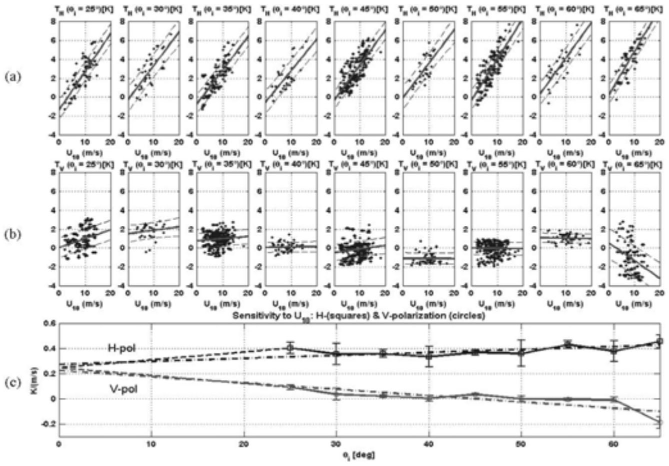

Fig 1. Derivation of the brightness temperature sensitivity to wind speed. (a) $\Delta T_{B\ h,\ wind}$ and (b) $\Delta T_{B\ v,\ wind}$ scatter plots, (solid line) linear fit, and (dashed lines) percentile 50% as a function of wind speed for incidence angles from 25° to 65°. (c) Derived $T_{B\ p}$ sensitivity to wind speed as a function of (solid line) polarization and incidence angle, associated ±1 σ error bars, and (dashed lines) linear fit . All data points used (Fig. 6 from [2])

Experimental activities conducted in the frame of the SMOS mission have shown that regressions in terms of the geophysical variables usually measured such as the wind speed (WS) and/or the significant wave height (SWH), exhibit a too high scattering (Fig. 1) to provide a satisfactory correction to perform the sea state correction for the salinity retrieval, and that it is advisable to retrieve an "effective" wind speed as well, that can compensate for modeling errors [2].

In 2003, the *PAU* (*P*assive *A*dvanced *U*nit for ocean monitoring) project was proposed to the European Science Foundation to test the feasibility of the use of GNSS signals of opportunity reflected over the sea surface to make sea state measurements and, jointly with IR observations, perform the corrections of the L-band brightness temperature [3; http://www.esf.org/activities/euryi/awards/2004.html]. The concept is simple: when the electromagnetic wave is scattered over the sea surface, the scattered signal comes from the specular reflection point, determined by the shortest distance between the transmitting GPS satellite and the receiver, but when the sea is roughed, the scattered signals come from a wider region that enlarges with increasing sea state, in a similar manner as the Sun reflecting over the sea (Fig. 2).

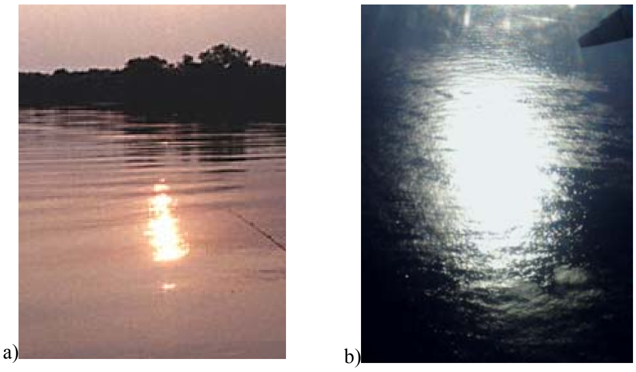

Fig. 2. Sun glint over the sea for a) calm and b) windy conditions.

When observing the GNSS reflected signals, two points over the sea surface correspond to the same delay and Doppler coordinates, with minimum delay corresponding to the specular reflection point (Fig. 3). In *PAU* it was proposed to measure the complete Doppler-Delay Maps (DDMs) to make the sea state correction of the brightness temperature, that is required for the salinity retrieval. The DDM is the square of the absolute value of the correlations of the reflected GNSS signals with local replicas of the transmitted signal, but shifted in delay and Doppler. The volume above a given threshold of the normalized DDM (peak equal to one, Fig. 4) provides a measurement of the width of the area over which the GNSS signals are scattered, and it can be related to geophysical variables without need of any intermediate model, either numerical to compute the scattering or for the sea surface spectrum [4, 5].

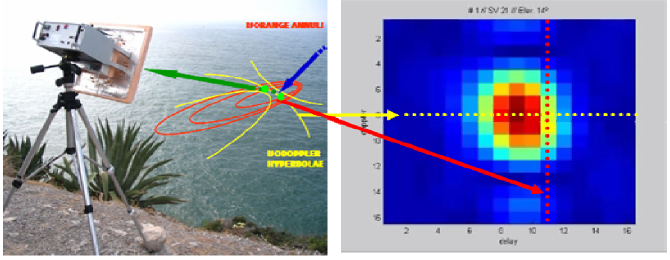

Fig. 3. (left) GNSS-R geometry of observation from Garraf coast (South of Barcelona). Red: isorange annuli (same delay), Yellow: isoDoppler hyperbolae (same Doppler), Green dots with same delay and Doppler. (right) measured DDM.

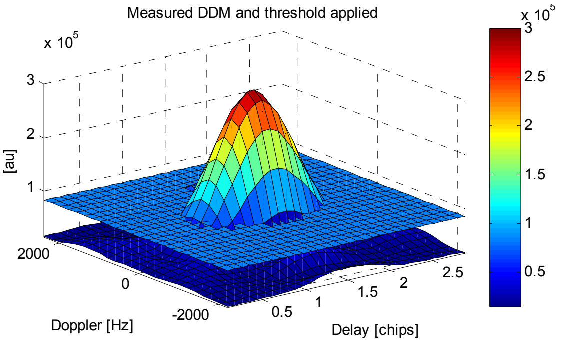

Fig. 4. Measured (not normalized) 1 s incoherently integrated DDM with the threshold applied to compute its volume. Noise is well below the threshold [6].

II. FIELD EXPERIMENTS

Under the EURYI-2004 grant a number of *PAU* prototypes have been developed (real and synthetic aperture versions of it, with just one receiver for ground tests and a lighter version for remote controlled aircraft operations). During May-June 2008 a one-receiver *PAU* was deployed at El Mirador del Balcón, La Aldea de San Nicolás, in the North-West coast of Gran Canaria ([http://www.grancanariavirtual.com/miradorelbalcon.php]), in the Canary islands, and gathered for the first time ever L-band radiometric and GNSS-R data, together with oceanographic data (sea surface temperature + sea surface directional spectrum buoys). The field experiment was repeated during the same period of time in 2009 with an improved version of the instrument (*griPAU*) that collected radiometric and GNSS reflectometric data collocated both in time and space using two different antennas with the same 25° beamwidth (Fig. 5).

Fig. 5. *griPAU* deployed during the ALBATROSS 2009 field experiment.

Now, the relationship between the sea state and the GNSSR observables (DDMs) and the changes in the brightness temperature start to be understood. Figure 6 shows the scatter plot of the measured DDM volume (in arbitrary units) vs. the SWH for different threshold values. It can be appreciated that increasing the threshold decreases the sensitivity to SWH since a lower volume is being considered. However, this threshold cannot be arbitrarily small, since it has to be above the noise threshold to provide meaningful observations (Fig. 4).

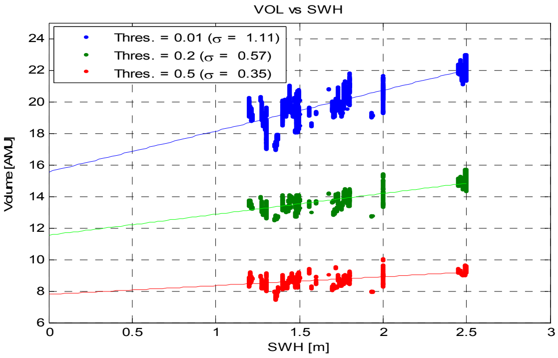

Fig. 6. Volume dependence on the SWH for three different thresholds [5].

The correlation of the instantaneous brightness temperature changes and the instantaneous DDM volumes observed during ALBATROSS 2009 is shown in Fig. 7 for incidence angles larger than 55°, since the cliff already imposed a 45° mask, and incidence angles between 45° and 50° were affected by multi-path.

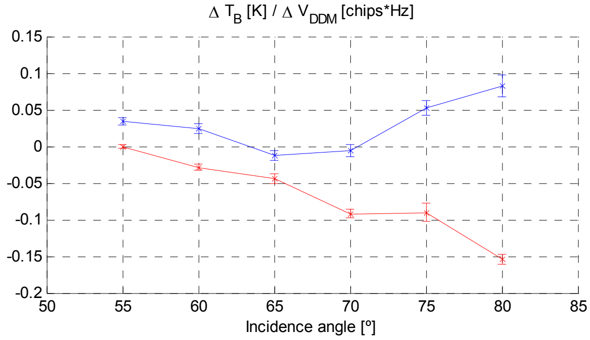

Fig. 7. Estimated brightness temperature sensitivity to changes in the normalized DDM volume at vertical (red) and horizontal (blue) polarizations respecively [6].

As it can be appreciated, the behavior is very similar to that shown in Fig. 1, including a zero crossing around 55° degrees at vertical polarization, which suggests that both descriptors (WS in Fig 1 and the volume of the DDM, V_{DDM}, in Fig 6) are measuring the same phenomena.

Despite these encouraging results, there is still a long way to go until meaningful physical quantities that can be successfully extracted from satellite data to be used by the oceanographic communities, and or they can be used to perform the sea state correction in sea surface salinity retrievals. More extensive data sets need to be gathered and processed.

The limited GNSS-R data gathered by the UK-DMC satellite and publicly available shows the potential of this technique, and supported the proposal of a *PAU* secondary payload in SeoSat/INGENIO (Spanish Earth Observation Satellite). This proposal went through phase A, but did not succeed to pass into phase B due to the accommodation issues with the primary payload raised after a configuration change. Simplified, lighter and less power consuming payloads are currently under development to be ready for future launches of opportunity or even in pico-satellites.

III. PROPOSED SATELLITE PAYLOADS TO TEST THE CONCEPT

PAU in INGENIO (formerly known as SeoSAT, Spanish contribution to the EU GMES program) was a simplified version of the full *PAU* instrument, following the concept described in [3], but with only one receiver and a LHCP (left hand circularly polarized) antenna with a 20º beamwidth. The platform will be in a Polar orbit (inclination = 98.9º) at 681 km height and the primary payload will be an optical VIS-NIR sensor. For the secondary payload a call for ideas among Spanish scientific community was issued in the Fall of 2006, and on December 2006 *PAU* was selected for selected for Phase A, which was developed during 2007. The *PAU* in SeoSAT/INGENIO instrument was designed in four trays to fit in the mass (9.8 kg), volume (< 200 x 200 x 500 mm) and power consumption (< 20 W) envelopes. Unfortunately, the complexity of the main payload limited the envelopes and *PAU* did not went into Phase B in February 2009.

Figure 8 presents an artist's view of (a) *PAU* in SeoSAT/INGENIO, and (b) payload formed by four trays.

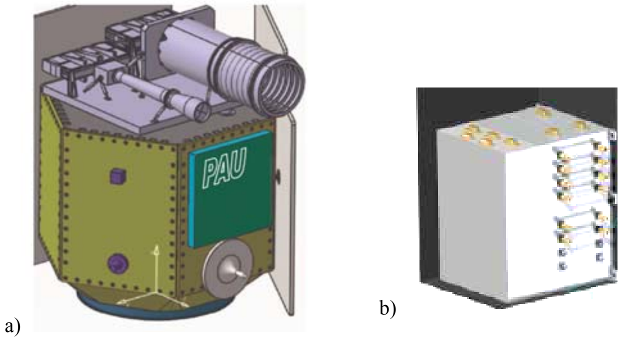

Fig. 8. a) Artist's view of the *PAU* antenna (in green) in the nadir-looking face of the platform of SeoSAT/INGENIO as the primary payload, and b) view of *PAU* payload.

IV. CONCLUSIONS AND FURTHER WORK

This paper has presented the –probably– most serious problem associated to the remote measurement of sea salinity using L-band radiometric measurements: the sea state correction.

The combined use of radiometric and GNSS reflectometric data was proposed [3] to make this correction using the full Delay-Doppler Map (DDM).

Under an ESF EURYI Award (2004) a number of series of *PAU* instruments have been developed. They combine in a single RF front-end the radiometer and GPS reflectometer (plus eventually an IR radiometer, for sea surface temperature measurements).

Results from field experiments have been presented showing a good correlation between: 1) the changes in the volume of the normalized DDM and the SWH, and 2) the changes in the brightness temperature at H- and V-polarizations, which opens a new way to make the sea state correction in future SMOS missions by using a GPS reflectometer.

A reduced satellite *PAU* payload was proposed to demonstrate this concept from space in the SeoSAT/INGENIO satellite, but did not pass to phase B in February 2009. At present, smaller and low-power consumption payloads are being developed to be launched in future launches of opportunity.

V. ACKNOWLEDGEMENTS

This work, conducted as part of a EURYI (European Young Investigator) Award, 2004, was supported by funds from the Participating Organizations of EURYI and the EC Sixth Framework Program. It has also been supported by research projects ESP2007-65667-C04 and AYA2008-05906-C02-01/ESP.

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