The COWVR Mission: Demonstrating the Capability of a New Generation of Small Satellite Weather Sensors

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***Abstract*—The Compact Ocean Wind Vector Radiometer (COWVR) is new type of conical sensor ideal for small satellite implementation. This paper provides an overview of the COWVR sensor, mission and provides perspectives for the future of this technology to enable low-cost sustainable passive microwave observations into the next decade.**

Keywords—microwave radiometer, calibration, wind vector

I. Introduction

Passive microwave radiometer systems, such as SSM/I, AMSR-E, AMSU, WindSat and GMI, have been providing important Earth observations for over 30 years, including by not limited to surface wind vector, atmospheric and surface temperature, water vapor, clouds, precipitation, snow and sea ice. These data are critical for weather forecasting and the longevity of the record, along with careful calibration, has also enabled the extraction of climate records. But the future of these systems, conically scanning systems in particular, is uncertain. The next generation conical sensor planned for NPOESS was canceled in part due to the sensor cost and complexity and a replacement has not yet been identified. A solution may lie in smaller, lower-cost but equally capable sensors manifested on free-flying small-satellites which can open the door to new possibilities and an avenue for sustainable passive microwave observation. Among the possibilities are deployment in constellations to shorten revisit time to improve weather forecasting or routine deployment of single sensors over time to ensure an unbroken long duration climate record.

In recent years, there has been significant technology development in microwave radiometers on CubeSats, but a fundamental limitation is the small size of the U-form factor (<10cm) constraining operation to higher frequencies (>90 GHz) where reasonable spatial resolutions can be achieved and limiting observations to atmospheric temperature, water vapor and precipitation. Lower frequency microwave radiometers (6-90 GHz), which are needed for measurements of sea surface temperature, wind vector, snow, sea ice, and rain, are more suited to ESPA-class spacecraft (EELV Secondary Payload Adapter) where larger apertures (>50cm) can be accommodated. In this paper, we will describe recent technology advances toward meter-class small-sat based conical passive microwave sensors. The paper will focus on the Compact Ocean Wind Vector Radiometer (COWVR), which was completed in September 2015 by the Jet Propulsion Laboratory (JPL) for a US Air Force paceborne technology demonstration mission. COWVR is currently awaiting integration with the spacecraft.

II. COWVR Sensor and Mission Description

A. Sensor Description

COWVR is an 18-34 GHz fully polarimetric radiometer with a 75cm aperture designed to provide measurements of ocean vector winds with an accuracy that meets or exceeds that provided by WindSat [1] in all non-precipitating conditions, but using a simpler design which has both performance and cost advantages.

The sensor consists of a rotating, solid aluminum reflector illuminated by a fixed, single broadband feed horn and stationary electronics. The enabling features for lowering the overall sensor cost and complexity include the use of a single fixed multi-frequency feed horn permitting a simple reflector rotating about the feed axis, as opposed to having to spin the entire radiometer system; internal calibration sources which enable fully polarimetric calibration and eliminate the need for an external warm load and cold sky reflector simplifying the mechanical design and enabling a complete 360º scan; and a compact highly integrated MMIC polarimetric combining receiver implementation, lowering the system mass and power which in turn makes the system well suited for deployment on smaller class, lower cost satellites. Because the feedhorn is fixed, the polarization is fixed to the instrument and rotates relative to the Earth polarization basis around the scan. This is corrected using a simple geometric rotation matrix and is termed the electronic polarization basis rotation technique [2].

A picture of the COWVR instrument in the thermal-vacuum chamber is down in Figure 1. Note, the pyramidal object pointing at the reflector is a feedhorn termination used during the test.

Fig. 1. Figure 1. COWVR sensor in the thermal-vacuum chamber.

B. *Pre-launch calibration and performance*

Given the nature of the mission - verifying a new sensor design, a very detailed instrument characterization plan was implemented. Detailed characterization was performed at each level of integration from component to sub-system to a final end-to-end verification. Consistency between each independent test provides the necessary confidence in the derived performance estimates and calibration parameters. The final sensor was demonstrated to meet all pre-launch performance objectives. The key tests used to verify the performance were a thermal calibration characterization test, where a the instrument was cycled over temperature while viewing a stable polarmetric target; a detailed antenna pattern measurements at three azimuth positions of the antenna; and an end-to-end polarization basis rotation validation test using a rotating polarized blackbody target [3]. An example from the end-to-end test is shown in Figure 2. The TA calibration error (random noise excluded) after polarization basis rotation was shown to be less than 0.1K. The total error (including NEDT) for each channel at the sensor resolution is < 0.3K for the 18.7 and 23.8 GHz channels and < 0.2K at the 33.9 GHz channel. The estimated wind vector retrieval performance based on the pre-launch campaign is shown in Table I.

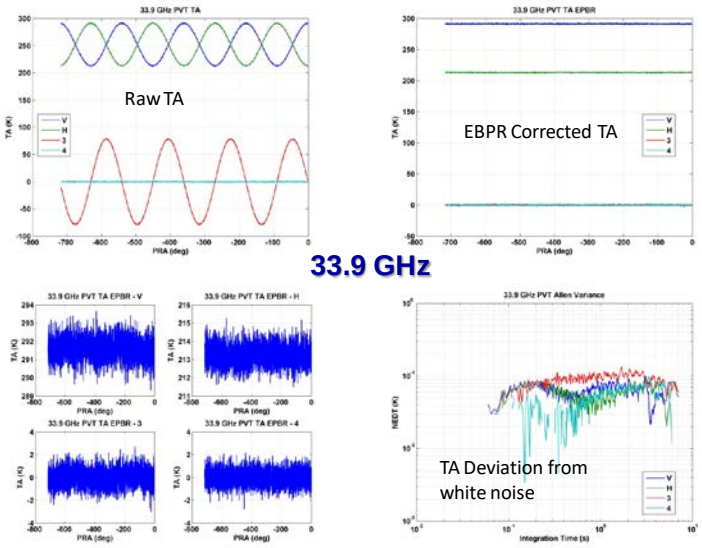

Fig. 2. Example results from the polarimetric end-to-end validation test. The first panel shows the raw TAs in the instrument polarization basis as a function of scan angle. The top right panel shows the TAs in the Earth polarization basis after application of the electronic polarization basis rotation. The bottom panels shows the residal error, which is less than 0.1K when accounting from the random noise.

TABLE I. COWVR PRE-LAUNCH WIND VECTOR PERFORMANCE ESTIMATE

COWVR Pre-launch performance estimate			
	Low Winds (< 6 m/s)	Moderate Winds (6-12 m/s)	High Winds (> 12 m/s)
Direction	36º	15º	8º
Speed	1 m/s		

C. *Novel Processing Algorithms: Polarization Un-mixing*

The offset parabolic antenna produces a small amount of mixing between the polarizations [4]. Traditionally, this is corrected using a cross-pol un-mixing matrix applied to each sample. Because the cross-pol for the polarimetric channels (3rd and 4th stokes) have positive and negative cross-pol lobes, errors can result in regions of large brightness contrast (e.g. near coastlines, convective cells). A new cross-pol correction algorithm is developed for COWVR to mitigate this error. The algorithm uses additional surrounding co-pol measurements to provide a better estimate of the integrated cross-pol brightness contribution over the main beam. The correction algorithm is given by (1). Here, the coefficients are derived from the antenna pattern and sampling geometry, which is shown in Figure 3 overlaid on one of the cross-pol patterns for the 3rd stokes channel. In practice, the maximum number of samples used in the correction will be kept below +/- 3 around the main beam for both computational efficiency and to support post-launch tuning. The performance of the algorithm is estimated by integrating the COWVR modeled antenna patterns with scenes taken from WindSat data. The performance is estimated as the difference between the true

brightness temperature integrated over the main beam and the cross-pol corrected antenna temperature. Figure 4 shows the errors for 1000 simulated scenes for the traditional single pixel algorithm (right) and the COWVR algorithm (left). The performance of the multi-sample cross-pol correction algorithm shows errors less than 0.05K for all realistic scenes.

$$T_{MB,V} = \frac{1}{a_{VV}}\left(T_{A,V} - \sum_{i,j} c_{VH}(i,j)T_{A,H}(i,j) - \sum_{i,j} c_{V3}(i,j)T_{A,3}(i,j) - \sum_{i,j} c_{V4}(i,j)T_{A,4}(i,j)\right) \quad (1)$$

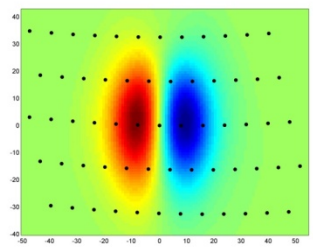

Fig. 3. Illustration of the sampling points used in equation (1).

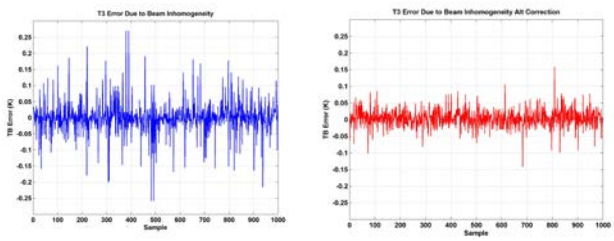

Fig. 4. Comparison of cross-pol correction algorithms applied to simulated data. Traditional algorithm (left) and COWVR algorithm (right).

D. Novel Retrieval Algorithms: Two-look radiometry

A significant benefit of COWVR is that there are no external calibration targets to block the scan enabling a full 360° scan. Because the wind direction signal over the ocean is periodic, the traditional single look algorithm results in several retrieval ambiguities. A significant improvement results from the two-look (fore and aft) observations from the 360° scan. There is a significant reduction in the number of ambiguities and the retrieval skill (probably of selecting the closest ambiguity) is greater than 90% for wind speeds greater than 5 m/s, a significant improvement over the single look algorithm. Results from detailed simulation studies are summarized in Figure 5. A significant improvement is expected, particularly for low winds where the signal is low.

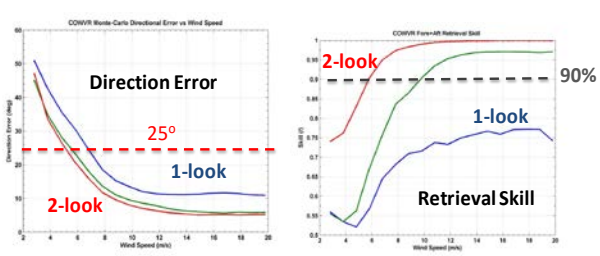

Fig. 5. Comparison between 1-look and 2-look wind vector retrieval algorithm performance.

III. Beyond COWVR: The Next Generation of Sensors

While the COWVR mission is a focused technology demonstration mission, the sensor design is scalable to a much broader frequency range while retaining its low-cost advantage. Extensions of the COWVR design have been developed which cover a broad frequency range and have larger apertures. Low-cost radiometer systems are appealing when deployed in a constellation scenario or climate monitoring scenario. In order to keep mission costs low, it is important that the sensors can be launched as secondary payloads or as dedicated launches on small lower-cost launch vehicles. This conflicts with the desire to have a large reflector for achieving high spatial resolution.

One solution is a deployable mesh reflector, as was used on SMAP, but the performance of this is only suitable for frequencies less than about 30 GHz. Our solution is a hybrid mesh reflector consisting of a smaller (< 1m) inner solid reflector with a large deployable mesh collar, extending the size to greater than 2 m. This enables a 2-m class sensor based on the COWVR architecture to operate from 6-200 GHz, yet still fit within an ESPA volume (< 80cm). This removes any limitations on the spatial resolution of the sensor, even when launched as a secondary payload in the constrained ESPA volume and opens new possibilities for sustained climate monitoring or frequent re-visit observations of key geophysical quantities (SST, wind vector, precipitation, sea ice, water vapor, cloud liquid water, temperature).

A prototype reflector was developed and tested at JPL, shown in Figure 6. The performance of the antenna was shown to be excellent for all passive microwave applications.

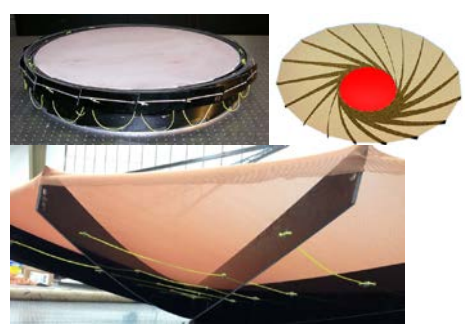

Fig. 6. JPL prototype hybrid deployable reflector prototype.

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