THE COMPACT OCEAN WIND VECTOR RADIOMETER: A NEW CLASS OF LOW-COST CONICALLY SCANNING SATELLITE MICROWAVE RADIOMETER SYSTEM

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1. INTRODUCTION

This paper describes the design and development of the Compact Ocean Wind Vector Radiometer (COWVR) which is currently being designed, built and tested by the Jet Propulsion Laboratory for an Air Force proof-of-concept technology demonstration mission planned for launch no earlier than 2016. COWVR is a low-cost, low-mass, low-power fully-polarimetric imaging radiometer system operating at 18.7, 23.8 and 33.9 GHz and based on the Jason-2/3 Advanced Microwave Radiometer (AMR) design. The fully-polarimetric observations enable retrieval of ocean surface wind vector, as well as other key environmental parameters such as precipitable water vapor, cloud liquid water, precipitation rate and sea ice. The measurement of ocean surface vector winds using a polarimetric microwave radiometer was first demonstrated by the Naval Research Laboratory WindSat radiometer (launched in 2003). Because this was a first-of-its-kind measurement, the system minimized use of new technology to ensure successful demonstration of the new measurement technique (Gaiser et al., 2005) and consequently had a large mass and power (450 kg and 350 W). The COWVR system utilizes a novel design to reduce the system complexity which in turn significantly reduces the cost, mass, power and volume from the heritage WindSat sensor, yet is predicted to maintain the same wind vector retrieval accuracy.

2. NOVEL INSTRUMENT DESIGN

Conically imaging passive microwave radiometer systems such as the Special Sensor Microwave Imager (SSM/I, SSMIS), the Advanced Microwave Scanning Radiometer (AMSR-E, AMSR-2) and WindSat, have been providing critical environmental data for over 30 years. But over this time, the overall sensor design has remained largely unchanged. These conical sensors have three basic attributes; (1) A large, massive spun portion containing the radiometer and electronics system; (2) A de-spun external un-polarized warm target and cold sky reflector and; (3) a large feedhorn array and individual receivers for each frequency and polarization. These design attributes drive the instrument mechanical complexity, spacecraft accommodation (e.g. momentum compensation) and instrument cost. For example, the WindSat needed to offset 189 Nms of spun momentum from the sensor (Koss and Woolaway, 2006). The sensors that were in development for NPOESS (CMIS and later MIS) were each expected to exceed 300 kg, 300 W and cost more than $100M (Chauhan, 2003). It is clear that a simplified design solution is needed to reduce the sensor mass, power, cost and accommodation, yet maintain the legacy performance.

The COWVR instrument uses an entirely different design to eliminate the instrument mechanical complexity that drives mass, power and cost. The enabling design features include (1) the use of a single multi-frequency feed horn permitting a simple antenna rotating about the feed axis, as opposed to having to spin the entire radiometer system and pass signals through the spin assembly; (2) 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 360^o scan and; (3) 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.

2. COWVR MISSION

COWVR is considered an Air Force proof-of-concept technology demonstration mission. The overall mission objective is the on-orbit performance demonstration of the COWVR alternative sensor design relative to the more complex heritage sensor design. The COWVR performance objectives are focused on the wind vector measurement. This is for two reasons. The Department of Defense (DoD) anticipates a measurement gap in the 2015 time frame and the wind

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vector measurement drives the overall sensor performance, meaning other products can be produced with sufficient accuracy if wind vector performance is met (e.g. PWV, TPW, sea ice). The driving performance requirements for COWVR are to meet demonstrated WindSat wind vector performance.

The mission is planned for a 450km, 6am/6pm sun-synchronous polar orbit. It is a 2-year mission with a 3-year goal. The COWVR instrument is scheduled for flight readiness by September 2015 with a launch date no earlier than first quarter of 2016.

4. COWVR INSTRUMENT DESCRIPTION

An illustration of the COWVR instrument design is shown in Figure 1. The instrument includes a single stationary multi-frequency feed horn that illuminates rotating reflector generating a 360^o un-blocked conical scan. The reflector rotates at 30 RPM and provides a spatial resolution <35km and a swath width of 1012 km from the mission orbit altitude of 450km. After the feed, an orthomode transducer is used to separate the signal into two linear orthogonal components which are then fed via waveguide into MMIC multi-frequency receivers to amplify and filter the signals. The output from the receivers is input to a hybrid combining polarimetric backend unit which performs the analog in-phase and quadrature phase cross-correlation of the two signals to produce the +45, -45 and left and right circular polarized outputs.

The instrument is calibrated using PIN-diode switches internal to the receivers and a correlated noise source. The switches are used to toggle each receiver between an ambient reference load and the antenna. The correlated noise source is capable of generating known polarized signals by injecting correlated noise with a defined phase offset between the two receiver chains.

Because the feedhorn is fixed, the instrument polarization is fixed to the instrument frame and rotates relative to the Earth polarization basis. Because the instrument measures the full stokes vector, which completely describes the polarization state of the scene, a simple geometric transform is used in ground processing to rotate the polarization from the fixed instrument frame to the Earth frame. This technique has been previously used in groundbased and airborne radiometer systems and is commonly referred to as Electronic Polarization Basis Rotation (EPBR) (Gasiewski et al., 1992; Lahtinen et al,. 2003). This actually presents a calibration advantage which is discussed further below.

The COWVR instrument mass is estimated to be 59 kg and the instrument power is estimated to be 47 W. Because the mission is a technology demonstration mission, the instrument mass and power hasn't been optimized and could be reduced for future implementations. A comparison of the COWVR design to WindSat is shown in Table 1. This table shows a clear reduction in mass, power and spun momentum from WindSat.

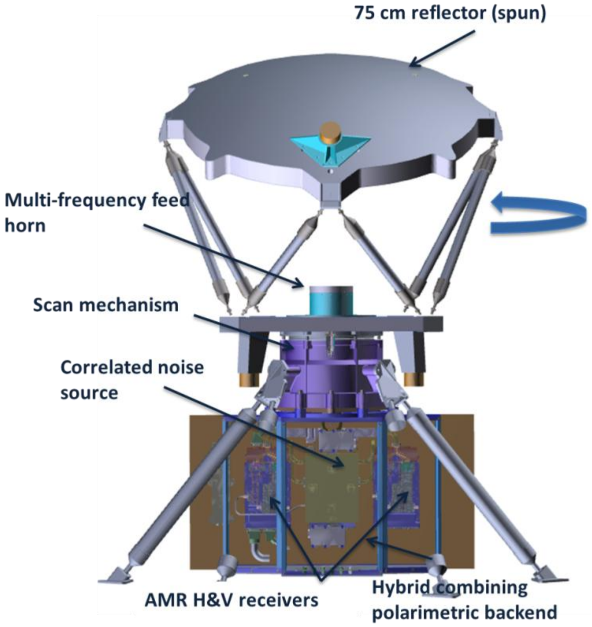


Figure 1. COWVR Instrument Design

Table 1. Comparison of COWVR to WindSat

	WindSat	**COWVR**
Channels (GHz)	6.8 (x2), 10.7 (x6) 18.7 (x6), 23.8 (x2), 36.5 (x6)	18.7 (x6), 23.8 (x6), 33.9 (x6)
Feeds	11	1
Receivers	22 independent receivers	2 three frequency polarimetric receivers
Mass	330 kg	58.7 kg
Power	350 W	47 W (inst. power)
Spun Momentum	190 N-m-s	4 N-m-s
EDRs	Wind vector, TPW, CLW, precip, sea ice, SWE, soil moisture, SST	Wind vector, TPW, CLW, precip, sea ice, SWE

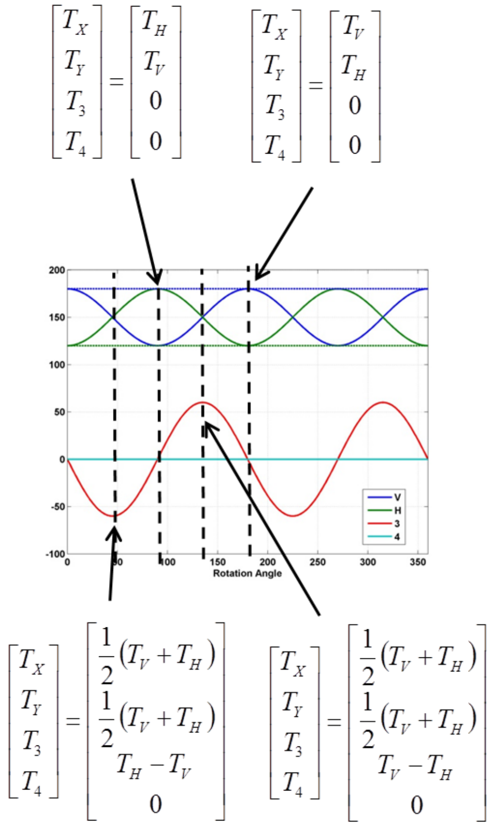
4. COWVR DESIGN ADVANTAGES

This COWVR instrument design has several advantages over the heritage sensor design in terms of calibration and performance. These advantages arise from the use of the EPBR technique and the 360^o un-obstructed observation geometry.

4.1 Calibration Advantages

On long time scales, the polarized global mean ocean brightness temperature (TB) becomes un-correlated with the instrument scan (azimuth) position. This assumption has been shown to be valid to better than 0.05K on times scales greater than 10-days using WindSat data. For traditional conically imaging radiometers, a long-term average of the TBs over scan position would yield a distinct constant TB value for each receiver (V,H,+45,-45,L,R). Because the polarization basis of COWVR rotates with the scan position, this azimuthally constant polarized signal from the Earth is modulated in a known way based only on the instrument geometry. Furthermore, the relative amplitudes of the signals for each Stokes parameter are related and deterministic. This is illustrated in Figure 2. The dotted lines illustrate the global mean ocean TB as a function of scan azimuth in the Earth polarization basis and the solid lines show the modulated signal in the COWVR fixed polarization basis. Not only does this provide a powerful constraint on the polarimetric gain and offset calibration of the receivers, it also forces inter-calibration consistency between the polarizations.

A second unpolarized warm target, such as the Amazon rain forest will also be used. The Amazon target, along with the ocean, provides sufficient constraints to simultaneously solve for gain, offset and mixing terms.



$$\begin{bmatrix} T_X \\ T_Y \\ T_3 \\ T_4 \end{bmatrix} = \begin{bmatrix} T_H \\ T_V \\ 0 \\ 0 \end{bmatrix} \qquad \begin{bmatrix} T_X \\ T_Y \\ T_3 \\ T_4 \end{bmatrix} = \begin{bmatrix} T_V \\ T_H \\ 0 \\ 0 \end{bmatrix}$$

$$\begin{bmatrix} T_X \\ T_Y \\ T_3 \\ T_4 \end{bmatrix} = \begin{bmatrix} \frac{1}{2}(T_V + T_H) \\ \frac{1}{2}(T_V + T_H) \\ T_H - T_V \\ 0 \end{bmatrix} \qquad \begin{bmatrix} T_X \\ T_Y \\ T_3 \\ T_4 \end{bmatrix} = \begin{bmatrix} \frac{1}{2}(T_V + T_H) \\ \frac{1}{2}(T_V + T_H) \\ T_V - T_H \\ 0 \end{bmatrix}$$

Figure 2. Illustration of COWVR global mean ocean calibration signal.

4.2 Performance Advantages

Another advantage arises because COWVR has an un-blocked 360^o scan, meaning it makes observations of each scene at two azimuth angles. This has advantages in terms of wind direction retrieval and also observations of 3-D storm structure.

The wind direction signal from the ocean is periodic. Observations of this signal at a single azimuth (as is currently done with WindSat), produces up to 4 ambiguous solutions. The addition of a second observation at a widely separated azimuth angle greatly improves the retrieval algorithm skill and accuracy. Monte-carlo simulations were performed to assess the improvement of the COWVR 2-look retrievals over single look retrievals. The metrics assessed were: Skill - The percentage of time the first ranked solution is true solution; First rank error – The RMS error of the best solution; Closest ambiguity error **–** The error after nudging using a NWP first guess and; Mean number of solutions – The number of ambiguities meeting the chi-square criteria. A comparison of the two algorithms is shown in Table 2. It is clear that the two-look algorithm offers a more accurate solution and requires less reliance on a priori information for ambiguity removal.

Table 2. Comparison of the traditional 1-look retrieval vs the COWVR 2-look capability

Avg. over 5-20 m/s	1-Look	COWVR 2-Look
Skill	65%	90%
First Rank Error	28°	18°
Closest Ambiguity Error	19°	16°
Mean number of solutions	2.7	2

Finally, the fore/aft observations can be used to reveal the structure of storms. This has been shown to be useful for tropical cyclone monitoring by revealing tilted eyes walls which are an indicator of upper level sheer (Turk et al., 2006).

5. CONCLUSIONS

COWVR is currently under development at the Jet Propulsion Laboratory for an Air Force proof-of-concept technology demonstration mission. The instrument successfully completed its preliminary design review on January 9, 2014. The critical design review is scheduled for June 3, 2014 and the instrument is planned to be flight ready by September 2015.

While COWVR is a focused technology demonstration mission, the design itself is scalable to a wider set of frequencies. Current efforts are underway to evaluate the performance of a 6-37 GHz and 19-90 GHz version of the system. Current assessments indicate that this sensor design is capable of meeting legacy sensor performance at a fraction of the cost with significantly reduced mass and power.

6. REFERENCES

Koss, S. and S. Woolaway**.** Lessons Learned from the Windsat BAPTA Design and On-Orbit Anomalies. Proceedings of the 38th Aerospace Mechanisms Symposium, Langley Research Center, May 17-19, 2006

Chauhan, N. NPOESS Conical Microwave Imager/Sounder: Issues and Progress. Geoscience and Remote Sensing Symposium, 2003. IGARSS '03. Proceedings. 2003: 10.1109/IGARSS.2003.1293779

Gasiewski, A.J.; Kunkee, D.B., "Laboratory demonstration of electronic polarization basis rotation," Microwave Symposium Digest, 1992., IEEE MTT-S International , vol., no., pp.329,332 vol.1, 1-5 June 1992: doi: 10.1109/MWSYM.1992.187979

Lahtinen, J.; Gasiewski, A.J.; Klein, M.; Corbella, I.S., "A calibration method for fully polarimetric microwave radiometers," Geoscience and Remote Sensing, IEEE Transactions on , vol.41, no.3, pp.588,602, March 2003: doi: 10.1109/TGRS.2003.810203

Turk, F.J.; DiMichele, S.; Hawkins, J., "Observations of tropical cyclone structure from WindSat," Geoscience and Remote Sensing, IEEE Transactions on , vol.44, no.3, pp.645,655, March 2006 doi: 10.1109/TGRS.2006.869926

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