WEATHER SATELLITE FOLLOW-ON – MICROWAVE (WSF-M) DESIGN AND PREDICTED PERFORMANCE

David Newell, David Draper, Quinn Remund, Brian Woods, Catrina Mays, Bill Bensler, Dan Miller, Ken Eastman

Ball Aerospace, Boulder, Colorado, USA

ABSTRACT

An overview of the Weather System Follow-on – Microwave (WSF-M) Mission is given. The design of the mission and the predicted top-level performance is presented. A summary of the ground system, space vehicle and the microwave imager is given. The status, including the status of prototype hardware builds, is given.

Index Terms—Weather Mission, Satellite Mission, Microwave Radiometer, Ocean Surface Vector Winds

1. INTRODUCTION

Ball Aerospace (Ball) is under a contract with the Air Force Space and Missile Systems Center (SMC) to provide the Weather System Follow-on – Microwave (WSF-M) Mission. As Mission Prime, Ball is responsible for delivering Environmental Data Record (EDR)-level performance for Ocean Surface Vector Winds (OSVW), Tropical Cyclone Intensity (TCI), Soil Moisture, Snow Depth, and Sea Ice Characterization, as well as providing Imagery products. The Ball WSF-M mission design provides the next-generation environmental satellite system for the Department of Defense (DoD) following the successes of Ball's civil weather systems: Suomi National Polar-orbiting Partnership (Suomi NPP), Joint Polar Satellite System (JPSS)-1, and the Global Precipitation Measurement (GPM) Microwave Imager (GMI) sensor. This paper presents an overview of the mission, the predicted performance, provides details on the instrument and spacecraft design, planned hardware demonstrations, and gives current status.

2. MISSION OVERVIEW

WSF-M is a Department of Defense (DoD) operational, low earth orbit (LEO), environmental satellite system that provides continuous space-based sensing of the terrestrial environment. Terrestrial sensing is currently provided by the Defense Meteorological Satellite Program (DMSP) and WindSat. The Space Segment consists of a LEO spacecraft bus and two payloads. The primary payload is a Microwave Imager (MWI) sensor that takes calibrated passive radiometric measurements at multiple microwave frequencies to enable derivation of Ocean Surface Vector Winds (OSVW), Tropical Cyclone Intensity (TCI) and additional EDRs. In addition, the government-provided Energetic Charged Particle (ECP) sensor provides in-situ space weather measurements to enable derivation of ECP flux and warnings. Both payloads provide sensor data to the spacecraft for combination with spacecraft telemetry to form the mission data which is downlinked to the ground system.

Mission data is downlinked to the Air Force Satellite Control Network (AFSCN) for routing to the Enterprise Ground Services (EGS) Data Operations Center where it is processed to separate the MWI and ECP data. The microwave instrument mission data is distributed to the Air Force's Air Combat Command (ACC) 557th Weather Wing (WW), and to the Fleet Numerical Meteorology and Oceanography Center (FNMOC). The weather centrals use the Ball developed algorithms to process the mission data into Temperature Data Record (TDR), Sensor Data Records (SDR) and EDR products meeting the required performance. The EGS Operations Center processes the raw ECP data into products that support host satellite anomaly resolution, and state of health trending and analysis.

In addition, WSF-M broadcasts Real-Time Data (RTD), including all ancillary data needed to process the real-time data, directly to equipped Department of Defense (DoD) direct readout sites that use the Ball-developed algorithms to produce EDR mission products. Space vehicle telemetry is downlinked from the spacecraft and relayed to the EGS Operations Center where they are used to monitor spacecraft and instrument status. Mission Telemetry, Tracking & Command (TT&C) Services are provided by the ground system.

3. PERFORMANCE OVERVIEW

We derive the MWI sensor requirements from the WSF-M Technical Requirements Document (TRD) through an end-to-end (E2E) simulation that includes surface and atmospheric models, sensor characteristics, calibration uncertainty, and EDR retrieval algorithms. The WSF-M EDRs require that the sensor include the channel set shown in Table 1. Ball has selected a Sun-synchronized 833 km orbit for the WSF-M space vehicle (SV) to meet the swath width and refresh rate requirements. For the selected WSF-M orbit, the MWI antenna provides the required horizontal resolution of less than 30 km for the 10 GHz channel, consistent with current WindSat performance.

Ball's WSF-M design meets all OSVW, TCI, and Imagery SDR requirements with margin. Predicted performance for OSVW across the wind speed range of 5 to 25 m/s is shown in Figure 1. Ball's E2E simulation generates MWI-measured scenes consistent with WindSat data and includes all significant error sources. The simulation's Noise Equivalent Delta Temperature (NEDT) and calibration uncertainty are based on GMI-verified on-orbit performance [5] providing high confidence in these values. Polarimetric parameters are based on measured performance of prototype polarimetric receiver hardware. These simulated MWI-measured scenes are input into the operational retrieval algorithms and the retrieved OSVW product compared to the input scene. The operational retrieval algorithms are provided by Ball partners Remote Sensing Systems (RSS) and Atmospheric and Environmental Research (AER).

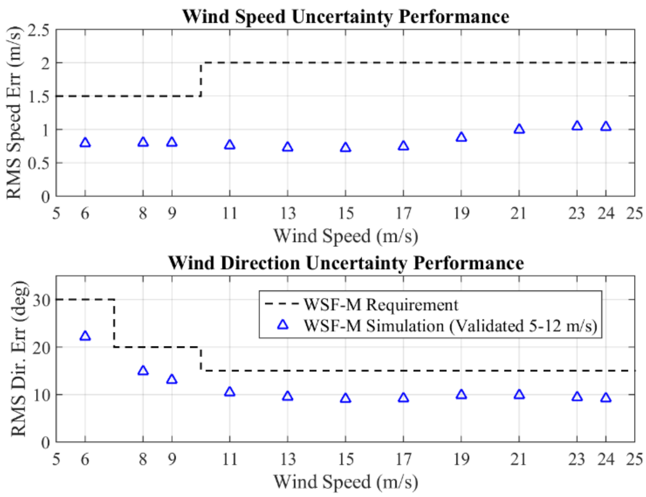

Figure 1. Speed and Wind Direction Uncertainty. Predictions from the mature validated E2E model show a minimum of 20% margin on wind direction and a minimum of 70% margin on wind speed for each 2 m/s wind speed bin.

4. SPACE VEHICLE OVERVIEW

The notional WSF-M Space Vehicle is shown in Figure 2. The WSF-M spacecraft is based on the Ball Configurable Platform (BCP) product line, a stable, agile, high-throughput spacecraft designed specifically for long-lived, remote-sensing missions like WSF-M. We have designed, built, and delivered ten BCP space vehicles and WSF-M joins three more SVs in development in our production line. Recent BCP examples include five commercial high-resolution satellite systems, Suomi-NPP, JPSS-1, and ICESat. The ECP is shown in the deployed configuration.

5. MWI INSTRUMENT OVERVIEW

The MWI requirements and design have been derived by Ball to meet the required EDR performance and leverage the heritage design features of the GMI Instrument that was built and tested by Ball for the National Aeronautics and Space Administration (NASA). The GMI instrument was launched onboard the GPM spacecraft on February 28th, 2014 and has operated continuously since then completing over 5 years of successful operation on-orbit. The flow down of WSF-M EDR requirements to MWI resulted in a set of requirements that is similar to GMI – providing a low-risk design foundation for the MWI.

The MWI instrument is shown in Figure 2. The MWI is a conically scanning polarimetric microwave radiometer with channels from 10 GHz to 89 GHz. Detailed characteristics for each of the 17 channels on MWI are shown in Table 1. These channels map closely to the GMI channel set [1], providing significant heritage in the receiver subsystem.

The MWI utilizes 3rd and 4th Stokes sensitivity to wind direction on the 10, 18, and 37 GHz bands to measure OSVW [2]. The MWI produces the 3rd and 4th Stokes polarimetric channels by digitally sampling and cross-correlating v-pol and h-pol amplitude signals. Digital polarimetry has the major advantages of reduced complexity and better calibration performance than analog designs [3].

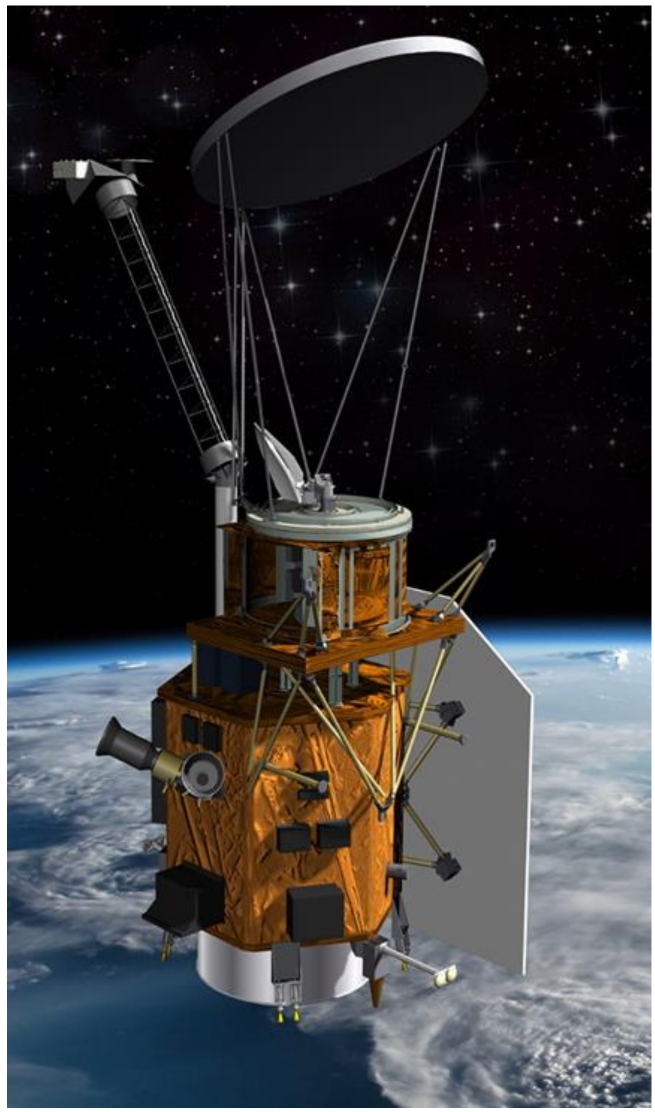

Figure 2. WSF-M Notional Space Vehicle

The 10, 18, and 36 GHz channels are fully polarimetric providing the V, H, 3rd and 4th Stokes. The designs of these polarimetric channels optimizes the use of the heritage GMI designs while incorporating the needed polarimetric capability. The RF front ends include phase-matched v-pol and h-pol channels based on the heritage GMI design. The analog outputs of the front end are down converted to an intermediate frequency enabling sampling by a high-speed analog-to-digital converter and processing by the digital backend. A digital processor directly computes the complex correlation between the v-pol and h-pol channels, yielding the 3rd and 4th Stokes parameters essential to OSVW retrievals. This digital-receiver-based approach for polarimetric channels has been proven on the NASA SMAP mission where the digital polarimetric capability has been used for ionospheric correction and for OSVW retrieval in hurricanes [4]. The receiver subsystem built by ITT Exelis provides low noise figures and very good stability for excellent radiometric performance.

Table 1. Channel Characteristics and Performance. The channel set for the Ball MWI includes the 10.85 to 89 GHz imaging channels with digital full Stokes outputs for 10.85, 18.85 and 36.5 GHz.

Channel	Channel Center Freq. (GHz)	Pol.	Band-width (MHz)	Sample Time (ms)	Beam Width (deg)	3 dB Footprint Size (km)
10*v*, 10*h*	10.85	*v*, *h*	500	1.8	1.06	38x23
3rd*, *4th		*3rd*, *4th*	500	1.8		
18*v*, 18*h*	18.85	*v*, *h*	500	1.8	0.66	23x15
3rd*, *4th		*3rd*, *4th*	500	1.8		
23*v*	23.8	*v*	370	1.8	0.58	21x13
37v_d, 37h_d*	36.75	*v*, *h*	500	1.8	0.43	15x10
3rd*, *4th		*3rd*, *4th*	500	1.8		
37v_a, 37h_a*	37.3	*v*, *h*	<2500	1.8		
89*v*, 89*h*	89	*v*, *h*	<6000	1.8	0.43	15x10

* The subscripts “d” and “a” denote the digital and analog outputs of the 37 GHz receiver, respectively.

The Antenna Subsystem consists of the 1.8-m Main Reflector (MR), four separate feed horns, and calibration targets. The Reflector Deployment Assembly (RDA) stows the MR and deploys it to the on-orbit configuration. This stowage gives the instrument a relatively compact stowed size given the 1.8-meter aperture size. The Spin Mechanism Assembly serves multiple functions; including conical scanning, signal transfer and power distribution through internal slip rings. The MWI Spin Mechanism Assembly is a build-to-print copy of the GMI SMA which has demonstrated over 5 years of on-orbit performance without any anomalies. The SMA also has significant heritage to the WindSat Bearing and Power Transfer Assembly (BAPTA) which has operated for over 15 years. The Instrument Controller Electronics (ICE) Subsystem provides the interface to the spacecraft and is responsible for MWI control.

Ball designed the MWI with multiple features proven on GMI to provide excellent calibration accuracy and provide the most accurate, precise and consistent data possible [5]. These features include proven VDA reflector coating technology that eliminates calibration errors from antenna emissions. Noise diodes on the 10-37 GHz channels provide on-orbit trending of non-linearity and backup gain calibration used in on-orbit calibration/validation activities to significantly improve GMI radiometric stability [6]. Also, tight hot load shrouding eliminates solar intrusion into the hot load [7].

Accurate, stable radiometric calibration of the Stokes parameters is essential to the on-orbit polarimetric receiver performance. The 3rd and 4th Stokes on-orbit calibration is performed via a Correlated Noise Source (CNS) included at the input of each receiver front end. The CNS employs stable heritage noise diodes used for the operational GMI payload that, together with a simple combining network, inject correlated calibration signals into the receiver front end.

6. PLANNED HARDWARE DEMONSTRATIONS

Prototype hardware is being developed in four areas: (1) RF Digital Polarimetric Receivers, (2) Main Reflector, (3) Reflector Deployment Assembly, and (4) Instrument Controller Electronics.

Ball’s partner Harris (EDO) is building the 37 GHz MWI polarimetric correlated noise source and down-converter assembly prototypes. This is combined with the Ball-built prototype Digital Receiver Assembly (DRA) and existing 37 GHz receivers from GMI to provide an end-to-end receiver at 37 GHz. The RF receiver includes a prototype of the electronics and digital controller board that incorporates redundancy and adds electrical interface capability to the Digital Polarimetric Receiver Assemblies.

Ball’s Reflector Deployment Assembly partner, Northrop Grumman (Orbital ATK), builds and tests the MWI RDA prototype scaled in size from the GMI RDA. Ball’s Main Reflector partner, AASC, builds and tests a MWI 1.8-m MR prototype scaled in size from the GMI 1.2-m MR. Following completion of subsystem testing, the MR and RDA are integrated and tested. Finally, Ball builds and tests the MWI Instrument Controller Electronics (ICE) prototype.

7. STATUS

Ball has completed MWI, SV, Ground System and Mission System Requirement Reviews. Ball has completed the preliminary design and successfully passed MWI, SV, and Mission Preliminary Design Review. Prototype hardware builds are nearing completion with delivery in the first half of 2019. MWI Critical Design Review is planned for spring 2019 and Mission Critical Design Review is scheduled for 11/2019. The launch of the first flight unit is planned for 11/2022.

8. REFERENCES

[1] Newell, D, et. al., “GPM microwave imager key performance and calibration results,” Proceedings IGARSS 2014, pp 3754 – 3757, 2014

[2] Gasiewski, A. J. and D. B. Kunkee (1994), “Polarized microwave emission from water waves,” Radio Science, vol. 29, no. 6, pp. 1449-1466, DOI: 10.1029/94RS01923.

[3] Piepmeier, J. R and A. J. Gasiewski (2001), “Digital correlation microwave polarimetry: analysis and demonstration,” IEEE Trans. Geosci. Remote Sens., vol. 39, no. 11, pp. 2392 – 2410, DOI: 10.1109/36.964976

[4] Yueh, S. H, A. G. Fore, W. Tang, A, Hayashi, B. Styles, N. Reul, Y. Weng and F. Zhang (2016), “SMAP L-band passive microwave observations of ocean surface wind during severe storms,” IEEE Trans. Geosci. Remote Sens., vol. 54, no. 12, pp. 7339 – 7350, DOI: 10.1109/TGRS.2016.2600239.

[5] Wentz, F. J and D. W. Draper (2016), “On-orbit absolute calibration of the Global Precipitation Mission Microwave Imager,” J. Atmos. Oceanic Tech., vol. 33, June 2016. DOI: 10.1175/JTECH-D-15-0212.1.

[6] Draper, D. W., D. A. Newell, D. Mckague and J. Piepmeier (2015a), “Assessing calibration stability using the Global Precipitation Measurement (GPM) Microwave Imager (GMI) noise diodes,” IEEE J. Sel. Topics Geosci. Remote Sens., vol. 8, no. 9, pp. 4239-4247, DOI:10.1109/JSTARS.2015.2406661.

[7] D. W. Draper, D.A. Newell, D.A. Teusch, P.K. Yoho, “Global Precipitation Measurement Microwave Imager (GMI) hot load calibration*,” IEEE Trans. Geosci. Rem. Sens.*, vol. 51, no. 9, Sep. 2013.