SSC20-III-09

BOWIE-M: A Microwave Sounder for Next Generation Operational Weather

Sean Geiger, Torie Hadel, Todd Pett
Ball Aerospace & Technologies Corp.
1600 Commerce St., Boulder, Colorado 80027; 303-939-6159
sgeiger@ball.com

ABSTRACT

The Ball Operational Weather Instrument Evolution-Microwave (BOWIE-M) is a compact cross-track scanning microwave radiometer combining design heritage from several radiometers as well as from IR&D efforts. Miniaturized RF electronics, a digital receiver and a compact antenna deliver operational performance, with reduced size, weight and power (SWaP) allowing ESPA-class spacecraft hosting.

The antenna's single 23 cm diameter reflector accommodates all operational bands and necessary resolutions up to the priority 832 km, high inclination orbits. A low loss polarizer splits the incident signals to two wideband feed horns attached to low noise and SWaP RF front end electronics (RFE).

Atmospheric temperature and humidity sounding is performed in 22 channels over 6 frequency bands ranging from 24 to 183 GHz, using channels in the 50 to 58 GHz range (V-band) for temperature sounding. K, Ka and W-band receivers are direct-detection designs while the V, D and G-band receivers are super heterodyne designs.

Channels near the most sensitive V-band oxygen resonance ensure temperature measurements accurately sound to the Earth's surface under the most demanding weather conditions. Use of digital receiver (DR) technology for V-band channels is reconfigurable to meet changing operational needs, even while on-orbit.

INTRODUCTION

Ball Aerospace has been developing the BOWIE-M concept for several years in anticipation of meeting future industry operational weather data collection needs. RF electronics, digital signal processing (DSP) and antenna technology all have advanced sufficiently to allow development of a microwave radiometer that both has operational performance and is compact enough to be hosted on a low Earth orbit (LEO) small spacecraft. In turn, the launch vehicle market has changed significantly in the last decade to make small launch payloads cost-effective. Development of the Evolved Expendable Launch Vehicle (EELV) and the associated EELV Secondary Payload Adapter (ESPA) standard is a game-changer for the space industry. BOWIE-M has been developed to exploit these technology benefits and sized to fit on an ESPA-class host spacecraft, delivering operational atmospheric sounding measurements for weather prediction at low cost.

Prior Ball-developed radiometer development strategies have been leveraged in this process, from the implementation-phase-level Ball ATMS design, to the operational GMI radiometer suite, and the in-development MWI radiometer suite on WSF-M. Key system design features, such as antenna field of view, noise processes, integration time, sampling rates, scan processes, pointing knowledge, and channel characteristics, have all been carefully examined and compared against prior implementation strategies to arrive at the final design architecture. The BOWIE-M design benefits from experience on these prior programs.

Ball received a study award for BOWIE-M in response to its 2019 NOAA LEO broad agency announcement (BAA) [1] white paper and proposal submissions. The study is underway and includes assessing fundamental channel characteristics needed for accurate numerical weather prediction (NWP) in NOAA's data retrieval process. Intermediate results from the channel characteristics portion of the study will be exploited in the second half of the study to determine optimal changes to the baseline BOWIE-M design.

INSTRUMENT OVERVIEW

Requirements

The BOWIE-M instrument design was initially developed with Ball-determined requirements similar to ATMS, then adjusted in 2019 to accommodate NOAA BAA "Target (Baseline)" requirements. The goal is to meet these target sounder performance requirements while exploring options to reduce cost/improve performance. The limited requirement set described in the BAA allows for a large trade space in architectures and concepts of operation; the NOAA study award will help narrow this trade space and associated derived requirements to drive towards an optimum hardware solution and final flight configuration that will meet the environmental data record (EDR) requirements specified by NOAA

Channel, Frequency, and Bands

The BOWIE-M microwave radiometer concept was envisioned from the outset to be an operational weather instrument. Toward this end, the decision was made early to generally follow use of the same channels that a current operational microwave sounder uses, e.g., ATMS. Over time, focused consideration of these channels' role in the data retrieval process has raised some questions about the need to directly replicate the functionality of ATMS. For the moment, all the same channel features utilized in ATMS are supported by BOWIE-M, but that is expected to change during the course of the trade study.

Presently, BOWIE-M provides atmospheric sounding measurements in 22 channels over 6 frequency bands ranging from 24 – 183 GHz using channels in the 50 – 58 GHz range (V-band) for temperature sounding, as shown in Table 1.

Use of V-band ensures that atmospheric temperature measurements satisfy NOAA requirements down to Earth's surface, even under cloudy, moist atmospheric conditions that are common at tropical latitudes. Providing continuity with ATMS channels also enables direct cross-calibration with on-orbit ATMS instruments guaranteeing compatibility between BOWIE-M data products and NOAA's proven data assimilation process as well as temperature and humidity retrieval algorithms.

Table 1: BOWIE-M channel, frequency and band designations

Channels	Center Frequency/Band
1	23.8 GHz/K-Band
2	31.4 GHz/Ka
3-15	54 GHz/V
16	88.2 GHz/W
17	165.5 GHz/D
18-22	183.3 GHz/G

Cross-Track Scanning

BOWIE-M is housed within a small, lightweight aluminum enclosure that is readily accommodated by a small spacecraft. The exploded view of BOWIE-M, shown in Figure 1 highlights the instrument electronics and antenna subsystem components built into the instrument. BOWIE-M employs an innovative antenna design requiring just a single 23 cm diameter reflector to accommodate all bands.

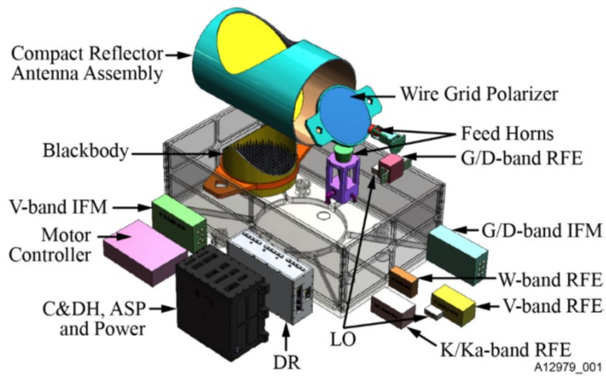

Figure 1: BOWIE-M Exploded View

The aperture, shown in yellow in the conceptual image in Figure 2, spins in a cross-track direction to the path of the spacecraft, and is large enough to ensure that the NOAA target (baseline) horizontal resolution requirements are met from the priority local time of the ascending node (LTAN) orbits up to the 832 km altitude JPSS orbit. Should instrument noise equivalent delta temperature (NEDT) performance requirements change in the future, flexible motor control integrated into BOWIE-M's design also allows for a variable rotation rate, increasing scan time over the Earth and improving NEDT. A low loss wire grid polarizer splits the incident signal to two wideband feed horns attached to low noise and SWaP RFE derived from proven designs, further assessed and modified with input from Ball parts and radiation experts to ensure continuous operation in the more demanding JPSS operational orbit.

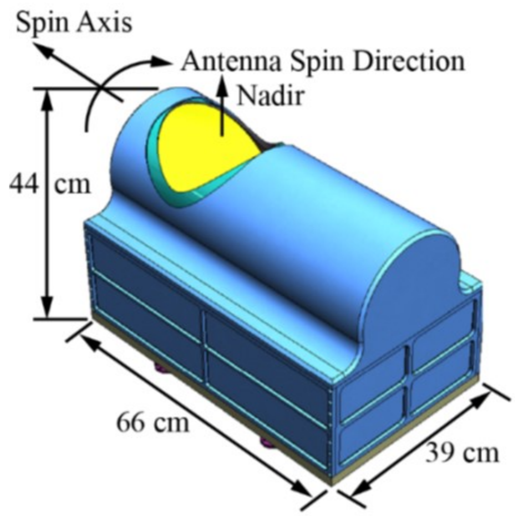

Figure 2: BOWIE-M Small Form Factor

The compact reflector is the only component that rotates and spins about the cylinder spin axis shown above.

Detection Methods

BOWIE-M's K, Ka and W-band RFE direct-detection designs eliminate the need for a frequency down conversion step and the associated components. Since each of these three bands contain just a single radiometer channel, this design is simple, reliable and satisfies NEDT sensitivity requirements. V, D and G-band RFE are superheterodyne designs requiring mixers and local oscillators (LO) to convert the incoming RF signals to a lower intermediate frequencies (IF) prior to processing. These IF signals are routed to IF module (IFM) hardware for additional amplification, channel shaping and detection. While more complex to implement, the superheterodyne design offers greater sensitivity than the direct-detection method by enabling the use of lower 1/f noise amplifiers and detectors available for the IF bands. Analog channel shaping filters are lower loss and easier to design at the IF band as well, providing more design solution choices. The digital receiver (DR) ingests and processes select V-band channels provided at IF frequencies compatible with its input circuitry. The superheterodyne technique provides additional design flexibility by enabling use of double sideband detection (e.g., in the G-band for water vapor sounding) further improving sensitivity. Analog-detected IFM and direct-detect outputs are digitized in the analog sampling and processing (ASP) card and multiplexed with DR and instrument telemetry for delivery to the spacecraft from the command and data handling (C&DH) unit.

The Zeeman splitting of the oxygen resonance into multiple narrowband features at high altitudes requires special consideration for V-band channels 11 – 15 (50 - 58 GHz), used for temperature sounding in the upper atmosphere. Many of these channels are very narrow band, and have traditionally required specialized hardware for accurate detection. Rather than rely upon a conventional analog filter implementation, BOWIE-M uses matured DR technology for the narrow channel definition and power detection via high speed analog to digital (ADC) paired with fast Fourier transform (FFT) DSP. Developed at Ball under IR&D for use on the WSF-M MWI, the DR enables BOWIE-M to deliver the required performance from a small module that can be reconfigured on-orbit to meeting changing operational needs. To fully utilize the multiple inputs and analog bandwidth capacity of the digital receiver, the DR also digitally processes the wider V-band ATMS channels 7 and 10.

Calibration

The BOWIE-M calibration system uses design heritage from the Ball GMI flight, WSF-M MWI and the ATMS study designs. Views of cold sky and an internal blackbody target during each antenna rotation provide the required stable radiometric temperature references for a two-point calibration. A high emissivity ($e > 0.9999$) blackbody target is maintained at a uniform temperature within the instrument enclosure. Platinum resistance thermometers (PRTs) are embedded near the tips of the pyramidal absorber cones at multiple locations providing accurate measurement of physical temperature and computation of temperature gradients across the target's surface. Since the cold sky (at ~3K) and the blackbody reference brightness temperature measurements are made through the main reflector, each BOWIE-M calibration measurement includes all signal losses from the reflector through the feed horns and components in the RF signal path to the RFE inputs. This technique minimizes calibration uncertainty and matches the proven method used by other operational sounders.

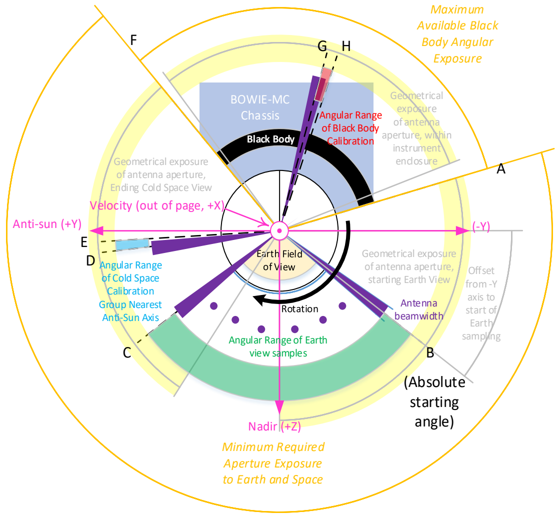

Figure 3: BOWIE-M Sampling Geometry

The diagram in Figure 3 has angular reference points described in the diagram and summarized in Table 2. The Earth field of view seen by the antenna reflector is shown in green towards the bottom of the figure, sweeping out approximately a 105° field of view. The reflector field of view then continues past the Earth's limb and reaches the cold space region.

As with ATMS, the design of BOWIE-M allows for multiple cold space beam groups. Cosmic background radiation is sampled several times within each beam group. Use of these samples in various combination provides the ability to remove some effects of Earth-viewed radiation, as well as host spacecraft radiation reflections received along with the desired background radiation. Unavoidably, celestial bodies such as the Moon will seasonally appear in the field of view, and such effects will need to modeled to mitigate their effect on measurement NEDT [2].

After leaving the cold space region, the reflector field of view continues to rotate into the black body region. The black body is entirely contained within the body of the BOWIE-M instrument, in a thermally-isolated environment. An array of temperature sensors embedded within the black body provide knowledge of the temperature variations across the geometry of the black body, improving the fidelity of the warm reference measurements.

Table 2: BOWIE Sampling Geometry Points

Angular Reference Point	Instrument Feature
A	Start Enclosure "Lip" Opening
B	Earth FOV absolute starting angle
C	Earth FOV absolute ending angle
D	Angular Range of Cold Space Calibration Group Nearest Anti-Sun Axis
E	
F	End Enclosure "Lip" Opening
G	Angular Range of Black Body Calibration
H	

INSTRUMENT PERFORMANCE

Performance Overview

Table 3 summarizes key BOWIE-M performance characteristics, demonstrating that the baseline instrument meets requirements from the BAA.

Table 3: BOWIE-M satisfies NOAA's Baseline horizontal resolution requirement from LTAN orbits in a SmallSat-compatible package

Parameter	BOWIE-M
Operational mode	Cross-track scanning total power radiometer
Swath width	2200 km
Antenna scan rate	23 RPM constant rate
Channels	22 total; 7 digitally-processed V-band channels
Horizontal res.	≤ 25 km from 832 km altitude
NEDT	ATMS performance or better
Data rate	< 50 kbps
Mass	35 kg
Power	70 W
Size	66 x 39 x 44 cm (LxWxH)
Spacecraft	SmallSat S/C including ESPA-compatible

Footprint Overlap

BOWIE-M's design is influenced by several parameters, including altitude, pixel sample size, and integration time. End use of the collected data by NOAA is critical in determining some design features, particularly the desired overlap of sampled pixels, called oversampling. An example of the geometry of overlapping adjacent cross-track samples is shown below in Figure 3, with an initial nadir sample in yellow, and the subsequent sample to the right of nadir overlapping it. Sufficient overlap between cross-track samples can support mathematical resampling (such as with the Backus-Gilbert method [2]), where data at a location on the cross-track measured surface may be interpolated from raw samples, improving NEDT. The along-track sample overlap approach is subject to the same constraints.

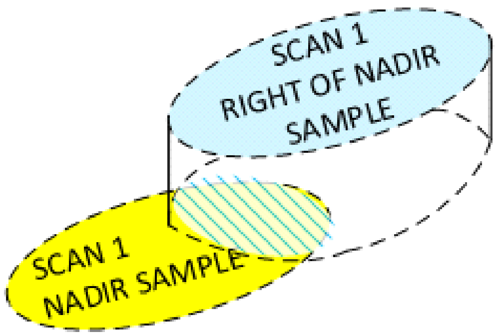

Figure 4: Overlapping Adjacent Radiometer Samples

An example of a sampling overlap approach in an operational instrument is illustrative. The operational ATMS microwave sounder was developed by Northrop Grumman and is part of the Joint Polar Satellite System (JPSS). On the operational JPSS platform, ATMS forms a single sounding system together with the Cross-Track Infrared Sounder (CrIS) to determine temperature information. This implementation required sampling alignment and synchronization of the two instruments, as described in [3]. The ATMS instrument IFOV for the V-band temperature sounding channels (3-15) is a 2.2° beamwidth, integrated over a cross-track scan angle of 1.11° (2.2/1.11 = 1.98 oversampling), with the along-track measurement repeating every 8/3 (=2.667) seconds. At the JPSS-1 828 km altitude, the ATMS IFOV pattern is diameter 31.79 km with an along-track velocity of 7.44 km/s, and an along-track IFOV repeat every 19.84 km (31.79/19.84 = 1.60 oversampling). Hence, at nadir the ATMS instrument has oversampling of 1.98 in the cross-track, and 1.60 along-track. This approach allows for resampling by NOAA to arbitrarily occur in the cross-track direction with minimum penalties, and with some artifacts present in the along-track direction.

BOWIE-M could replicate the sampling approach utilized by ATMS; whether this is selected relates in part to the outcome of the sensitivity analyses study underway. Also, the BOWIE-M based SounderSat instrument could be flown in conjunction with an IR instrument similar to ATMS/CrIS, driving a desired sampling scheme, but no specific need has as yet been identified [1]. If the BOWIE-M sounder were to provide the most flexible sampling scheme to synchronize with an IR instrument, the scanning approach would require Nyquist sampling of two samples (2.0) per instantaneous field of view (IFOV) in both along and cross track dimensions. This ideal amount of sample overlap drives the scan rotation rate and integration time, however. Implementing a constant angular scan rotation rate over an entire revolution is certainly a simpler mechanism solution, but proves difficult in maintaining sufficient integration times to achieve desired NEDT values. Use of the Backus-Gilbert method in post-processing mitigates this NEDT degradation somewhat, but there are still physical and performance constraints in the raw data sampling process.

To estimate the impact overlapping samples would have on the BOWIE-M sounder, initial analyses have been performed assuming 1.5 samples/IFOV for both along- and cross-track dimensions as a starting point. These analyses assume that the BOWIE-M will scan at a constant angular rate (a simplification on the operational ATMS), and supports a smaller footprint than the ATMS, consistent with the BAA baseline requirements.

TRL

BOWIE-M draws extensively from design heritage gained from the Ball ATMS design, GMI, WSF-M MWI, other Ball space flight programs and technology IR&D funded by Ball. This design inheritance reduces risk, development time, and cost. Most technologies are currently at technology readiness level (TRL) 6 or above. Instrument electronics development is underway to bring key lower-TRL systems to this level 6 or higher.

Predicted NEDT Tables

The top-level performance object of the BOWIE sounder instrument is to meet the radiometric sensitivity needs of the NOAA LEO BAA. The sensitivity is generally specified in terms of the Noise Equivalent Delta Temperature (NEDT) which is defined as the minimum detectable change of the microwave power (in brightness temperature units) incident at the antenna aperture. It is the end-to-end resolution of the radiometer, including all contributing factors, defined for a single operational sample. For the BOWIE-M instrument, this has been projected for each channel and is summarized in Table 4 below.

Table 4: BOWIE-M Projected NEDT

Channel Number	Center Frequency [GHz]	Band Label	Polarization	NEDT [K]
1	23.8	K	V	0.55
2	31.4	Ka	V	0.69
3	50.3		H	0.68
4	51.76		H	0.45
5	52.8		H	0.45
6	53.596 ± 0.115	V	H	0.55
7	54.4		H	0.47
8	54.94		H	0.50
9	55.5		H	0.54
10	57.290344 (f0) ± 0.0875		H	0.53
11	f0 ± 0.217		H	0.76
12	f0 ± 0.322 ± 0.048	V	H	0.76
13	f0 ± 0.322 ± 0.022		H	1.08
14	f0 ± 0.322 ± 0.010		H	1.51
15	f0 ± 0.322 ± 0.004		H	2.49
16	88.2	W	V	0.27
17	165.5	D	H	0.36
18	183.31 ± 7		H	0.37
19	183.31 ± 4.5		H	0.39
20	183.31 ± 3	G	H	0.51
21	183.31 ± 1.8		H	0.49
22	183.31 ± 1		H	0.61

TRADEOFFS OF SMALLSAT MICROWAVE SOUNDERS VS. TRADITIONAL SPACECRAFT PLATFORM HOSTING

Sounder Data Needs

NWP has benefited from spaceborne microwave sounder instruments for half a century [4]. Microwave sounders deliver key data sets utilized by national weather services worldwide in respective NWP models, which in turn provide weather forecasts for populations across the globe. Microwave sounding provides the greatest benefit to improving weather forecast skill. Additionally, microwave sounders' data may be used to improve spaceborne IR weather instruments data's end use [5]. What is the best way to gather this data, to what fidelity, under what conditions, and at what cost? The answer to these questions affects instrument and spacecraft solutions to varying degrees.

Traditional Instruments and Spacecraft Host Platform

Much of the 50-year history of spaceborne microwave sounders includes those instruments being co-located with other instruments, such as dedicated infra-red (IR) instruments. Co-location of multiple instruments is beneficial due to guaranteed simultaneous data collection of the same geographical location, allowing correlation of multiple data sets. Larger host spacecraft have typically been needed to support the multi-instrument approach. Such spacecraft have been able to provide physically stable inertial platforms, offer larger volumes, high power delivery capability, and excellent pointing ability. They have been the basis for much of the operational atmospheric dataset collected over decades.

Downsides of the multi-instrument, larger host spacecraft approach include launch costs, increased schedule and logistical complexity, and potentially long development times.

Large spacecraft need their own launch vehicle. Launch costs for the Delta II used to launch the JPSS-1 spacecraft as a primary payload were roughly $100M, though availability of SpaceX's Falcon 9 have brought those costs down to something closer to $65M for a new vehicle (or perhaps $10M less if a re-used first stage is utilized).

Coordination of multiple instrument integration onto a host spacecraft is not a trivial issue: it frequently results in snowballing costs driven by one (or more) long development poles of the instrument providers or even the spacecraft host provider itself. Additional complexity and cost results when instruments need to be synchronized to each other.

Instrument development costs themselves can be driven by high performance expectations from the customer, which are in line with an infrequently-built, but highly reliable multi-instrument operational spacecraft approach.

SmallSat Spacecraft Host Platform

Smallsat-based microwave sounder solutions also have their own set of advantages and disadvantages.

Beneficial characteristics of small satellite microwave sounder solutions include launch costs, decreased schedule and logistical complexity, potentially shorter development times, and attractiveness of constellation deployment.

SpaceX's embracing of supporting the ESPA standard on the Falcon 9 provides an alternative and cost competition to the EELV. An efficiently-managed manifest on an ESPA ring can cost approximately $3M.

Schedule and logistics can be significantly improved in a dedicated smallsat microwave sounder mission. Use of standard spacecraft hosts is possible, particularly for ESPA berths, which both reduces cost and brings more determinism to the schedule. In the case of an ESPA berth, both host and sounder are subject to the schedule of the launch provider – this itself can be a beneficial forcing function to which primary payload launch vehicle missions are less sensitive to.

Increased revisit rates over the same geographical points on the globe further improve the availability of temporal data used in the NWP process; the revisit rate is related to how many sounder instruments are on orbit, however.

Larger quantities of small satellite instrument platforms may be deployed to improve overall system reliability, even if reliability of a per-instrument basis is lower. Constellations may be refreshed multiple times within a decade, allowing for design updates provided by technology advances, with incremental performance improvement over time at an incrementally lower cost.

Small satellite microwave sounder missions can have their downsides as well: resources, volume, and other platform constraints.

Small satellites necessarily have more limited resources: available power is less, delta-V is less or non-existent, and both host and payload vie for limited volume. Pointing accuracies can also be limited depending on the choice of spacecraft host platform, although sub-arcminute platform pointing accuracies have been developed for ESPA-class smallsats [6].

Given these considerations, we believe that the case for microwave sounders hosted on small spacecraft is strong. Larger quantities of low-cost sounders may be flown for the same cost as a single sounder of years past. Constellations of sounders provide inherent redundancy, allowing "gradual degradation" of revisit times in the event of a single instrument's failure, as well as the ability to improve performance with available technology refreshes on individual builds. The time has arrived for operational microwave sounders to fly on small satellites.

Acknowledgments

The authors would like to acknowledge Ball Aerospace & Technologies Corp. for funding development of the primary design of BOWIE-M and for the time spent preparing this paper, and to the National Oceanic and Atmospheric Administration for funding the study, contract 1332KP20CNEEP0073, awarded in response to Ball's proposal submission for [1].

References

1. Office of Systems Architecture and Advanced Planning (OSAAP), National Environmental Satellite, Data, and Information Service (NESDIS), National Oceanic and Atmospheric Administration (NOAA), "Low Earth Orbit (LEO) Sounding Satellite (SounderSat) Concept Exploration Broad Agency Announcement", document BAA-NOAA-LEO-2019, October 3, 2019.
2. Backus, G. and F. Gilbert, "The Resolving Power of Gross Earth Data", Geophysical Journal International, Vol. 16, Issue 2, October 1968
3. Goddard Space Flight Center, Joint Polar Satellite System (JPSS) Ground Project (code 474), "Joint Polar Satellite System (JPSS) Advanced Technology Microwave Sounder (ATMS) SDR Radiometric Calibration Algorithm Theoretical Basic Document (ATBD)", document 474-00043, Greenbelt, MD, October 2011.
4. Menzel, W. P., T.J. Schmit, P. Zhang, and J. Li, "Satellite-Based Atmospheric Infrared Sounder Development and Applications," Bulletin of the American Meteorological Society, vol 99, no. 3, March 2018.
5. Wang, P., J. Li1, M.D. Goldberg, T.J. Schmit, A.H.N. Lim1, Z. Li1, H. Han1, J. Li1, and S.A. Ackerman, "Assimilation of thermodynamic information from advanced infrared sounders under partially cloudy skies for regional NWP", Journal of Geophysical Research: Atmospheres, vol. 120, issue 11, June 2015.
6. Unpublished internal Ball Aerospace "Operational Class" small satellite preliminary design review (PDR) documentation.