PolarCube: ALL-STAR as a Platform for Passive Radiometric Sensing

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Abstract

The CubeSat microsatellite standard facilitates rapid, inexpensive deployment of small scientific satellites. The ALL-STAR program at CU has further decreased costs and development time by allowing payload developers to ignore satellite operations. With the ability to focus entirely on the scientific payload, the RadSat team has been developing an ALL-STAR payload called PolarCube to remotely measure atmospheric temperature at various altitudes and map surface emission. Brightness temperature spectra near the 118.750 GHz O₂ resonance will be monitored and recorded along with spacecraft attitude and time. After downlinking the data will be analyzed by calibration, geolocation, and linear inversion to produce a three-dimensional temperature map of the atmosphere. These data will be used to study climate change, with an area of specific interest being temperature over and surface emission of polar sea ice. The development of a small, low-cost, passive radiometric imaging satellite opens the door for a new era of data collection to aid in weather prediction and monitoring climate change.
1. Introduction

Current spaceborne radiometric imaging sensors are often large, heavy, and (partly as a result) are expensive investments. As a result, failures in any one satellite, as occurred during the launches of the NASA 2011 Glory and 2009 Orbiting Carbon Observatory missions, are major blows to climate science, expensive from the standpoints of absolute cost and available data. Similar costly interruptions of service can occur upon the failure of operational weather satellites. In order to reduce such risk as well as to increase sampling rate the development of a low cost imaging radiometer using a platform-scanned microsatellite is being undertaken. This satellite uses passive radiometric imaging technology similar to what could be used for future weather and climate missions.

As a result of the anthropogenic release of greenhouse gases the temperature of the troposphere has been observed to be increasing at a rate approaching 0.1 °C/decade in the last decade. Through the development of PolarCube a subset of this warming phenomenon relevant to the polar ice caps will be investigated. Specifically, PolarCube is being designed to measure the temperature profile in the troposphere and relate mesospheric thermal structure to changes in sea ice concentration. In doing so PolarCube will also demonstrate for the first time the capability for a fleet of low-cost orbiting passive microwave sensors to provide global weather data on temperature, moisture, and clouds for high resolution forecasting of severe weather and cloud climate studies. The RadSat team has developed an engineering development unit (EDU) for the radiometric sensor in PolarCube. The team is now seeking to test and miniaturize this radiometer as well as develop a deployable antenna for space flight of the radiometer aboard a 3-U CubeSat using the ALLSTAR bus.

2. Radiometry Background

The atmosphere preferentially absorbs and emits certain frequencies of microwave radiation more than others (Figure 1). The predominant resonant peaks in the microwave spectrum are due to either oxygen (O₂, identified by “O”) or water vapor (H₂O, identified by “W”). The isolated O₂ resonance at 118.750 GHz is uniquely suited for temperature profiling due its large range of zenith opacity.

As a result of thermal radiative equilibrium, radiation is both absorbed and emitted by the atmosphere. Some of this emitted radiation is emitted vertically toward the radiometric sensor. Of this energy that is emitted, some is reabsorbed by the atmosphere above it. The emitted radiation that is not

![Figure 1: Atmospheric zenith opacity in dB (Klein & Gasiewski, 2000)](image)
reabsorbed by the atmosphere is the radiation that is detected. The radiative transfer equation governs the intensity observed at a given frequency. Its derivation is beyond the scope of this paper:

\[ I_v(z, f, \theta) = \int_0^z B(f, T(z')) W(f, z', \theta) dz' + I_v(0) e^{-\tau(z, f, \theta)} \]

\( I_v \) is the observed radiative intensity, the physically measured quantity. \( z \) and \( \theta \) represent the sensor’s altitude and observation angle away from zenith, respectively. \( z' \) is the variable of integration representing the altitude. \( f \) is the frequency being observed, and \( T(z') \) is the temperature. The \( I_v(0) \) term outside the integral is an initial condition. By integrating from \( z' = 0 \) up to \( z' = z \), radiated energy from all altitudes of the atmosphere are accounted for.

The radiative transfer equation gives rise to the weighting function, \( W(f, z', \theta) \). The weighting function, \( W(f, z, \theta = 0) \) represents the proportion of radiation emitted from altitude \( z \) that was not reabsorbed by the atmosphere as observed by a zenith-looking sensor. Zenith-looking weighting functions are desirable because they have a peak – a dominant altitude. By observing frequencies around the center frequency, the peak in the weighting function is altered. This allows a radiometric sensor to observe many different altitudes by observing different frequencies, as in Figure 2.

Finally, by inverting the radiative transfer equation and solving for \( T(z') \), the temperature for a given altitude is determined.

3. PolarCube System Description

The PolarCube system consists of the ALLSTAR payload referred to as RadSat, and the ALLSTAR bus itself.

3.1 RadSat Requirements

RadSat must be able to take radiometric measurements of the atmosphere at various altitudes. Eight distinct altitudes will provide enough resolution to obtain useful data while remaining within the form factor of the microsatellite. RadSat should collect data that has been conditioned and amplified in analog circuitry and average a configurable number of these samples together to produce a data point. The desired sampling resolution is 24-bits. The collected and averaged data will be stored in the .rad file format (Appendix 6.1). RadSat must be able to calibrate its radiometric instrument periodically as the nominal levels observed will change with temperature. The desired maximum ground spot size is 10 km. The RadSat instrument should be able to sample signals in the range of 118.75 GHz ± 6 GHz.

3.2 ALL-STAR / RadSat Interface

ALL-STAR is responsible for satellite operations by design. This includes ground station communications, satellite orientation, geospatial awareness, orbit control, and activating/deactivating the payload. ALL-STAR provides 3.3V, 12V, and an unregulated battery voltage for the payload to use.

RadSat is responsible simply for doing its scientific mission. When ALL-STAR activates RadSat by providing power to it, RadSat should initialize and begin collecting data samples.

The ALL-STAR Interface Control Document can be seen in full in Appendix 6.2. An additional communications layer is implemented over the network layer outlined in Appendix 6.2 by the Embedded Software and Payload Server.

3.3 EDU Implementation
The RadSat implementation for the EDU has been divided into five basic components – three hardware divisions and two software packages. These are the Radio Frequency Front End, Intermediate Frequency Filtering, Sampling and Digital Interface, Embedded Software, and the Payload Server.

The Radio Frequency Front End is responsible for receiving incident radiation, amplifying it and down-mixing it to a manageable frequency. The Intermediate Frequency Filtering section includes amplification, channel splitting, and signal detection. The Sampling and Digital Interface contains the analog to digital converter (ADC), an embedded microcontroller, and the power conversion systems. The Embedded Software runs on the embedded microcontroller; it controls sampling and communications with ALL-STAR. The Payload Server runs on the ALL-STAR microcontroller. It is mission-specific software designed by the RadSat team. A block diagram of the system as a whole can be seen in Figure 3.

### 3.3.1 Radio Frequency Front End

The radio frequency front end contains the feed horn antenna, isolators, pin switch, low-noise amplifier, local oscillator, and mixer. The schematic for the RF Front End developed for the EDU can be seen in Figure 4.

The feed horn receives the actual radio frequency radiation around 118.75 GHz and transfers energy into waveguide. The switch is enabled by a control signal to cut off the signal from the horn. When the horn signal is cut off, the receiver is observing the noise temperature of the switch as the primary source of radiation. By attaching a precision thermistor to the pin switch, its temperature can be determined. The instrument can be calibrated in this way by correlating the temperature of the pin switch with the brightness temperature observed. The second calibration point is the known temperature of deep space and the brightness temperature observed there.

The isolators separate the pin switch and feed horn from the mixer. Without the isolators, signals from the mixer could reflect from the feed horn and create a feedback effect.

The mixer and local oscillator are the final section of the RF front end. The local oscillator is tuned to 59.375 GHz so that, when multiplied in the time domain with the incident radiation by the mixer, a convolution occurs in the frequency domain, shifting the band of the signal from 118.75 GHz to DC. The radiation targeted is now in the DC – 6 GHz band.

### 3.3.2 Intermediate Frequency Filtering

Having down-converted the incident radiation, it can now be amplified and filtered. A schematic of the intermediate frequency filtering section from the EDU can be seen in Error! Reference source not found.. The implementation itself can be seen in FIGURE MM. Because the signal power is so low, the Intermediate Frequency Filtering boards must be well shielded from any kind of interference. To this end, the printed circuit boards are mounted inside aluminum carriers. The carriers have feed-throughs to allow power to enter and signals to enter and exit.

The intermediate frequency filtering and conditioning section is fed the DC – 6 GHz output of the mixer. Until the signal enters the carriers, it is carried in semi-rigid SMA cabling. The signal is amplified by a low-noise amplifier and split by a diplexer before being fed to the carriers. Further power splitting, amplification, and channel filtering occurs on Duroid (Rogers 3000 series) PCBs in the
carriers. Channel filtering is accomplished with six-pole band pass filters. The channel center frequencies and bandwidths for the EDU can be found in Appendix 6.4, along with amplifier gains, channel attenuations, and signal power parameters.

After the channels have been separated and filtered, the signal is passed to detection diodes that produce a voltage proportional to the power of the signal. This output voltage is buffered and amplified by video amplifiers, which are the output to the Sampling and Digital Interface.

In this schematic, the down-mixed radiation data is fed to an SMA-connected low noise amplifier and is then split by the diplexer. The diplexer is connected by semi-rigid SMA cables to carriers one and three. Carrier two is fed by an output from carrier one. Carriers one and three both contain active amplifiers to boost signal strength followed by power dividers. Carrier two has only the power divider. In all three carriers, after the power has been split, it is filtered through six-pole band pass filters and then attenuated to reach the correct signal level for the detection diodes. The output of the detection diodes is fed to the video amplifiers, which produce the output to the ADC.

3.3.3 Sampling and Digital Interface

The Sampling and Digital Interface consists of a pair of 8-channel, simultaneous sampling, 24-bit ADCs, power conversion circuitry, an embedded microcontroller, memory, and the electrical interface to the ALL-STAR bus. The schematic for the Sampling and Digital Interface can be seen in Appendix 6.3.

The video amplifiers in the Intermediate Frequency Filtering section require bipolar voltage rails at +/- 5 V. The ADC also requires a very stable 5 V for its analog supply. A 5 V line is not provided by ALL-STAR, so the 12 V regulated line is converted by a linear, low-dropout regulator to 5 V and heavily decoupled. This 5 V analog line is then inverted by a switched-capacitor charge pump to produce a -5 V source.

The ADCs are connected to the microcontroller via a read-only SPI interface. Input pins on the ADCs control all of their configuration settings. Most of
these are hard-wired with pull-up or pull-down resistors on the board because they will never change.

The electrical interface to the ALL-STAR bus is described in detail in Appendix 6.2. The communication link between ALL-STAR and RadSat is a high-speed SPI connection with ALL-STAR as the master. There are also interrupt signaling lines that RadSat can use to command attention from ALL-STAR. Also included in the electrical connections is a precise 1 Hz pulse from the ALL-STAR GPS unit along with some general-purpose lines that the Embedded Software and Payload Server can utilize.

3.3.4 Embedded Software

The Embedded Software is responsible for commanding the embedded microcontroller to control sampling, average data samples to obtain data points, format the data points into a .rad file, and communicate with the Payload Server running on the ALL-STAR microcontroller.

In addition to the radiometric data produced by the embedded software, health and status data must also be reported. This health and status data includes temperature information necessary to calibrate RadSat and information about RadSat’s current mode of operation.

The architecture is best described as a main loop plus interrupt service routines (ISRs). The software initializes the on-board devices, including the clock source, SPI modules, and interrupts, then enters the main loop and waits.

As interrupts trigger, the appropriate ISRs are executed. ISRs exist to handle the 1 Hz pulse from ALL-STAR, completed SPI transactions (both master and slave), and timer interrupts. Onboard timers control the ADC sampling rate and maintain microsecond resolution.

The communications interface is handled almost entirely by the SPI slave “transaction complete” ISR. A complex state machine manages the bus state and handles incoming and outgoing SPI data appropriately. The complex nature of this state machine arises from the packet and frame protocol outlined in Appendix 6.2.

3.3.5 Payload Server

The payload server is a mission-specific application that runs on the main microcontroller of the ALL-STAR bus. This software is the RadSat interface to all data about the satellite, communications, and power information. The Payload Server responsible for communicating with RadSat to receive .rad data, send configurable parameters, and send time data.

The payload server will ultimately be configured using a graphical user interface provided by the ALL-STAR development team. For the purposes of development and demonstration, the RadSat team developed an emulator for the ALL-STAR bus in LabView. It has been very effective in communications with RadSat and visualization and analysis of received data.

3.4 CubeSat Implementation

While the EDU stands as a good proof of concept, significant development tasks remain in preparing for launch aboard a CubeSat. The launch model will differ from the EDU in a number of significant ways in addition to satellite-specific development. This stage of development is ongoing.

3.4.1 Radio Frequency Front End

On the Radio Frequency Front End, the double isolators will be replaced by a single isolator of higher attenuation. This will reduce the volume and physical length of the RF components, contributing to decreases in overall volume. Many of the flanges on the RF components can be reduced in size or completely eliminated to further reduce the size of the system.

3.4.2 Intermediate Frequency Filtering

In order to meet the volume constraint, the Intermediate Frequency Filtering section is being redesigned to use only eight radiometric channels instead of nine. This will allow for the carriers to be reduced to two carriers of four channels each, instead of three carriers of three channels each. In addition, a replacement for the bulky SMA-connected diplexer is being sought. Ideally, a drop-in power divider that can be mounted on a PCB would replace the diplexer.

3.4.3 Sampling and Digital Interface

The Sampling and Digital Interface board is being redesigned to meet the cross-section of the ALL-STAR payload. The new board uses the same outline and mounting technique as the ALL-STAR CDH boards. The ADCs selected for the EDU are 8-channels each, so the reduction to 8-channels of
radiometric data will eliminate the need for one of the two ADCs on the EDU, simplifying and reducing the cost and size of the Sampling and Digital Interface board.

The isolator ICs used on the EDU board were deemed unnecessary. They were included as a precaution on the EDU board but created SPI timing errors. Additionally, the switched capacitor charge pump used on the EDU is obsolete and being replaced by a modern equivalent.

The Intermediate Frequency Filtering carriers and Sampling and Digital Interface board are being designed together so that the carriers can plug directly into the Sampling and Digital Interface board. This will almost entirely eliminate cabling within the payload section and further reduce unused volume.

### 3.4.4 Embedded Software

The entire software architecture is currently undergoing a redesign to make it faster, asynchronous, and more reliable. In the new system, incoming data is handled entirely by interrupt service routines (ISRs) and placed into software queues. When the interrupt service routines have placed a complete set of data into the queue, a flag is set to indicate to the main program that new data is ready to be processed. The main loop will manage data processing and communications protocol-level processing.

There are three low-level software queues that relate directly to hardware. All three correspond to SPI interfaces. Two are related to the SPI slave module that interfaces with the ALL-STAR bus (the ALL-STAR slave); one contains received data (RX) while the other holds data to be sent (TX). The third (ADC RX) is related to the SPI master module that reads data from the ADC (the ADC master) and contains received ADC sample data.

An external interrupt is connected to the ADC’s data ready line. When the ADC signals that it has completed a conversion, this interrupt is responsible for beginning the first read of the ADC data. Once this first read has begun, the ADC master SPI module takes over.

On every byte received from the ADC, the ADC master SPI module triggers an interrupt. This ISR is responsible for tracking the number of bytes received from the ADC and pushing them into a software queue. Since there are eight channels with 3-bytes of resolution each, it is known that 24 bytes of data represents a complete set. Once 24 bytes have been received and pushed into the queue, this ISR sets a flag to indicate to the main loop that there is ADC data ready to be processed.

Each data frame (see the network link layer specification contained in Appendix 6.2) contains a header that specifies the length of data in the frame. Every time the ALL-STAR slave receives a new byte of data from ALL-STAR, it is pushed into the RX queue, which is sized to hold one maximum-length network frame. The ISR that handles this is responsible for checking the length of data in the frame and determining if the frame is complete. If the frame is complete, a software flag is set and the main loop will process the received frame. Simultaneously, since SPI is a full-duplex interface, data must also be sent as it is received. The same ISR is responsible for checking for data in the TX queue. If there is data present, it is loaded into the SPI slave to be transmitted as the next byte. Otherwise, the data sent back will be blank.

The ALL-STAR interface control document implements a packet layer on top of the frame layer. Each packet includes 16 bytes of overhead. The packet-level processing will be handled by the main loop.

The main loop checks for all these software flags and runs task managers appropriately. For example, if there is a complete set of ADC data waiting, the main loop begins the averaging process and counts the number of sample sets that have been averaged. When enough samples have been averaged together, the main loop begins the process of creating a line in a .rad file. After every scanning raster, the embedded software creates a data packet from the .rad file and indicates to ALL-STAR that it is ready to send the data.

An in-depth specification of the embedded software can be found in Appendix 6.5. The specification for the embedded software evolves as the software is developed.

### 3.4.5 Payload Server

A new payload server simulator is under development by the PolarCube team. Rather than being written in LabView, the new simulator is written entirely in C++ to provide higher speed and
more a more reliable communications interface with RadSat.

Before launch, the ALL-STAR team expects to finish its payload server configuration program. Ultimately, this configuration program will be used to develop the payload server for the flight unit.

3.4.6 CubeSat-Specific Development

In addition to the functional changes required, some additions are required in order to interface with the ALL-STAR structure.

Each of the Radio Frequency Front End components needs to be secured to the payload frame in a way that will not allow vibration or place stress on the waveguide connections. This work is in progress and the actual mechanism has not yet been determined.

A deployable antenna structure is under development. By deploying the lens and a reflector plate, less of the satellite’s volume is occupied by the optical cone. This leaves more space for the necessary electrical components. During launch and ALL-STAR system deployment, the antenna and splash plate are stowed (Figure 6). After ALL-STAR has finished its own deployment, PolarCube will deploy its lens and splash plate (Figure 7).

This deployable lens and splash plate allow for the necessary optical power while retaining the maximum possible internal volume for electrical components.
4. Expected Results

As the PolarCube project advances, ALL-STAR will be put to the test as a platform for passive radiometric sensing. Successful development of the project will include a completed radiometer that has been shown to accurately measure brightness temperature across the 118.75 GHz ± 6 GHz band in eight distinct channels. The instrument will include an eight-channel ADC and embedded microcontroller circuitry to process the data and interact with the ALL-STAR bus.

A launch window in late 2013 will allow for deployment of PolarCube and the beginning of collection of useful data. As data is continuously collected and downlinked, a 3-dimensional temperature map of the troposphere will be developed and populated. As this map fills in with continuously obtained data, it can be used for weather prediction and climate analysis.

If the PolarCube mission proves to be successful and beneficial, it would pave the way for a fleet of similar microsatellites to provide similar data. Using the same frequency bands for many satellites will allow the data to be updated more frequently, providing temperature data that is closer to real time. As the quality of the data improves and the amount of data increases, the corresponding science and prediction will correspondingly improve.

5. References
6. Appendices

6.1 .rad File Format

Filename: Unix Time (in seconds)

Format: .rad files are binary files so no newline or null characters can be used to represent the end of a record. The locations of the records will be determined by byte offsets from the beginning of the file. Each “line” of the .rad file represents a single data point for the instrument, called a record. A record contains three basic fields:

<table>
<thead>
<tr>
<th>Field:</th>
<th>Timestamp</th>
<th>Data</th>
<th>Flags</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size(bytes):</td>
<td>4</td>
<td>Channels * bytes per channel</td>
<td>1</td>
</tr>
</tbody>
</table>

Field Descriptions:

*Timestamp*: time since the beginning of the second in the filename, in microseconds.

*Data*: Radiometric data samples. For the RadSat instrument, this is 24 bytes (8 channels * 3 bytes)

*Flags*: 8 bit-flags to indicate the status of the instrument:

<table>
<thead>
<tr>
<th>Bit Number</th>
<th>7</th>
<th>6</th>
<th>5</th>
<th>4</th>
<th>3</th>
<th>2</th>
<th>1</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flag</td>
<td>Currently Unused</td>
<td>Currently Unused</td>
<td>Currently Unused</td>
<td>Currently Unused</td>
<td>Currently Unused</td>
<td>Currently Unused</td>
<td>Switch Active</td>
<td>Calibration Active</td>
</tr>
</tbody>
</table>
6.2 ALL-STAR Interface Control Document

ALLSTAR ICD.pdf

6.3 Digital Interface Schematic

Schematics.pdf

6.4 RadSat Instrument Specifications

RadSat specification spreadsheet.xlsx
6.5 Embedded Software Architecture

This documentation will be replaced with Doxygen-generated documentation

6.5.1 Global Variables

Required global variables:
- SPI Software Buffers
  - ADC_RX
  - ALLSTAR_RX
  - ALLSTAR_TX
- ALLSTAR Bus State
- Unix time
  - + microsecond resolution

6.5.2 Interrupts

6.5.2.1 SPI RX/TX Complete

The SPI modules can be configured to raise an interrupt every time a byte transaction is complete. Configuring the SPI modules in this way will allow asynchronous processing of communications data.

6.5.2.2 Master of ADC

For the SPI module that is the master of the ADC SPI bus, when a byte is received, the interrupt will be raised. The ISR will place the byte into a software buffer for received ADC data. The ISR will track the number of bytes received from the ADC and raise a software flag to indicate that a new, complete data set is available in memory to be handled by the main loop. If the complete data set is not yet available, the ISR will begin another byte transfer.

6.5.2.3 Slave to ALLSTAR

When an ALLSTAR byte transaction is complete, the SPI module that is a slave to the ALLSTAR SPI bus will raise an interrupt. The ISR will take the received byte and place it into a software buffer for data received from ALLSTAR. If this data completes a received packet, the ISR will raise a software flag to indicate that a new, complete data packet is available in memory to be handled by the main loop.

A DMA transaction can be configured so that if there is data ready to transmit in the ALLSTAR_TX buffer, the next byte is automatically transferred to the SPI module without CPU intervention.

6.5.2.4 Timer Interrupt at desired fundamental ADC sampling frequency

One of the xmega timers should be configured to produce an interrupt at the desired fundamental ADC sampling frequency. This ISR should release the SYNC line to allow the ADC to begin converting a new sample.

6.5.3 External Interrupts

6.5.3.1 GPS 1 Hz Pulse

The 1 Hz pulse from the ALLSTAR GPS should be configured to raise an interrupt. On this interrupt, the microsecond resolution timer/counter should be reset to 0.

6.5.3.2 Data Ready (DRDY) from ADC

When the ADC has completed a conversion, it will assert the DRDY line. This action should raise an interrupt. The ISR will assert the SYNC line to prevent the ADC from starting another sample immediately. The ISR will also begin a SPI transaction to receive data from the ADCs. This ISR will also reset the count of bytes received from the ADCs to 0.

6.5.4 Software Buffers

6.5.4.1 SPI:
6.5.4.1.1 ADC_RX
A 24-byte buffer to hold the data received from a single ADC sampling cycle. It will be populated from data received by the SPI module interfacing with the ADC via the SPI ISR. The data in this buffer will be processed by the main loop.

6.5.4.1.2 ALLSTAR_RX
A buffer sized to hold data equivalent to the maximum size packet that ALLSTAR can send. This buffer will be populated by data received by the SPI module interfacing with the ALLSTAR bus. This data will be processed by the main loop.

6.5.4.1.3 ALLSTAR_TX
A buffer sized to hold data equivalent to the maximum size packet that ALLSTAR can accept. This buffer will be populated by the main loop and sent to SPI by DMA transfer.

6.5.4.2 Packets

6.5.4.2.1 PACKET_RX
A higher-level array that will buffer packets received from ALLSTAR. The array will store pointers to packet structs.

6.5.4.2.2 PACKET_TX
This buffer is a higher-level buffer that will buffer packets to send to ALLSTAR. The array will store pointers to packet structs.

6.5.5 Structures

6.5.5.1 Packet
Contains header information, data, and checksum for a complete ALLSTAR packet

6.5.5.2 Frame
Contains the 2-byte header and data array for a network frame

6.5.5.3 radLine
Contains the 4-byte timestamp and 24-bytes of radiometric data plus flag byte

6.5.5.4 CDH_t
Contains data pertaining to the current status of the ALL-STAR CDH module

6.5.5.5 mission_params_t
Contains variables that are derived from the RadSat performance spreadsheet. These include orbital data parameters, radiometer parameters, communications information, and sampling parameters.

6.5.5.6 system_t
Contains globally useful variables that are related to the core of the embedded software. These include the current unix time, and the current outputs to .rad files and health-and-status files.

6.5.6 Main Loop
TBD