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The Doppler Wind and Temperature Sounder (DWTS) Flight Evaluation and Experiments (TES-16,17)

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ABSTRACT

The Doppler Wind and Temperature Sounder instrument (DWTS) developed by Global Atmospheric Technologies and Sciences (GATS) is a simple yet powerful tool with the potential to become a new window through which the study of upper atmosphere dynamics can occur. Based around a defense-grade infrared camera peering through a static gas cell used as a scanning spectral filter, a DWTS instrument can infer wind velocities and kinetic temperatures throughout the stratosphere and lower thermosphere. The DWTS achieves this scanning by measuring the induced Doppler shift and Doppler broadening of emissions as they pass through the DWTS field of view (Gordley, Marshall, 2011). The DWTS holds promise in improving accuracy in weather determination among other terrestrial benefits, and the core technology can be easily adapted to study the dynamics of other planetary atmospheres.

In partnership with GATS, NOAA, and other collaborators, NASA Ames and the Nano-Orbital Workshop (NOW) group have been working to evaluate the DWTS instrument on orbit and optimize it as a flexible payload for nanosatellites. The first mission selected for DWTS technical evaluation is preparing for flight in early 2024, which will be followed by a more capable science mission in 2025, with both missions being part of the TES-n/NOW heritage flight series. The first rapid technology demonstration flight, TES-16/DWTS-A, will demonstrate a single DWTS instrument in an approximately 2U payload volume. With an estimated power consumption of 50 watts, the instrument will maintain the imaging sensor plane at 80K during instrument performance evaluation periods using an integrated Stirling cryocooler. Data from DWTS will be captured and processed via a NOW-designed custom data interface unit before being transmitted via S-band radio back to select ground stations, with instrument command and control maintained via L-band global-coverage radio. The subsequent TES-17/DWTS-B mission will be a dedicated science mission tasked with validating the instrument's full altitude coverage capabilities, currently estimated from 20 to 200 km during both day and night. This new atmospheric observational capability will come from a single small satellite equipped with three DWTS imagers, each hosting a different gas cell chemistry, to form a complete instrument.

The intention of this flight series, and one of NASA's interests in this instrument, is not only to advance Earth atmospheric dynamics, but to advance a Martian atmospheric study instrument as well (Colaprete, Gordley, et al) which, if successful, would greatly further understanding of Martian atmospheric dynamics. This document describes the flight series in detail, including challenges facing the TES-16 flight tests and the projected challenges and application of Mars study. Additional detail regarding the possible applications of a Cognitive Communication technique in current flight development by NOW collaborators at the NASA Glenn Research Center is also discussed, including the implications of using an automated User Initiated Service (UIS) protocol to maximize the data collected per orbit.

INTRODUCTION

The Doppler Wind and Temperature Sounder

The Doppler Wind and Temperature Sounder (DWTS) is a cryogenically cooled infra-red (IR) radiometry camera assembly that employs gas filter correlation radiometry to measure the doppler shift and doppler broadening of emission spectra to infer both wind and kinetic temperature. The gas filter cell built into the DWTS instrument is filled with nitrous oxide (NO), which acts as a high-resolution "notch" filter, producing a dip in the IR emission measurement of atmospheric NO. The technique used by DWTS correlates a dip in the signal received as a function of the angle the signal is coming from. The dip in signal occurs for every observed Earth limb position as it passes through the field of view (FOV) of the sensor. The angular direction of the dip minimum provides the wind velocity of the observed air, and the angular width of the modulation, or dip width, provides the temperature.

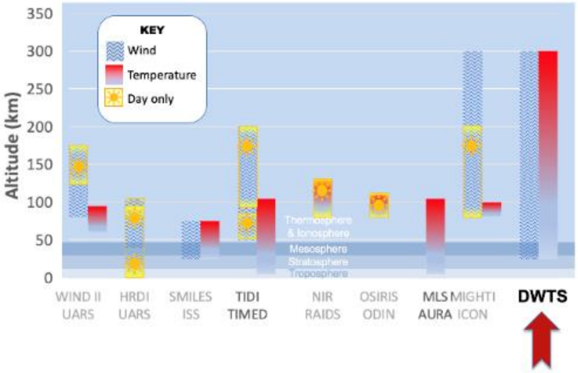

Figure 1: Comparison of DWTS's measurement range with other weather observation platforms. TIDI and MLS are currently in service; others are past missions. DWTS is an upcoming mission, important for observations of Earth's atmosphere because of its higher resolution, wide altitude range, and continuous day and night observational capability.

A DWTS instrument, once proven in orbit, will be capable of measuring numerous atmospheric features of interest including forces that increase satellite drag, precursors to catastrophic weather events, and dynamics impacting ballistic flights. A typical two-minute observation 'image' will be derived from over 100 one-second observations, producing a vertical resolution approaching 2 km. This allows significant horizon-scanning of atmospheric motion and temperature from approximately 25-50 km and 85-250 km using a single imager. Profiles for a DWTS instrument consisting of three imagers with gas cells of different chemistries will span altitudes from approximately 20-200 km.

The potential impacts of the DWTS instrument are wide ranging, and not limited to Earth science fields. A DWTS-equipped science mission in LEO will potentially improve weather forecasting by providing higher resolution upper atmospheric data than that currently available to current lower atmosphere weather models, enabling potential improvement in forecasting through the inclusion and linking of data from upper atmosphere dynamics and patterns, particularly resolving high frequency gravity waves (figure 2). For potential Mars study, data from DWTS observation instruments in Martian orbit will inform Martian global circulation models which could shape the operations of future landers, orbiters, and entry systems. The DWTS measurement principle is applicable to virtually any location with an atmosphere, as the contents of the gas cell used by each imager module can be tailored to allow readings of winds and temperature from most known planetary atmospheric compositions.

Figure 2: Gravity waves created by wind at lower altitudes, sometimes revealed in cloud formations, extend into the upper atmosphere, creating a telltale wind pattern 'fingerprint.' An example of the potential linking of upper atmospheric observations to lower atmosphere dynamics.

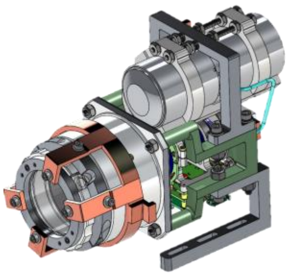

Figure 3: The Doppler Wind and Temperature Sounder Instrument

Technology Education Satellite (TES) 16/17 and the Nano-Orbital Workshop (NOW)

The Nano-Orbital Workshop (NOW) group at NASA Ames Research Center builds on the experience of the Technology Education Satellite rapid research and development program, colloquially known as TechEdSat or TES. The TechEdSat program has maintained a long-running series of collaborative works and orbital missions which pair post-secondary student projects with NASA researchers to facilitate the evaluation of new technologies for use in small satellites. Since inception in 2012, approximately twenty TechEdSat direct and associated missions have flown with an overall success rate exceeding ninety percent. NOW intends to build on this heritage by adopting TechEdSat's flight validated systems, processes, procedures, and methods to establish a reliable and configurable bus architecture, enabling easy orbital access for science activities from NASA, other governmental agencies, and international or domestic partners and scientists. Trailblazing this new NOW paradigm, the Doppler Wind and Temperature Sounder flight test is set to be flown on the first TES missions that are themselves incrementally proving the new NOW bus architecture. These flights, TechEdSat-16 (TES-16) and TechEdSat-17 (TES-17), still adhere to the procedural, technical and administrative requirements dictated by NASA and tailored by the TechEdSat team (Murbach et al., 2020), but are referred to as the TES-n/NOW flight series during this transitional period.

DWTS DEMONSTRATION MISSION DESIGN

An orbital technology demonstration mission is planned to validate the DWTS instrument's Doppler measurement technique as practical ground-based testing methods are incapable of achieving the speeds needed to induce the Doppler shift the DWTS instrument observes and infers atmospheric dynamics from. This orbital demonstration will make the instrument more appealing to future planetary missions and reduce technical risk for future terrestrial and Martian science missions implementing DWTS instruments. This low-cost, rapid proto-flight experiment is designed to also demonstrate the viability of the critical sub-systems needed to support the DWTS instrument for long-term continued operation on-orbit as well as to evaluate the data products, calibration processes, and effectiveness of the instrument for use in a mature and more rigorous science mission. The technology development experience of the NOW/TES group along with their high launch cadence has made them an ideal partner for the development of a technology demonstration mission for this novel instrument.

Demonstration Mission Requirements

The high-level requirements outlined in the below Table 1 for the technology demonstration mission derive from a desire to accelerate schedule and minimize system complexity while still testing the functionality of the instrument and supporting sub-systems. Cost and complexity are minimized by reducing the requirements for robustness, data through-put, and continuous instrument run time in a manner appropriate to a technology demonstration mission. These requirements will need to be increased for a dedicated science mission but are not critical to an initial evaluation of the DWTS instrument.

Table 1: Objectives for DWTS technology demonstration vs science missions.

Mission Objectives	Technology Demonstration Mission	Full Science Mission
Gather continuous IR frames with Earth limb in 20˚ FOV	Two minutes of continuous data	One orbit period of continuous data
Synthesize resultant data to retrieve wind and temperature data	Data elimination to a single downlink packet	Data reduction from all acquired data (no loss)
Validate/Calibrate resulting wind and temperature measurements with independent source e.g., Measurements from existing satellite remote or sounding rocket direct measurement	Data acquisition between 20-50 km and 85-250 km using a single DWTS imager	Data from multiple regions between 17-200km using three individual imagers with NO, N2O, & CO2 gas filters

Instrument Operations

The DWTS operates in two main modes during flight: imaging and calibration. In normal imaging mode, the DWTS is pointed towards Earth's limb, ortho-normal to the spacecraft velocity vector, with maximum drift rates <0.2 arcmin/s. Calibration modes involve pointing towards deep space or an area of known brightness, such as the moon. During imaging, the spacecraft will orient itself such as to maintain a stable thermal environment long enough for the instrument to take a series of measurements. Depending on the launch opportunity, a housekeeping mode may also be needed to charge the power system as solar arrays will likely be shaded during imaging operations to reduce incident thermal energy. A design which covers all desired demonstration modes has been architected and is outlined below in Table 2.

Table 2: DWTS Operational Thermal and Pointing Characteristics

Trait	Attribute
Gas Cell Lens Operating Temperature	150-200K, stable over measurement duration
IDCA Hot End Max. Temperature	313K
IDCA Cold End Operating Temperature	80K
IDCA Transient (Cool Down) Heat Dissipation	37.7W, given rejection temperature of 296K
IDCA Steady State Heat Dissipation	16.2W
Gas Cell Lens Assembly Heat Dissipation	<1W
Operational Pointing Direction	25 degrees below tangent plane at limb, ortho-normal to velocity vector. <1 degree uncertainty in all three axes and drift rate <0.2 arcmin/sec in all three axes
Calibration	Lunar pointing, deep space pointing Limb scanning

A SURVEY OF RELEVANT CRYOCOOLED NANOSAT MISSIONS

A critical part of the DWTS instrument, apart from the gas cell imager technology, is the cryocooler required by the instrument to maintain a cryogenic temperature at the IR imager focal plan array to reduce thermal noise. The integration of this cryocooler presents the greatest technical challenge to the host spacecraft in terms of hosting a DWTS device given the thermal, electrical, and mechanical design implications presented by compact cryocoolers, especially on nanosatellites. In recent years, the advent of relatively inexpensive tactical cryocooler technology has enabled a variety of provocative missions in the 6-12U nano-satellite class hosting a cryocooler device, listed below in Table 3. These missions were contacted in an effort to collect lessons learned prior to the design of the TES-16 mission. Thus far, only one on the list has flown, the Lunar Icecube mission, which unfortunately suffered a failure unrelated to the integrated cryocooler. All other missions listed in Table 3 are expected to be launched within the next few years, providing more confidence in incorporating such sub-systems on future missions. All the missions listed utilize an SF070 or similar tactical cryocooler made by AIM Infrarot-Module GmbH of Germany. These models of cryocooler are dual opposed piston linear Stirling coolers originally developed for military IR applications with a mean time to failure (MTTF) of over 10,000 hours. The cooler, with a properly positioned radiator, is found to be able to cool the DWTS instrument's detector to the required <80K. While the signal to noise ratio naturally improves with a colder detector temperature, the critical initial demonstration of the DWTS concept can occur at a higher temperature should mission limitations prevent ideal thermal operations. Also, as the first DWTS mission is intended as a proof-of-concept, the mission requirements for a first flight are not as stringent as that of a scientific research mission, for example the HyTI mission listed in Table 3. Thus, the hardening and batch testing requirements imposed on the selected cryocooler and key electronic components are not as stringent for this first flight as they will be for follow-on scientific missions. This new class of tactical cryocooler is seen as opening the horizon of IR related missions that were not possible in such small, and therefore less expensive, missions just a few years ago.

Table 3: Comparison of relevant nanosatellite missions containing cryocooled instruments.

Mission	TechEdSat-16	HyTi	Lunar IceCube	ARCSTONE
Spacecraft Size	12U	6U	6U	6U
Spacecraft Mass	15kg	--	14kg	--
ILC Date	January 2024	December 2023	November 2022	Spring 2025
Orbit	550km, Sun Sync	400km, 51° inc.	100x5000km, 90° Lunar	550km, Sun Sync
Bus Power	80W	40W	120W	--
Instrument	DWTS	HyTi	BIRCHES	ARCSTONE
Instrument Volume	4U	3.5U	2.5U	4U
Instrument Type	IR Radiometer	IR Hyperspectral Interferometer	Miniaturized IR Spectrometer	Hyperspectral Spectrometer
Cryocooler Type	AIM SF070	AIM SF070	AIM SX030	AIM SF070
Cryocooler Controller	AIM DCE100	Creare MCCE-TS	IRIS Technology LCCE	AIM DCE100
Nominal Required Power	38W	45W	40W	27W - Cooldown
Thermal Control Method	Passive Radiators	Heat Sink – Graphite Flex Straps	--	Passive heat rejection to spacecraft body
Maximum Heat Rejection Temperature	40° C	40° C	55° C	71° C
Instrument Cooling Requirement	<80K FPA	<68K FPA	<115K Detector/FPA	<140K FPA

Mission Orbit Considerations

In examining the competing thermal, pointing, and operational requirements of the DWTS (Table 2), high inclination orbits with a local time of ascending node (LTAN) near dawn or dusk were found to reduce the technical design complexity of the demonstration mission. The near steady-state illumination and resultant heat flux characteristic of a dawn or dusk orbit aids in the development of stable passive thermal rejection, and reduces the complexity of mission operations, particularly the burden on the ADCS to orient the imager and maintain favorable thermal radiator attitude simultaneously.

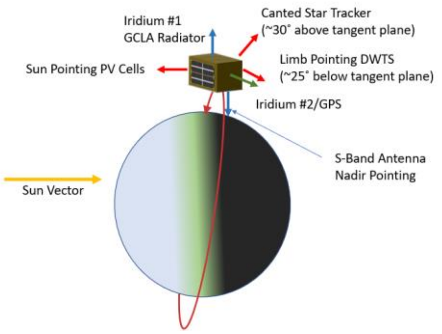

Figure 4: Pointing Constraints for Solar, Communication, and DWTS (not to scale)

Given that the DWTS technology demonstration orbit will be dependent on ride-share availability for its launch, a high inclination orbit for the first technology demonstration is not guaranteed. A concept of operations for limb imaging at lower inclinations requires further analysis to determine compatibility with the desired passive thermal management design.

SPACECRAFT PAYLOAD INTERFACE DESIGN

Electrical and Mechanical Hardware Topology

The first NOW-DWTS technology demonstration will rely on heritage TechEdSat core avionics for power, command, and data handling. The block diagram and related topology for the proposed initial mission are shown in Figure 5 following. The three principal avionics segments are: the TES-n/NOW avionics, the TES-n/DWTS interface payload stack module, and the DWTS instrument and cryocooler assembly. The TES-n/NOW avionics stack contains the basic nano-sat power, command, and communication elements, along with a commercial ADCS to meet the pointing needs of the DWTS. The TechEdSat core avionics are able to provide 150Wh of storage deliverable up to 80W at 8.4VDC, and is uniquely scalable to 300Wh of storage for future missions where longer data collection times are required. The key interface to the DWTS in terms of electronics and software resides in the TES-n/DWTS payload interface stack, which serves to provide a variety of data and power interfaces between the core avionics and the instrument itself. The payload stack module provides power and data conversion between the TechEdSat core avionics and the DWTS instrument, and is made up of several sub-modules each supporting a different aspect of the DWTS device.

Central to the DWTS interface stack is an NVIDIA® Jetson™ TX2 module on a custom NOW/TES carrier board which will manage the operations, data processing, and data handling of the entire DWTS payload (item 1 in the following Figure 5). On this carrier is a mini-PCIe COTS-Industrial FPGA-based frame-grabber image capture card that interfaces with the DWTS MWIR imager via a standard Camera Link bus (item 2 in Figure 5). After initial data processing is performed by the TX2, processed data frames will be transferred to the TES S-band SDR radio for ground capture via the TES avionics onboard Wi-Fi network. Following the primary payload controller and data capture unit is the power converter for the DWTS cryocooler, the second most electronically complex module in the DWTS payload interface. The cryocooler power supply unit will consist of a DC-DC converter able to boost the TES Avionics bus voltage from 8.4VDC to the 28VDC required by the DCE100 cryocooler driver (item 3 in Figure 5). To do this at the power required by the SF070 cryocooler, a synchronous push-pull converter topology was selected utilizing GaN HEMT primary and rectification switches with planar magnetics to achieve 500KHz switching with a target design output exceeding 100W and a design density above 1W/cm^2 utilizing a TPS7H5005-SEP radiation-tolerant PWM controller from Texas Instruments. As with all components of the core avionics and payload interface, this custom converter is being designed and tested in-house by the TES/NOW team. An additional power converter (item 4 in Figure 5) will drive a thermoelectric cooler to maintain the required temperature of the DWTS gas lens. This converter will consist of a constant-current switch-mode supply fed from either the avionics bus or the output of the 28V converter depending on the final thermoelectric cooler selection. Two additional sub-modules (items 5 and 6 in Figure 5) will provide data and control interfaces to the DCE100 cryocooler driver, and monitoring of engineering instrumentation sensors on the DWTS instrument and surrounding structure to aid in thermal performance evaluation and model correction. Due to the relatively short duration of the initial demonstration mission, the subsystem elements are not designed to be fully radiation or multi-fault tolerant, for example the H-bridge drive topology of the AIM DCE-100 cryocooler driver is highly susceptible to failure from an SEL, though there is a clear evolutionary design path which would permit such an improvement. For example, the primary power converter utilizes a radiation tolerant PWM controller coupled with naturally tolerant GaN switches, which could be hardened further, and the DCE-100 could be replaced with a space-rated drive module such as the Creare MCCE-TS being used by the HyTi mission. This development path and modularity helps to constrain development risk, as well as providing a vehicle for future incrementally improved system performance.

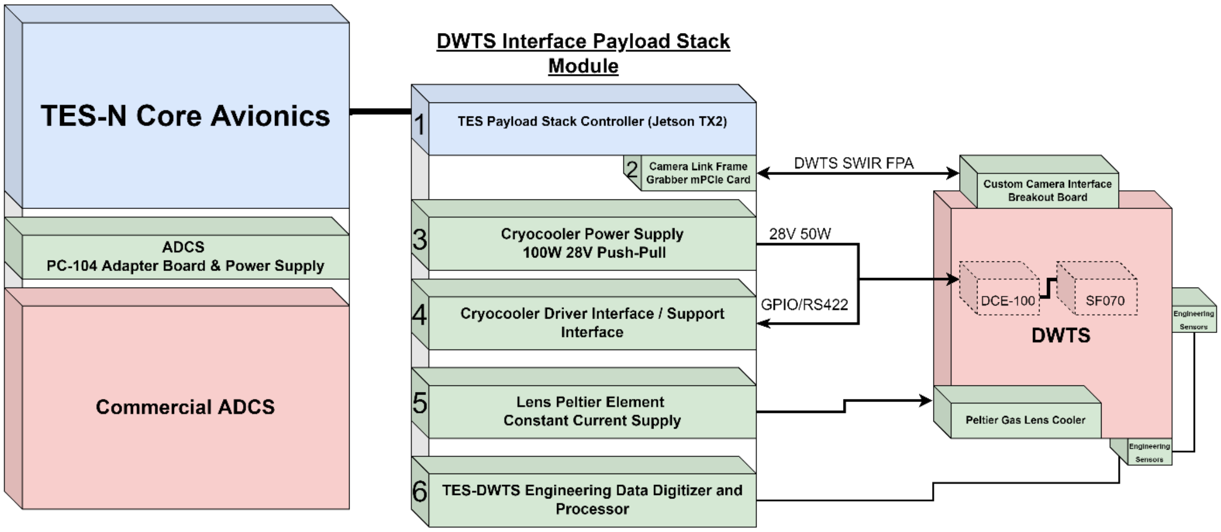

Figure 5: DWTS Payload Interface with TES-n Bus Architecture

Nominally 2U [200mm x 124mm x 80mm] in volume, the DWTS is physically compatible with both 6U and 12U nanosatellite form factors. Based on opportunity, the first technology demonstration of the instrument may use either of these platforms with mechanical and thermal design implications having been evaluated for both, shown in Figure 6. The volume requirements for the instrument and supporting subsystems are estimated at a minimum of 6 Liters, resulting in a densely packed 6U or more distributed 12U. Necessary subsystems in this volume include batteries (~1U), processors and radios (~1U), ADCS (~1U), DWTS instrument (~2U), and a deployable exo-brake, an exo-atmospheric drag device for end of mission hardware disposal via expedited orbital decay (1U and 2U pre-deployment volume for 6U and 12U bus topologies, respectively), a core technology developed and experimentally improved by the TES project.

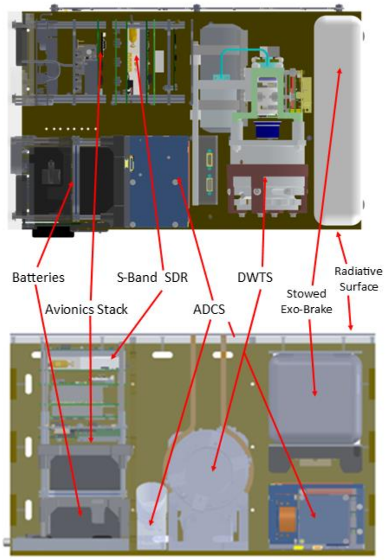

Figure 6: Volume allocation in 6U (top) and 12U(bottom) form factors.

Thermal Considerations and Design

With a sustained peak power consumption expected to exceed 50W, in addition to operational temperature requirements driven by the cryogenic systems, DWTS thermal management imposes a notable constraint and challenge on the design space. In terms of thermally sensitive components, the DWTS consists of two sub-assemblies with separate temperature and heat rejection requirements: the Integrated Dewar-Cooler Assembly (IDCA) and the Gas Cell Lens Assembly (GCLA) (see Table 2 previously). The IDCA consists of the AIM SF070 cryocooler with cold-finger and Focal Plane Array (FPA) MWIR detector integrated in a vacuum dewar. The self-contained nature of the FPA minimizes need for additional thermal isolation, though the hot-end must be provided a means of rejecting 16.2W of waste heat at temperatures between 220K-353K in steady state operation. Benchtop testing suggests that during the transient cooling phase at DWTS startup, peak heat generation will be on the order of 40 watts over a period of 4.5 minutes. Meanwhile, the GCLA contains a gas cell filter with glass optics and must be maintained at a stable temperature between 150-200K during calibration and imaging periods. Parasitic heat transfer to the GCLA is estimated at <1W, which must be removed to maintain this required temperature. Both the GCLA and IDCA heat loads will be rejected via passive, body mounted radiator panels. However, the dissimilar operational rejection temperatures of the IDCA and GCLA make it impractical to couple both to the same radiator. To maintain the GCLA at well below ambient bus temperatures, it is conductively and radiatively de-coupled from the rest of the instrument with G-10 glass epoxy bracketry and will be attached to its dedicated body-mounted radiator via heat strap. Further insulation will be provided by an MLI wrapping. Given that radiator heat rejection capacity is directly proportional to surface area and has a quartic dependency on surface temperature, the total required radiator area is reduced by isolating the relatively low temperature GCLA radiator from the other radiative surfaces. The GCLA radiator is located on the zenith-pointing face, such that the view of dark space is maximized during limb-pointing operation.

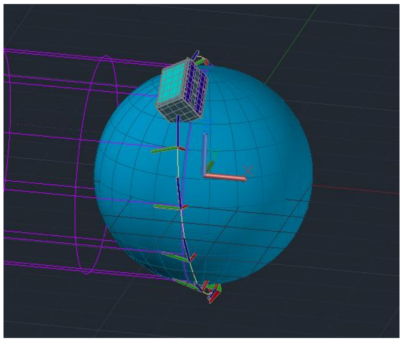

Figure 7: Orbit and attitude configuration for thermal analysis. 557km Dusk SSO shown with instrument rolled 25° towards the limb. Lens radiator shown in turquoise.

A preliminary thermal model was implemented to verify feasibility of passive waste heat rejection for the DWTS instrument. The rudimentary Thermal Desktop$^{®}$ model incorporates a defeatured 12U TES-n primary structure (thermal properties of 6061 aluminum) with stood-off solar panels (radiative coupling was modeled, conduction is assumed negligible as TES-n designs maximize conductive isolation between solar panels and primary structure). A 2Ux3U body-mounted radiator was modeled on the zenith face, also with radiative coupling to the bus (see Figure 7), and a conductive path to the GCLA. The GCLA was prescribed a 1W volumetric heat load and the 13.9W IDCA waste heat load was coupled to the four remaining external faces of the bus structure. The radiator and all external faces were assigned optical properties of white paint (absorptivity=0.09, emissivity=0.88), a flight-proven solution for achieving a low ratio of absorptivity to emissivity. Three readily accessible orbits and attitude configurations were considered, all at a 557km altitude with an evening LTAN. First, an ideal polar orbit was modeled with the spacecraft oriented in a velocity/nadir pointing mode (such that the limb view and solar panel beta angle remain constant). Shown in Figure 8 below, a stable GCLA temperature of ~184K is achieved in this attitude/inclination configuration. Two additional cases were considered in a Sun Synchronous Orbit (SSO) inclination at the same altitude, first with a zenith facing radiator, and then with a 25-degree roll below the tangent plane. Both cases result in a tolerable GCLA temperature of 184K, with <2K of variation over an orbit, after steady state is achieved. The latter case is representative of a bus configuration that reduces the complexity of mechanical design. This initial modeling suggests that passive cooling of the optics assembly is feasible for these high inclination terminator orbits, alleviating the complexity of active cooling for both optics and FPA.

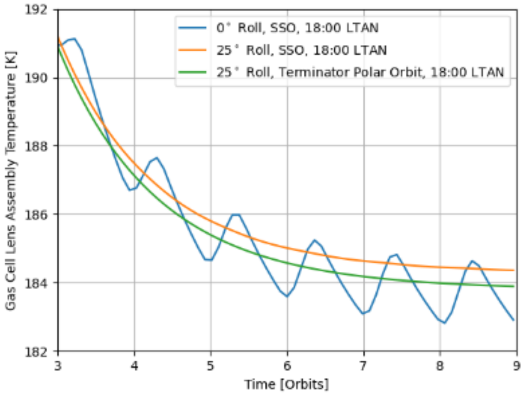

Figure 8: Simulated Gas Cell Lens Assembly Temperature.

CONCEPT OF OPERATIONS

The TES-n/NOW system utilizes two communication systems that are at the core of the Concept of Operations (CONOPS) for the proposed DWTS demonstration mission. The basic command and control of all nano-sat functions occurs through one of three L-band Iridium Short Burst Data (SBD) modems. These flight-proven modems provide quick constant command capability and are a feature in all TES-n/NOW flights. Specific DWTS subsystem commands are specified within the 340 byte SBD packet and data packets from the spacecraft confirm and validate execution of the command string and the spacecraft's general state. The more voluminous imagery data from DWTS calibration and experimental data collection are transferred via bus-internal Wi-Fi (another unique TES-n/NOW attribute) to an S-band SDR. Included in the DWTS science data will be GPS position data, which will later be essential in calculating the wind velocities from the Doppler information. Once a downlink opportunity is available, there are two means of proceeding: A traditional S-band downlink with manual scheduling and management, or a User Initiated Service (UIS) protocol. The UIS concept is a recent collaborative development (Chelmins et al., 2019) which will eventually permit a semi-autonomous means of efficiently downlinking data. The UIS, once initiated, will perform on-board orbital determination calculations to schedule optimum over-flight of ground telemetry assets (e.g., Amazon Web Service receiving locations). The autonomous scheduling utility running onboard the TES/NOW avionics will then initiate the S-band downlink and complete the data transfer automatically. The CONOPS protocol would then be repeated with eventual automation of the entire calibration, data collection and downlink process.

SUMMARY

DWTS turns wind disturbance Doppler phenomena into a technique for measuring wind direction and temperature. To definitively show that these disturbances can in fact be used for accurate measurements, a demonstration in orbit is needed. The TechEdSat series is well suited to rapidly fly this small instrument on orbit, and to downlink the quantities of data it will collect to evaluate the potential of this instrument. Commercial and government customers await the proving of the DWTS technique and the increased accuracy and range it promises. The goal of this demonstration mission is to lower the risk of launching a fleet of these instruments to eventually cover the globe, and, perhaps, Mars as well.

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