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Tethered Balloon System (TBS) Instrument Handbook

D Dexheimer
Z Cheng
K Gaustad
C Longbottom
G Whitson
J Sammon
F Mei

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ARM

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D Dexheimer, Sandia National Laboratories (Sandia)
G Whitson, Sandia
Z Cheng, Pacific Northwest National Laboratory (PNNL)
J Sammon, Sandia
K Gaustad, PNNL
F Mei, PNNL
C Longbottom, Sandia

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Acronyms and Abbreviations

3D	three-dimensional
ADS-B	Automatic Dependent Surveillance Broadcast
agl	above ground level
AMF	ARM Mobile Facility
ARM	Atmospheric Radiation Measurement
DC	direct current
DESI-HRMS	desorption electrospray ionization high-resolution mass spectrometry
DTS	distributed temperature sensing
EMSL	Environmental Molecular Sciences Laboratory
FROST	Fielded Remote Organic Sampling Technology
GPS	Global Positioning System
HP	horsepower
IOP	intensive operational period
OD	outside diameter
PNNL	Pacific Northwest National Laboratory
POPS	portable optical particle spectrometer
PTFE	polytetrafluoroethylene
RH	relative humidity
SAIL	Surface Atmosphere Integrated Field Laboratory
SGP	Southern Great Plains
SLWC	supercooled liquid water content
sm	statute mile
Sandia	Sandia National Laboratories
STAC	size-and-time-resolved aerosol collector
TBAC	total bulk aerosol collector
TBS	tethered balloon system
TD-GC-QTOFMS	thermal desorption gas chromatography coupled to quadrupole time-of-flight mass spectrometry
TEM	transmission electron microscopy
TRACER	Tracking Aerosol Convection Interactions Experiment
TRAVIS	time-resolved automated volatile organic compounds sampling system
UTC	Coordinated Universal Time
VAC	volts alternating current
VOC	volatile organic compound

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1.0 Instrument Description

The U.S. Department of Energy Atmospheric Radiation Measurement (ARM) user facility's tethered balloon system (TBS) is an unmanned aerial system composed of a helium-filled balloon, tether, winch, and sensors. The TBS is flagged and lighted and operated with a manual- and Global Positioning System (GPS)-activated emergency deflation device in addition to an Automatic Dependent Surveillance Broadcast (ADS-B) out transponder. Individual components of the system may change with each flight based on the desired measurements, atmospheric conditions, operating location, and flight strategy. The TBS operates under a Certificate of Authorization from the Federal Aviation Administration specific to each mission location. Unless otherwise specifically authorized, TBS flights are generally conducted 152 m (500') below the base of any cloud, in 3 sm or greater of visibility, and to a maximum altitude of 1.5 km (4,921') agl. In-cloud flights are generally conducted within Restricted Airspace. Night flights are currently conducted at SGP and require specific FAA authorization. The deviation of the tether angle from zenith increases with wind speed, and tether angle is not allowed to exceed 45° in flight. Individual ARM TBS missions are typically two weeks in length, during which daily flights are conducted as conditions allow.

2.0 Technical Specifications

2.1 Balloons

The payload and operating guidelines for the TBS vary significantly with location and environmental conditions. A general procedure is that aerostats are operated with science payload weights of 8-33 kg, and other balloon types may be operated for science payload weights under 8 kg. Science payload is defined as the remaining payload available on the TBS after all TBS operational components are included. Aerostats are not launched in sustained surface wind speeds above 10 m/s. Flights are suspended and the balloon is retrieved if wind speeds aloft exceed 14 m/s. The ARM TBS deploys 74-128 m^3 Skydoc aerostats.

Figure 1. TBS using 122 m^3 aerostat in flight at SGP in September 2023.

2.2 Winches

The TBS electric winch employs a 5-HP DC permanent magnet motor powered from a reversible, regenerative-driven, variable speed controller connected to a 7000-W gas-powered generator. It uses a 75:1 double-reduction planetary-to-worm-gear-driven gear box to multiply and transmit torque to the winch. The gear box coupling to a motor brake prevents the winch from rotating unless the winch motor is powered. A secondary hydraulic brake is available to apply additional force against the motor during ascent, or in the event of a gearbox, variable speed controller, or motor failure. The winch system is equipped with two separate generators, a primary and a secondary backup. The TBS winch system may also be operated from a shore power 220-VAC source, or an off-grid power system constructed from six 315-W solar panels, a 1.6-kW wind turbine, and eight 12-V, 110-Ah sealed lead-acid batteries. Any of the winch systems shown in Figure 2 may be deployed depending on the flight mission requirements.

Figure 2. Four of the five winch trailers in the TBS fleet as of November 2023.

2.3 Tethers

The tether on the electric winch uses up to a 10,000’ length of 3/16” OD plasma 12-strand and a published minimum breaking strength of 5,500 lbs. Tethers are load tested every 150 hours of flight and provide a 4.6x safety factor when used with a 128 m^3 aerostat at peak winds of 15 m/s at sea level in a standard atmosphere. An aerostat loses roughly 1% net lift and will exert a corresponding decrease in line tension during descent for every approximate 100 m it is operated above mean sea level.

2.4 Inflated Balloon Storage

When the TBS is planned to conduct multiple deployments to a site, ARM may deploy an inflatable 112’ x 80’ temporary hangar. The hangar is either anchored into the ground or held in place with 8 tons of sandbags. ARM may also deploy a 26’ x 40’ temporary highboy structure which is anchored to 3’-long concrete blocks. For shorter-duration flight deployments, ARM may store the inflated balloon under a cargo net on the winch trailer.

Figure 3. Clockwise from top left: inflated balloon under inflatable hangar, temporary highboy, and netted storage.

2.5 Instrumentation

2.5.1 ICI Mirage 640 MWIR Imager and 8640 LWIR Imager (Datastreams: tbscam)

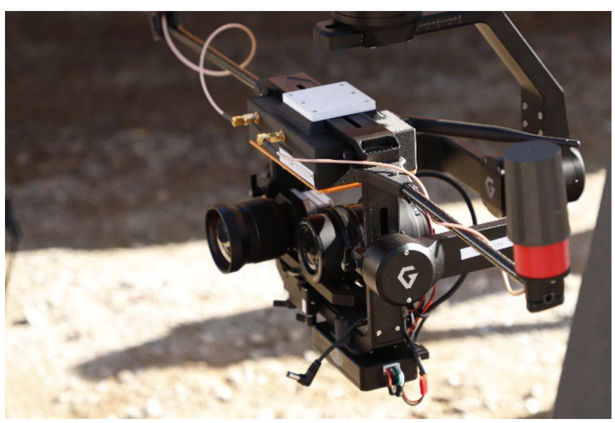

Figure 4. Mirage 640 MWIR imager and Sony R10C visible imager.

The imagers are operated in flight to provide thermal images of surface temperature. Depending on the desired field of view and resolution, the Mirage 640 LWIR may be operated with an 11-mm or 27-mm lens, and the 8640 LWIR may be operated with a 12.5-mm or 50-mm lens.

Table 1. Thermal imager specifications.

	Pixel resolution	Accuracy (°C)	Range (°C)	Spectral band (µm)	Thermal sensitivity (°C)
Mirage 640 MWIR	640 x 512	+/- ≤1	-55 - 350	1.5 - 5	< 0.012 °C at 30 °C
8640 LWIR	640 x 512	+/- ≤1	-20 - 120	7 - 14	< 0.02 °C at 30 °C

2.5.2 TSI CPC 3007 (Datastreams: tbscpc, tbsmerged)

Figure 5. TSI CPC 3007 in flight with diffusion dryer.

The condensation particle counter (CPC) instruments are used to measure airborne aerosol number concentration from 10 nm to >1 µm diameter once a second. Six CPC units are available, and multiple CPCs may be operated on the same TBS flight at different altitudes. CPCs are operated with a diffusion dryer.

Table 2. TSI CPC 3007 specifications.

Detectable particle size range	10 nm – > 1.0 µm
Maximum particle concentration range with < 10% coincidence error	100,000 #/cm^3
Particle concentration accuracy	+/- 20%
Sample flow rate	Detected aerosol 100 cm^3/min Inlet 700 cm^3/min
Operating temperature range	10 °C to 35 °C
Laser	Class I

2.5.3 Silixa XT DTS and Sensornet Oryx+ DTS-XR (Datastreams: tbsdts)

Figure 6. Silixa XT DTS.

A Sensornet Oryx+ DTS-XR and Silixa XT distributed temperature sensing (DTS) system collect air temperature measurements based on Raman scattering distributed temperature sensing. The TBS DTS system measures atmospheric temperature using only the properties of a fiber optic cable. The fiber serves as the thermometer, and the laser housed in the ground-based DTS system serves as the illumination source.

Two PT100 temperature probes and 15-m-long fiber coils are deployed into calibration baths at the surface during DTS operation. One bath is filled with circulating ice water and maintained at a constant temperature, and one bath is heated at a constant temperature, to represent the minimum and maximum temperatures expected during airborne DTS measurements. One fiber is generally deployed from the DTS in the Ch1 position and is spliced into a fiber optic rotary joint on a shaft connected to a motorized fiber optic reel. The fiber optic reel motor spools and unspools the fiber at a matching rate to the balloon tether. Light is transmitted from the rotating fiber reel through the fiber optic rotary joint to the stationary DTS. An iMet 4-RSB radiosonde is typically deployed at the end of the fiber immediately below the balloon and is used as an end-point calibration reference for the DTS fiber measurements. A second fiber may be deployed from the DTS in the Ch2 position when the balloon is stationary aloft. The Ch2 fiber does not operate through a fiber optic rotary joint.

Table 3. DTS specifications.

	Sampling resolution (cm)	Temperature resolution (°C)	Temperature accuracy (°C)	Range (km)	Measurement time (s)
Silixa XT DTS	25	0.09	+/- 0.4	0 - 5	30
Sensornet Oryx+ DTS-XR	100	0.12	+/- 0.6	0 - 12	30

2.5.4 NRG IceFree3 Heated Anemometer, Campbell Scientific EE181 Temperature and Relative Humidity Probe, Setra 278 Barometer (Datastreams: tbsground, tbsmerged)

Figure 7. TBS ground station sensors at ARM's Southern Great Plains (SGP) observatory.

These instruments are used on the ARM TBS ground station to collect continuous, surface-based observations of wind speed, gust wind speed, temperature, relative humidity, and pressure once a second. One-second data is averaged over one minute in tbsground output variables except for wind_speed_max, which is the maximum one-second gust speed recorded within one minute. Measurements are collected from the anemometer at approximately 4 m above the surface, from the temperature and relative humidity sensor approximately 2 m above the surface, and from the pressure sensor approximately 1 m above the surface. The TBS is generally operated with a collocated ceilometer to provide cloud base and mixing layer heights, but the ceilometer is currently operated independently from the TBS ground station. Similarly, it is advantageous for the TBS to operate near a Doppler lidar, but ARM Doppler lidars are operated independently of the TBS and TBS operations do not typically require an adjacent Doppler lidar.

Table 4. TBS ground station instrument specifications.

	Resolution	Accuracy	Range	Response time
Pressure (hPa)	0.01	+/- 0.5	600 - 1100	<100 ms
Temperature (°C)	0.01	+/- 0.2	-40 - 60	≤ 22 s
Relative Humidity (%)	0.1	+/- (1.3 + 0.003*RH)	0 - 100	≤ 22 s
Wind Speed (m/s)	2.5 m	12 m vertically	n/a	1 s

2.5.5 iMet Radiosonde (Datastreams: tbsimet, tbsmerged)

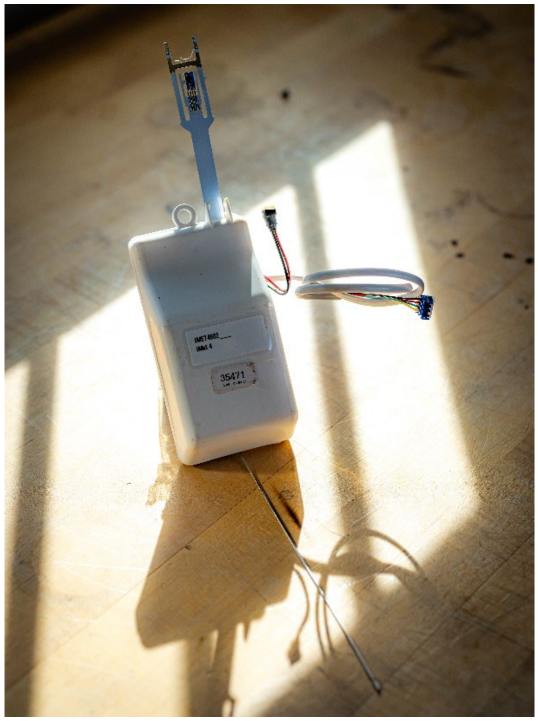

Figure 8. iMet-4 RSB radiosonde used on ARM TBS.

interMet iMet-4 radiosondes used on the TBS are identical to free-release iMet-4 radiosondes, and provide measurements of temperature, relative humidity, pressure, 3D GPS, and geopotential height once a second. Multiple iMet radiosondes may be operated on the same TBS flight at different altitudes.

Table 5. iMet-4 RSB radiosonde specifications.

	Resolution	Repeatability	Range	Response time	Type
Pressure (hPa)	0.01	1.0	1200 - 10	0.5 ms	Sensor
Temperature (°C)	0.01	0.2	-90 - 60	2/ < 1 s still air/5 m/s wind	Glass bead
Relative humidity (%)	0.1	5	0 - 100	0.6 s @ 25 °C 61 s @ -40 °C	Capacitive polymer
GPS pressure	0.1 hPa	2 hPa	0 – 3	1 s	U-Blox CAM-M8
GPS position	2.5 m	2.5 m	n/a	1 s	U-Blox CAM-M8
Geopotential height (pressure derived)	0.1 m	15 m	Sfc - 40 km	1 ms	Sensor
Geopotential height (GPS derived)	0.1 m	30 m	Sfc - 40 km	1 s	U-Blox CAM-M8

2.5.6 iMet XQ2 Sensor (Datastreams: tbsietxq2, tbsmerged)

Figure 9. iMet XQ2 sensor used on ARM TBS.

iMet XQ2 sensors are used with each TBS wind speed and direction sensor to provide measurements of temperature, relative humidity, pressure, and 3D GPS position data once a second at the same altitude as the wind sensor. Several iMet XQ2 sensors may be operated on the same TBS flight at different altitudes.

Table 6. iMet XQ2 specifications.

	Resolution	Accuracy	Range	Response time
Pressure (hPa)	0.01	+/- 1.5	10 - 1200	10 ms
Temperature (°C)	0.01	+/- 0.3	-90 - 50	1 s @ 5 m/s wind
Relative humidity (%)	0.1	+/- 5	0 - 100	0.6 s @ 25 °C 5.2 s @ 5 °C 10.9 s @ -10 °C
GPS position	2.5 m	12 m vertically	n/a	1 s

2.5.7 Handix POPS (Datastreams: tbspops, tbsmerged)

The portable optical particle spectrometer (POPS) instruments are used to measure airborne aerosol concentration and particle size distribution from 140 nm to 3 µm diameter once a second. Six POPS units are available, and multiple POPS units may be operated on the same TBS flight at different altitudes (Mei et al. 2020). POPS are operated with a diffusion dryer.

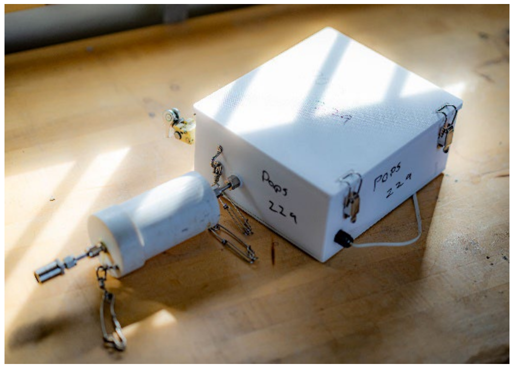

Figure 10. Handix POPS and diffusion dryer.

Table 7. POPS specifications.

Detectable particle size range	140 nm – 3.0 µm
Maximum particle concentration range with < 10% coincidence error	1250 #/cm^3
Particle concentration accuracy	+/- 10 % < 1000 #/cm^3 at 0.1 LPM sample flow rate
Sample flow rate	0.05 – 0.35 LPM
Operating temperature range	-40 °C to 35 °C
Laser wavelength	405 nm

2.5.8 SLWC (Datastreams: tbsslwc, tbsmergedincloud)

Figure 11. Anasphere SLWC sonde on TBS tether.

Anasphere supercooled liquid water content (SLWC) sondes are deployed on the TBS only when operating inside of clouds during flights in Restricted Airspace. The SLWC sondes deploy a vibrating wire. The frequency depression of the wire over time, due to ice accreting on the wire in the presence of supercooled liquid water, is used to calculate supercooled liquid water content (Serke et al. 2014, Dexheimer et al. 2019) approximately every three seconds.

Table 8. Anasphere SLWC sonde specifications.

	Vibrating wire resolution (Hz)	SLWC resolution (g/m^3)	Accuracy (g/m^3)	Measurement time (s)
Anasphere SLWC	0.02	+/- 0.01	≤ .04	3

2.5.9 NRG 40H Anemometer, RM Young 27106T Vertical Anemometer, Tallysman HC872 Helical Antennas, Hemisphere GNSS Vega 28, LI-560 Trisonica Sphere (Datastreams: tbswind, tbsmerged)

Figure 12. TBS wind sensor boom with vertical wind and cup anemometers and wind direction antennas.

These instruments are used on ARM TBS wind speed and direction sensor booms in different combinations to measure horizontal wind speed, vertical wind speed, wind direction, and sonic-based 3D wind speed. Ten wind sensor booms are available. All measurements are collected at 1 Hz, except for sonic-based 3D wind speed, which is collected at 60 Hz. Multiple wind sensor booms may be operated on the same TBS flight at different altitudes.

Table 9. TBS wind sensor boom specifications.

	Resolution	Accuracy	Range	Response Time
Horizontal wind speed (m/s)	0.765	+/- 0.1	1 - 96	<1 s
Vertical wind speed (m/s)	0.4	+/- 1 %	0 - 25	<1 s
Wind direction (°)	0.1	+/- 0.08	0 - 360	0.1 s
GPS position	1 ppm	≥ 8 mm	n/a	0.1 s
3D Sonic wind speed (m/s)	0.01 m/s	+/- 1 %	0 - 50	0.02 s

2.5.10 PNNL EMSL STAC (Datastreams: Available from PNNL EMSL)

Figure 13. EMSL STAC in flight enclosure.

The PNNL Environmental Molecular Sciences Laboratory (EMSL) Size-and-Time-Resolved Aerosol Collector (STAC) provides size-and-time-resolved individual particle morphology and chemical composition for particles from 0.07 to 2.3 µm diameter. The STAC deploys 20 miniaturized cascade impactors composed of four stages where size-resolved particles are collected on multiple substrates. The d50 cutoff sizes for each stage shown below in Table 10 represent the aerodynamic particle diameter at which a 0.5 collection efficiency occurs. There are three substrate holders in each stage, which may include carbon type-B transmission electron microscopy (TEM) grids, carbon lacey TEM grids, and silicon nitride substrates (Cheng et al. 2022, Lata et al. 2023). STAC samples can be analyzed by high-resolution microscopy and nano-desorption electrospray ionization high-resolution mass spectrometry (DESI-HRMS). The STAC is also integrated with environmental sensors to measure relative humidity, temperature, altitude, and aerosol light-absorption properties.

Table 10. EMSL STAC specifications.

Stage	50% cutoff size (µm)
A	2.3
B	0.62
C	0.42
D	0.12
E	0.069

	Resolution (s)	Accuracy	Range
Operation flowrate (LPM)	N/A	N/A	3
Particle number (# from 0.3-2.5 µm diameter)	1	+/- 10	N/A
Light absorption coefficient (mg BC/m^3)	N/A	N/A	0-1
Temperature (K)	1	+/- 1	250-350
Relative humidity (%)	1	+/- 5	5-95
Altitude (m agl)	1	+/- 10	0-2000

2.5.11 PNNL EMSL TBAC (Datastreams: Available from PNNL EMSL)

Figure 14. EMSL TBAC in flight enclosure.

The Total Bulk Aerosol Collector (TBAC) provides time-resolved, high-resolution mass spectrometry analysis of bulk aerosol particles collected through five time-resolved valves. Quartz or 47-mm PTFE filters for various bulk chemical analyses are used in each valve (Vandergrift et al. 2022).

2.5.12 PNNL EMSL TRAVIS (Datastreams: Available from PNNL EMSL)

Figure 15. EMSL TRAVIS in flight enclosure.

The Time-Resolved Automated Volatile Organic Compounds Sampling System (TRAVIS) provides chemical analysis using thermal desorption GC-MS on six time-resolved inlets where samples are collected onto sorbent tubes. EMSL conducts high-throughput thermal desorption gas chromatography coupled to quadrupole time-of-flight mass spectrometry (TD-GC-QTOFMS) for off-line volatile organic compound (VOC) measurements. The operational flowrate is 300 sccm.

Table 11. EMSL TRAVIS specifications.

	Resolution (s)	Accuracy	Range
Temperature (K)	1	+/- 1	250-350
Relative humidity (%)	1	+/- 5	5-95
Altitude (m agl)	1	+/- 10	0-2000
GPS (%)	1	+/- 5	

2.5.13 Sandia FROST(Datastreams: Available from Sandia)

Figure 16. FROST VOC sampler in flight enclosure.

The Fielded Remote Organic Sampling Technology (FROST) provides chemical analysis of four time-resolved sorbent samples on a LECO GCxGC bench time-of-flight mass spectrometer, using a Gerstel MPS Thermal Desorption System. Samples collected via FROST can be analyzed on one of two instruments. One instrument will provide ultra-high mass spectrometer resolution (up to four decimal points or m/z data) and can be used to identify true unknowns. Data can include suspected formulas of species not included in any current mass spectra database. This instrument also has a low limit of detection of known species (tens of femtogram range). The second instrument can provide an-order-of-magnitude-lower limits of detection (into the single-digit femtogram range) for known species currently in mass spectra databases. This system is also more resilient to environmental samples that contain higher levels of moisture.

Table 12. FROST specifications.

	Resolution
Detected Species	>10,000

3.0 Data

The TBS outputs the following datastreams on ARM's Data Discovery: tbscam, tbscpc, tbsdts, tbsground, tbsimet, tbsimetxq2, tbspops, and tbswind. These datastreams are merged with surface-based ceilometer estimates of cloud base and boundary-layer height in the tbsmerged Value-Added Product. The tbsmerged_incloud product builds upon tbsmerged to incorporate the tbsslwc datastream, which estimates in-cloud supercooled liquid water content. Each datastream includes quality control variables for each scientific variable.

3.1 Data Description

3.1.1 tbscam

The tbscam datastream includes .csv, .jpg, and .pdf file types. Jpg files include three different image types: images named as '_MWIR' are images captured with the Mirage 640 MWIR, images named as '_LWIR' are images captured with the 8640 LWIR, and '_R10C' images are visible images collected with the Sony R10C. The image files follow a naming convention of "YYMMDD_HHMMSS_altitude in m MSL_imagetype". Example filenames are "230406_000538_2973_MWIR.jpg" for an MWIR image and "230406_000533_2974_R10C.jpg" for a visual image. Csv files contain a calibrated radiometric temperature estimate for each pixel in the image associated with the filename. Pdf reports generated for each flight contain simultaneous images from thermal and visible imagers and the associated metadata. Reports are named as, "Report_2023-04-06.pdf" where the year, month, and day are the flight date in UTC.

3.1.2 tbscpc

The primary tbscpc measurement output is total number concentration of aerosol particles from 10 nm up to 1.0 µm in diameter every second. The tbscpc datastream also includes the following variables from an iMet radiosonde operating on the tether within one meter of the CPC: altitude above mean sea level (alt), gps_derived pressure (gps_pressure), barometric pressure (imet_pressure), latitude (lat), longitude (lon), relative humidity (relative_humidity), and air temperature corrected for solar radiation (temperature).

3.1.3 tbsdts

During TBS flights, distributed temperature sensing records two external reference temperatures (°C), the length span of the fiber over which the measurement was collected, the uncalibrated calculated temperature (°C), and the Stokes and anti-Stokes return intensities. Measurements are typically collected every 30 seconds. These uncalibrated temperature data are converted into calibrated temperature values using the two surface-based calibration bath references and reference temperatures from an iMet radiosonde at the terminal airborne end of the fiber. The primary tbsdts output variables are calibrated air temperature (temperature) and the height above ground level associated with the temperature value (height).

3.1.4 tbsground

The tbsground datastream is continuously collected at the surface during TBS deployments, as opposed to other TBS datastreams, which are only created when the TBS is in flight. Primary tbsground measurements include air pressure (pressure), temperature (temperature), relative humidity (relative_humidity), average 1-minute wind speed (wind_speed), and 1-second gust wind speed (wind_speed_max).

3.1.5 tbsimet

The primary tbsimet measurement outputs are air temperature corrected for solar radiation (air_temperature) and relative humidity (rh). The following variables are also provided: gps-derived altitude (alt), frost point (frostpoint), barometrically derived ascent rate (ascent_rate), gps-derived ascent rate (gps_ascent_rate), gps-derived pressure (gps_pressure), barometrically derived altitude (imet_altitude), latitude (lat), longitude (lon), barometric pressure (pressure), potential temperature (theta), water vapor mixing ratio (vapor_mixing_ratio), and total column water vapor (total_column_water).

3.1.6 tbsimetxq2

The primary tbsimet measurement outputs are air temperature corrected for solar radiation (air_temperature) and relative humidity (rh). The following variables are also provided: barometric pressure (pressure), relative humidity measured by the temperature sensor (rh_sensor_temperature), latitude (lat), longitude (lon), and altitude above mean sea level (alt).

3.1.7 tbsmerged and tbsmergedincloud

tbsmerged integrates data from instruments flown on ARM's TBS missions that collect in situ measurements of temperature, humidity, wind speed, wind direction, and aerosol properties with estimates of cloud base and boundary-layer height from a surface-based ceilometer to improve the ease of use of TBS data sets. tbsmergedincloud includes supercooled liquid water content (tbsslwc) measurements collected within the cloud. Specific TBS data products included in tbsmerged are: tbsground (surface temperature, pressure, wind speed, gust wind speed, and relative humidity), tbspops (airborne aerosol number concentration and size distribution from 140 nm to 3 µm), tbscpc (airborne aerosol number concentration from 10 nm to 1 µm), tbsimet and tbsimetxq (airborne temperature, pressure, relative humidity, and altitude), and tbswind (airborne wind speed, gust wind speed, and wind direction). Surface-based ceilometer estimates of cloud base and boundary-layer height are included. Full details of the tbsmerged Value-Added Product are available in Dexheimer et al. 2023.

3.1.8 tbspops

The primary tbspops measurement outputs are aerosol particle size distribution (dn_135_150, dn_150_170, dn_170_195, dn_195_220, dn_260_335, dn_335_510, dn_510_705, dn_705_1380, dn_1380_1760, dn_1760_2550, dn_2550_3615) and total particle number concentration. The tbspops datastream also includes the following variables from an iMet radiosonde attached to the POPS: altitude above mean sea level (alt), gps_derived pressure (gps_pressure), barometric pressure (imet_pressure), latitude (lat), longitude (lon), relative humidity (relative_humidity), and air temperature corrected for solar radiation (imet_temperature).

3.1.9 tbswind

The primary tbswind measurement outputs are the vertical wind speed component measured by an RM Young 27106 propeller anemometer (vertical_wind), horizontal wind speed measured by an NRG 40H cup anemometer (wind_speed), horizontal wind gust speed measured by an NRG 40H cup anemometer (wind_gust), and wind direction measured using two Tallysman HC872 helical antennas separated by 1 m and a Hemisphere GNSS Vega 28 compass board (wind_direction). The ascent and descent speed of the wind sensor boom are corrected for in the vertical_wind variable by applying an offset for the calculated change in altitude reported by the Vega 28 compass board each second. Additional tbswind variables include: the pitch of the wind sensor boom from horizontal (pitch), the roll of the wind sensor boom around the axis from the front to the tail (roll), latitude (lat), longitude (lon), and altitude above mean sea level (alt).

4.0 Historical Background

The ARM TBS operating locations and data durations from each location are shown in Table 13.

Table 13. Historical ARM TBS operating locations from 2017 to 2024.

ARM facility	ARM IOP	Site identifier	Data duration
AMF3	N/A	oli	2017-2020
SGP C1	N/A	sgp C1	2019-2024
SGP E9	N/A	sgp E9	2020-2021
SGP E36	N/A	sgp E36	2020-2022
AMF1	TRACER	hou S3	2022
AMF2	SAIL	guc M1	2021-2022
AMF2	SAIL	guc S4	2023

5.0 Maintenance Plan

5.1 Balloons

Balloons are inflated with air for leak testing and the rigging and skirt are inspected at the surface upon receipt from the vendor. Each new balloon undergoes an un-instrumented test flight upon its initial inflation with helium, and the rigging and flight characteristics are tested and adjusted. Balloons are inflated with air for leak and seam testing annually and are inspected for leaks during the helium inflation process at the start of each flight day.

5.2 Winches

Winches undergo annual one-minute deadlift testing using a stationary load that provides a 1.3x safety factor in comparison to the lifting force generated by an aerostat in 17 m/s wind speeds at sea level in a standard atmosphere. In late 2024 it is expected that load testing will transition to pulling a weighted cart up and down an angled ramp to better simulate the line speed and regenerative braking experienced under full load ascent and descent conditions.

5.3 Tethers

ARM TBS tethers are load tested to failure every 150 flight hours using three test lengths from the exterior end and three test lengths from the interior end of the tether in relation to the winch drum.

5.4 Instrumentation

ARM TBS instrumentation is calibrated as indicated in Table 15. Additionally, the CPC and POPS undergo daily flow rate and zero filter checks during field campaigns. The wind sensor booms undergo heading checks at the start of each field campaign against a reference compass bearing. At the start of each flight day, the relative humidity and temperature reported by each iMet radiosonde planned for flight on the TBS, and the wind speed reported by each NRG 40H cup anemometer planned for flight on the TBS, are compared with the respective reference outputs reported by tbsground sensors.

Table 14. TBS instrument calibration information.

Instrument	Calibration frequency (when in use)	Calibration mode
TSI CPC 3007	Prior to each campaign	Instrument mentor
TSI flowmeter	Annually	Vendor
Handix POPS	Prior to each campaign	Instrument mentor
NRG 40H cup anemometer	Annually	Vendor
NRG IceFree3 anemometer	Annually	Vendor
RM Young 27106T anemometer	Annually	Vendor
Campbell Scientific dataloggers	Every three years	Vendor
iMet XQ2	Annually	Vendor
iMet 4-RSB radiosondes	Annually	Vendor
Silixa XT DTS	Annually	Vendor
Sensornet Oryx DTS	Annually	Vendor
ICI Mirage and 8640 imagers	Annually	Vendor
Campbell Scientific EE181 temperature and RH sensor	Annually	Vendor
Campbell Scientific CS100 barometric pressure sensor	Annually	Vendor

6.0 Citable References

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