A Fiber Optic Distributed Temperature Sensor for Continuous *in situ* Profiling 2 km Beneath Constant-altitude Scientific Balloons

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Abstract. A novel fiber optic distributed temperature sensing instrument named the Fiber-optic Laser Operated Atmospheric Temperature Sensor, or FLOATS, was developed for continuous *in situ* profiling of the atmosphere up to 2 km below constant altitude scientific balloons. The temperature sensing system uses
15   a suspended fiber optic cable and temperature dependent scattering of pulsed laser light in the Raman regime to retrieve continuous 3 m vertical resolution profiles at a minimum sampling period of 20 s. FLOATS was designed for operation aboard drifting superpressure balloons in the tropical tropopause layer at altitudes around 18 km as part of the Stratéole 2 campaign. A short test flight of the system was conducted from Laramie, Wyoming, in January 2021 to check the optical, electrical, and mechanical systems at altitude and
20   to validate a four-reference temperature calibration procedure with a fiber optic deployment length of 1170 m. During the 4-hour flight aboard a vented balloon, FLOATS retrieved temperature profiles during ascent and while at a constant float altitude of about 19 km. The FLOATS retrievals provided differences of less than 1.0°C compared to a commercial radiosonde aboard the flight payload during ascent. At float altitude, a comparison of optical length and GPS position at the bottom of the fiber optic revealed little to no curvature
25   in the fiber optic cable suggesting that the position of any distributed temperature measurement can be effectively modeled. Comparisons of the distributed temperature retrievals to the reference temperature sensors show strong agreement with root mean square error values less than 0.4°C. The instrument also demonstrated good agreement with nearby meteorological observations and COSMIC-2 satellite profiles. Observations of temperature and wind perturbations compared to the nearby radiosounding profiles provide
30   evidence of inertial gravity wave activity during the test flight. Spectral analysis of the observed temperature perturbations shows that FLOATS is an effective and pioneering tool for the investigation of small scale gravity waves in the lower stratosphere.

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1 Introduction

Distributed temperature sensing (DTS) uses fiber optic cable to obtain continuous profiles of temperature along the length of the fiber at a high time resolution. The sensing method is distinct from single point fiber optic techniques like fiber Braggs gratings in that it uses temperature dependent light scattering in the Rayleigh, Brillouin, or Raman regimes within the fiber optic core in conjunction with optical time domain reflectometry to acquire uninterrupted temperature along the longitudinal axis (Lu et al., 2019). Raman spectra DTS has gained popularity within the earth sciences because it is a lower cost and simple method for measuring temperature in harsh environments and for sensing temperature gradients over large spatial domains relative to pointwise sensors (Tyler et al., 2009). Applications of DTS in environmental sensing have largely been centered around hydrologic and geologic research (Drusová et al., 2021; Henninges and Masoudi, 2021; Lagos et al., 2020; Selker et al., 2006; Sinnett et al., 2020; Tyler et al., 2009), but there has been increased interest in using DTS for atmospheric measurements over the last decade. Past atmospheric measurements with DTS can generally be categorized into three fields including surface layer to air interactions (Peltola et al., 2021; Petrides et al., 2011; Thomas et al., 2012), boundary layer dynamics (Egerer et al., 2019; Higgins et al., 2018; Keller et al., 2011), and wind measurements (Sayde et al., 2015; van Ramshorst et al., 2020). In two aerial studies, including measurements aboard a tethered balloon (Keller et al., 2011) and aboard an unmanned aircraft (Higgins et al., 2018), Raman spectra DTS was found to be reliable compared to traditional temperature sensors.

Here we present a novel balloon-borne DTS system for atmospheric temperature profiling of up to 2 km within the upper troposphere and lower stratosphere (UTLS). The UTLS is a globally important region of the atmosphere defined by its thermal structure, with a positive lapse rate in the troposphere terminated at a cold point and a subsequent shift to a negative lapse rate in the stratosphere. Temperature structure within the UTLS plays a role in the transport and chemistry of trace gases and aerosol. In the tropics, for example, stratospheric water vapor concentrations are controlled by the thermal structure of the Tropical Tropopause Layer (TTL; Chang and L'Ecuyer, 2020; Fueglistaler et al., 2009; Randel and Jensen, 2013). Routine temperature measurements in this region are made by satellite sensors and a sparse network of equatorial radiosondes. Current space-based temperature measurements made by Global Navigation Satellite System (GNSS) radio occultation (GNSS-RO; e.g. COSMIC-2) or nadir sounding (e.g. AMSU) provide near-global coverage making them ideal for broad climate studies (Khaykin et al., 2017). However, nadir sounding measurements have limited vertical resolution and are limited in their diurnal sampling, whereas GNSS-RO systems have highly variable spatial coverage. Both systems have horizontal resolutions ranging from a few kilometers to hundreds of kilometers. Balloon-borne radio soundings of atmospheric temperature are

performed on a regular basis at numerous locations as they are part of the daily observations used for aviation

and meteorology. Radiosonde temperature measurements provide high vertical resolution (5 - 100 m), over

70 a large altitude range (~0-30 km), but only retrieve one vertical profile per flight and have low temporal

resolution as they are typically performed once or twice per day. Thus, neither technique is ideal for

investigating small scale thermal structure and its evolution over space and time, such as may occur due to

gravity waves. The instrument described here overcomes both these limitations by collecting near-

continuous, 3 m vertical resolution temperature measurements through the vertical extent of the UTLS.

75 To investigate the thermal structure of the UTLS the novel Fiber-optic Laser Operated Atmospheric

Temperature Sensor (FLOATS) instrument was developed. The conception of the instrument was motivated

by Stratéole 2, an international mission, which aims to investigate dynamics, transport, and chemistry within

the TTL and tropical lower stratosphere using constant density balloons with flight durations up to 4 months

(Haase et al., 2018). The FLOATS instrument was deployed on two long-duration balloon flights during the

80 2021 Stratéole 2 campaign. In this work, however, we describe results from a shorter duration constant

altitude mid-latitude flight of the FLOATS instrument that was performed to validate the instrument for the

Stratéole 2 mission. Temperature calibration and analysis techniques validated with the mid-latitude flight

provide the necessary proof of concept for the long-duration flights and demonstrate that DTS is an effective

tool for vertical profiling of the UTLS.

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2 Design and Methods

2.1 Instrument Overview

FLOATS is a DTS system that deploys up to 2000 m of fiber optic cable, unreeled from an internal

spool, below a high-altitude balloon gondola to obtain temperature profiles at 3 m vertical resolution with a

90 minimum sampling period of 20 s. The instrument is comprised of three major components including a DTS,

mechanical reeling system, and an end of fiber unit (EFU) sub-gondola (Fig 1a). These components were

developed for deployment aboard high altitude balloons during the Stratéole 2 mission and are therefore

designed to withstand harsh environmental conditions, run semi-autonomously with limited supervision from

the ground, and to meet the low power, low mass, and regulatory requirements of high altitude ballooning.

95 FLOATS was built to meet the requirements for a multi-month flight aboard a Centre national d'études

spatiales (CNES) superpressure balloon at a pressure level near 70 hPa, approximately 18km, in the TTL, at

latitudes between 15°N and 20°S. This region of the atmosphere is one of the coldest regions below the

mesosphere, mean temperatures < -75°C (Fueglistaler et al., 2009)

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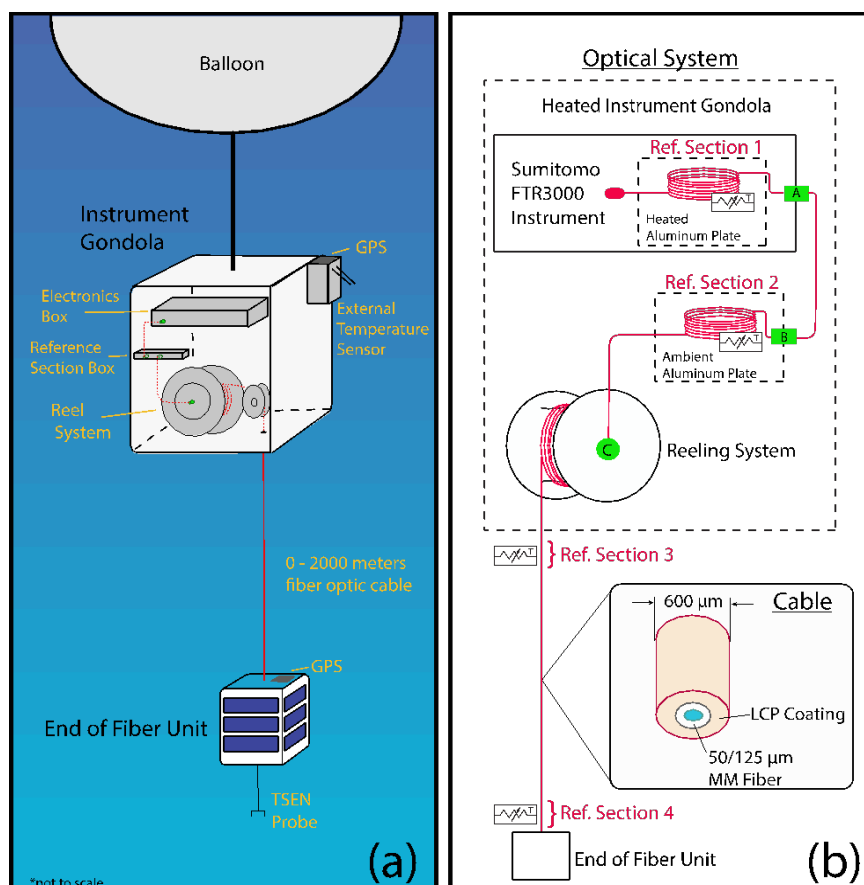
Figure 1: Illustration of the components of the FLOATS instrument (a) and optical system (b). Fiber optic connections are depicted in panel b with green icons. The thermistor electrical symbols depicted in panel b are used to represent the location of a reference temperature sensor.

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2.2 Optical System

The optical system of FLOATS, illustrated in Figure 1b, is comprised of a commercial DTS optical

125 bench, modified for high altitude operation, control electronics, reinforced multimode fiber optic cable, coiled sections of fiber optic cable at uniform temperature, and reference temperature sensors. The sections of fiber optic cable at uniform temperature combined with reference temperature sensors are identified as Ref. Section X in Figure 1 and RSX in the text, where X is the reference section number. All of the components with the exception of the fiber optic cable when deployed for measurements, are contained within a temperature-

130 controlled balloon gondola (-30° C – 30° C). The commercial optical bench is a Sumitomo Electric Industries, Ltd, FTR3000 instrument. The FTR3000 pulses 785 nm Class 1 laser light through the fiber optic cable and

senses the Stokes and anti-Stokes scattering at 760 nm and 810 nm, respectively, as a function of time using optical time domain reflectometry. For temperature calibration, the instrument contains a 25 m length of coiled unbuffered fiber laid on a temperature-controlled aluminum plate and immersed in a semi-solid gel (RS1). The FTR3000 with the factory single point calibration system and a ~1 minute sample integration time has a manufacturer specified temperature accuracy of ±0.7° C at 500 m distance along the fiber, ±1.0° C at 1000 m, and ±2.0° C at 2000 m. The manufacturer reports a spatial resolution of 3 m defined as the distance between the 10th and 90th percentile of the temperature step change.

In FLOATS, the FTR3000 is connected to a second 30 m section of unbuffered multimode fiber optic cable coiled upon a 100 x 100 x 0.81 mm aluminum plate and overlaid with self-leveling silicone adhesive with imbedded temperature sensors all held within an ABS plastic box (RS2 in Fig 1b). The coil is then connected to a fiber optic rotary joint (Princtel, Inc; RFCX-850-50) coupled to the reel system spool which is in turn connected to up to 2000 m of deployable multimode fiber optic cable.

The fiber optic cable used for ambient temperature sensing outside of the balloon gondola is size 50/125 μm multimode fiber optic coated in a proprietary linear crystal polymer (LCP) manufactured by Linden Photonics, Inc for a total diameter of 600±40 μm (Fig. 1b). The 600 μm diameter LCP fiber optic was chosen to provide a minimum breaking strain of 140 N to meet CNES safety standards and a maximum breaking strain of 230 N for the EFU sub-gondola to be classified as a 'light balloon' by ICAO regulatory standards (i.e. Rules of the Air ICAO Appendix 4 Annex 2). The LCP coated fiber optic was also chosen because it exhibits low breaking strain degradation with 90-day equivalent exposure to stratospheric level ultraviolet (UV) light.

The end of fiber optic cable is attached mechanically, but not optically to the EFU sub-gondola. Optical unions between sections of the fiber are component specific and referencing Figure 1b include: A, E2000-APC for the connection of FTR3000 to short patch cord; B, FC-APC for the patch cord to RS2 connection; C, FC-PC for the reference section to rotary joint to spooled cable assembly. Reference temperature sensors (i.e. 10 k ohm NTC thermistors and 100-ohm platinum RTD sensors) are placed on the aluminum plates of RS1 and RS2 for the temperature calibration procedures, which is discussed in Sect. 2.5.

2.3 Reeling System

The mechanical reeling system is designed to deploy the spooled fiber optic cable during flight and retract the fiber optic cable at the end of flight. The system consists of a laser sintered carbon-fiber reinforced nylon spool driven by a brushless DC servomotor, planetary gearhead, and electromagnetic brake combination, a stepper motor driven 'level-wind' carriage assembly, nylon redirect pulleys, and an electrical

control system. The reeling system is functionally and mechanically similar to the system used by the balloon-

165   borne water vapor, cloud, and temperature reel-down instrument RACHuTS fully described in (Kalnajs et
al., 2021), with some minor differences. The DC servomotor assembly, for example, is rated for lower loads
compared to the RACHuTS instrument (i.e. maximum design load of 19 N vs 35 N) to meet differing mass
requirements. Additionally, a larger spool diameter (12 cm) and wider bend radius pulleys for redirection of
the cable compared to RACHuTS were chosen to minimize optical losses attributed to bends in the fiber optic

170   cable (Zeidler et al., 1976). The reeling system is capable of performing multiple deployments and retractions
of the entire length of fiber, or variable lengths and variable speeds depending on flight requirements. Typical
deployment/retraction speeds are between 0.4 m/s and 0.5 m/s and the system has a maximum speed of
approximately 0.65 m/s. Therefore, for a flight in which 2000 m of fiber optic is required, it will take about
1 hour to reach full deployment. It should be noted that at least 50 m of fiber optic remains spooled on the

175   reeling system at any point, to act as a friction anchor and prevent the loss of the cable and end of fiber unit
while in flight.

2.4 End of Fiber Unit

The end of fiber unit is a 700 gram self-contained sub-gondola used to acquire GPS position, ambient

180   temperature, and pressure at the end of the FLOATS fiber optic cable. The exterior of the EFU is a box made
of extruded polystyrene foam with the dimensions of 12.5 cm x 12.5 cm x 20 cm. The fiber optic cable is
secured to the internal hollow tube frame of the EFU. The closest 10 m of fiber optic to the EFU are reinforced
with a hollow core Ultra High Molecular Weight Polyethylene (UHMWPE) braid with a breaking strain in
excess of 400 N for dynamic shock load protection during the launch of FLOATS at which point only the

185   reinforced section is exposed to the load from the EFU. The interior is insulated with Cabot Thermal Wrap
silica aerogel blankets and temperature controlled to -5° C with a 1.6 W flexible amide heater wrapped on
the battery pack. The sub-gondola is powered by a 24 Wh lithium ion battery pack that is charged with four
2 W photovoltaic arrays. Ambient temperature and pressure measurements are made with a
Thermodynamical SENsor (TSEN) supplied by LMD and designed for sampling in the UTLS (Hertzog et

190   al., 2007). The TSEN used by FLOATS is the same configuration used with the RACHuTS instrument and
a broader description can be found in Kalnajs *et al*. (2021). Previous measurements have shown the TSEN
design to be effective at reducing solar radiative heating biases normally associated with high altitude
measurements. TSEN has an accuracy and precision of 0.25° C during the day and 0.1°C at night (Hertzog
et al., 2004). The TSEN temperature probe hangs ~1 m below the EFU with small gauge

195   Polytetrafluoroethylene (PTFE) coated wire to reduce the effect of radiant heating from the EFU surface

during daylight hours. The GPS measurements are made with a UBlox MAX-M8C module and have a specified position accuracy of 2.5 m. All engineering data, TSEN, and GPS data are collected every 10 s and transmitted via a Long Range (LoRa) radio module to the instrument gondola.

200 **2.5 DTS Temperature Calibration**

The conversion of the temperature dependent Raman backscattering per unit distance of the fiber optic cable to ambient temperature was adapted from the single ended DTS calibration methodologies provided in   Hausner et al., 2011 and Suárez et al., 2011. In both methodologies, the temperature of a fiber optic cable can be estimated by (Suárez et al., 2011, Eq. 1):

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$$T(z) = \frac{\gamma}{ln\,[C] - ln[R(z)] + \Delta\alpha\,z} \qquad (1)$$

where $T(z)$ is the temperature in K at the distance along the fiber z in meters, γ is the shift in energy between the incident laser wavelength and Raman scattering wavelength in K, C is a dimensionless calibration

210 parameter, $\Delta\alpha$ is the differential attenuation between the backscattered Stokes and anti-Stokes intensities, and $R(z)$ is the measured ratio between the power of the Stokes backscattering to the anti-Stokes backscattering. To retrieve temperature, γ, C, and $\Delta\alpha$ must be known. Once $\Delta\alpha$ is known for a given profile, $ln[C]$ can be estimated as follows (Suárez et al., 2011, Eq. 4):

215 $$ln\,[C] = \frac{(ln\,[R(z_1)] - \Delta\alpha z_1)\,T(z_1)}{T(z_1) - T(z_2)} - \frac{(ln\,[R(z_2)] - \Delta\alpha z_2)\,T(z_2)}{T(z_1) - T(z_2)} \qquad (2)$$

and γ can be estimated by (Suárez et al., 2011, Eq.5):

$$\gamma = (ln\,[C] - ln\,[R(z_1)] + \Delta\alpha\,z_1)\,T(z_1) \qquad (3)$$

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In both equations, z_1 and z_2 are points or sections of fiber optic cable at an externally measured uniform, but different, temperature. For FLOATS, $T(z_1)$ and $T(z_2)$ are the temperatures of RS1 and RS2, and are measured independently (Fig. 1b). These sections are held at different temperatures by actively heating RS1 to a set point of 30°C and allowing RS2 to passively heat to the internal gondola temperature, typically in the range

225 of -30 – 30°C.

With the Hausner et al. (2011) methodology, the Δ parameter of a DTS system can be independently calculated for each DTS profile by finding *dln[R(z)]/dz* from a section of the fiber optic cable at uniform temperature. In laboratory thermal chamber experiments the FLOATS reference sections were found to produce widely different $\Delta\alpha$ compared to the sensing fiber optic possibly because of dissimilarity in fiber

230   optic cable, or because of low temperature related effects like strain on the fiber optic and microbending loss (Hanson, 1979). The reference sections are therefore not reliable benchmarks for attenuation of the deployable fiber optic cable in the UTLS environment. Additionally, under an ideal DTS setup there would be no connections between components, hence zero loss. For FLOATS this is not possible and the fiber optic unions along the optical path of the DTS generate insertion loss, or step losses in Raman backscattering

235   signal. Hausner et al. (2011) shows that step losses can be corrected by applying a linear offset to *ln[R(z)]*, but this method likely assumes that the fiber optic union and ±0.5 unit distance of the spatial resolution from the center of the union is at a uniform temperature. This is also not the case with FLOATS because the fiber optic unions are between reference components held at different temperatures, or optically undefinable sections like the spooled section of fiber. Optical unions in this orientation are required for integration of the

240   optical components (i.e. reference sections and rotary joint) into the optical system and for assembly into the instrument gondola. Therefore, methods were developed to account for the temperature effects on $\Delta\alpha$ and optical union step loss in the FLOATS system by a two-step optimization scheme. These methods are fully described in Appendix A, but are summarized here. First the step loss between the Reference Sections internal to the gondola for the experiment is found empirically as the difference in Raman backscattering between

245   RS2 and RS1 when the temperature offset between the two sections is equal to 0°C. Second, the step loss between the remaining optical unions and $\Delta\alpha$ for each profile is determined by minimizing the absolute mean bias between the calculated temperature and the independently observed temperature of each reference section as outlined in Hausner et al., (2011). By these methods the parameters required to calculate temperature using Eq. 1 (i.e. γ, C, and $\Delta\alpha$) can be determined dynamically for each profile within a given

250   experiment.

2.6 Wyoming Test Flight

A validation flight of FLOATS was conducted on 22 January 2021 from Laramie, Wyoming (41.3° N, 105.7° W; 2228 m above sea level) to test and characterize the instrument for the Stratéole 2 mission. The

255   flight, named WY933, was aboard a 283 m³ Raven Aerostar zero pressure vented balloon with a target constant altitude float level of 20 km. The flight launch time was 05:43 Local Time (LT). The flight train consisted of the balloon, a time and altitude controlled balloon cut away device, a secondary balloon cut away

device, a parachute, a strobe light, a time controlled parachute cutaway device, a radar transponder, and an instrument gondola. The instrument gondola was built of T-slotting framing rails with extruded polystyrene

260 walls for insulation and approximated a Stratéole 2 gondola. Outside of the gondola was a GPS tracking device, and an iMet-1-RSB radiosonde (Fig 1a). The radiosonde provided high accuracy pressure, temperature, relative humidity, winds, and GPS position at the gondola flight level at a sampling rate of 1 second. The radiosonde telemetry was received by a mobile ground station. FLOATS was equipped with a 1200 m spool of fiber optic cable.

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3 Results and Discussion

3.1 WY933 Flight Summary

Figure 2 shows the instrument gondola GPS altitude and vertical distance between the gondola and EFU determined by the EFU GPS as a function of time for WY933. The fiber optic reel out started at 05:58

270 LT, 15 minutes after launch, at a GPS altitude of 5820 m. The reel out completed at approximately 06:30 LT with the complete deployment of 1167 m of fiber optic cable, based on optical length, at an altitude of 13600 m. The gondola reached its float altitude of 19140 m at 06:45 LT about 110 km down range from the launch site. The fiber optic remained fully deployed until 08:15 LT when automated fiber optic retraction began. The gondola was cut-away after drifting horizontally for nearly 90 km. All flight control times were designed

275 to provide adequate time for ascent, fiber optic reeling, fully deployed temperature profiling and parachute descent while maintaining a radio communicable flight distance.

FLOATS retrieved a total of 381 DTS profiles with a sampling period of 20s and a deployment length greater than 8 m. The gondola crossed the tropopause at about 11 km with a temperature of -53° C. At float altitude, the ambient temperature ranged from -62.6° C to -54.8° C with an average of -57.9° C (Fig. 2). The

280 iMet-1-RSB temperature, however, did report large spikes in temperature, at 07:15 and 08:30 LT for example, suggestive of the temperature sensor being in direct sunlight and poorly ventilated for short periods of the flight. Based on the gondola-altitude adjusted solar zenith angle (SZA) shown in Figure 2, SZA <90° were observed by the gondola at about 16 km or 06:40. The observed SZA less than 90° reveals that FLOATS was in some degree of direct sunlight for the entirety of time the fiber optic was fully deployed. Thus, the effect

285 of solar radiative heating on the fiber optic cable and the resulting DTS temperature cannot be assessed from WY933. Solar radiative heating is a known concern for ground-based atmospheric DTS systems (de Jong et al., 2015), but ventilation by vertical wind shear along the length of the fiber optic cable will likely reduce the effect of solar heating on the FLOATS temperature profiles. Vertical wind shear and radiative heating will be addressed in the Stratéole 2 campaign where large daytime and nighttime datasets will be available.

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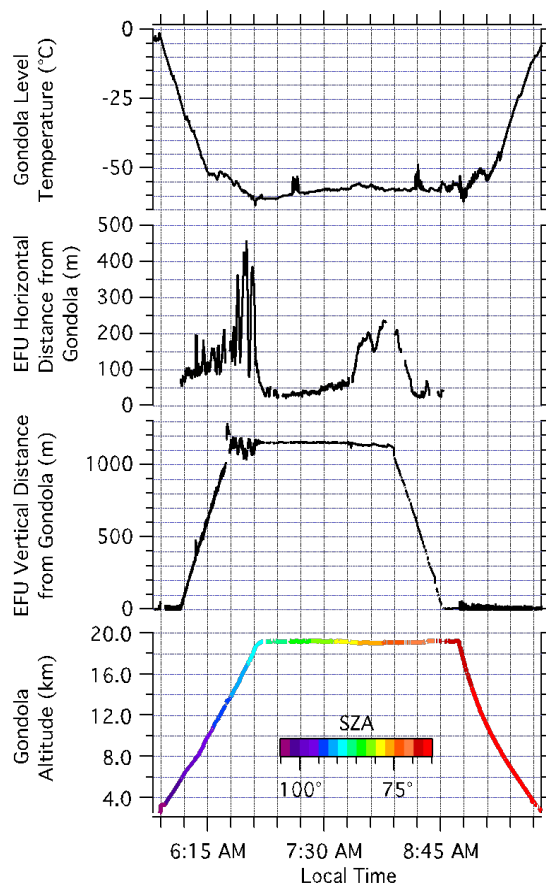
Figure 2: Summary of flight conditions of the 22 January 2021 WY933 zero pressure balloon fight. Altitude-adjusted solar zenith angle is displayed in rainbow.

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Unfortunately, the EFU TSEN thermistor was damaged during the WY933 launch and was unable to report end of fiber temperature, although the position of the EFU was recorded. Because of the damaged sensor, modifications to the temperature calibration method discussed in Section 2.2 and Appendix A were

315   made to retrieve temperature from the WY933 Raman backscattering profiles. These modifications are unique for the ascent/descent profiles and the float altitude profiles. For the ascent/descent profiles, RS4 temperature was derived from the iMet-1-RSB temperature profile by matching GPS altitudes from radiosonde and the EFU. For the float altitude profiles, a static attenuation parameter was estimated from the ascent profiles closest to the float level. The float level temperature profiles were then retrieved from a 3-

320 Reference Section calibration where only the rotary joint step loss value was optimized as discussed in
Appendix A.

3.2 End of Fiber Position

The position of the end of the fiber is a useful tool to evaluate the position of any point along the fiber
325 and thus the geospatial position of any FLOATS distributed temperature measurement. As seen in Figure 2
the end of fiber altitude relative to the instrument gondola altitude during WY933 is not constant even after
the fiber optic is fully deployed. For example, the vertical distance between the gondola oscillated in the
lower stratosphere before reaching float altitude. These oscillations are related to the horizontal offset
between the instrument gondola and EFU estimated with the Haversine formula to calculate great circle
330 distance. The EFU horizontal distance from the instrument gondola is given in Figure 2 and shows an inverse
relationship to the vertical distance. Here the maximum horizontal distance was observed during the
oscillation period prior to when float altitude is reached and then dampens to a minimum of 27 m at the start
of the float altitude period. The horizontal separation increases with time during the float altitude period and
reaches another maxima directly prior to the fiber optic reel in. The inverse relationship between the vertical
335 and horizontal displacements of the end of fiber suggests that a right triangle model within a Cartesian plane
may be used to describe or partially describe the position of the entire fiber relative to the gondola.

Using the right triangle model, by defining the hypotenuse as the shortest distance between the
gondola and the EFU, the average distance between them while fully deployed was estimated to be 1153±7
m. Given the spatial inaccuracies of both GPS units and other uncertainties, the estimated orthogonal distance
340 compares well with the 1167 m deploy distance estimated by DTS optical length. Therefore, there was likely
little to no curvature in the deployed fiber optic cable during WY933 and the right triangle model can be used
to evaluate the geospatial position of the FLOATS fiber optic. Curvature of the deployed fiber optic can lead
to difficulties interpreting geospatial results and therefore should be flagged in any dataset. A case where the
calculated hypotenuse is significantly shorter than the optical length of the fiber optic cable, would suggest
345 that the fiber is exhibiting significant curvature resulting in increased uncertainty in the derived geometric
altitude for positions along the fiber.

Figure 3a gives the three-dimensional translation of the end of fiber position by showing the position
of the end of fiber in degrees from the nadir view of the gondola as a function of geographic bearing for the
ascent and float altitude phase of flight. Over the course of the WY933 flight the end of fiber angle from
350 nadir had an average value of 6.7°±5.0° with a range of 1.0° to 29°. The angles were observed during all
periods of ascent and the fiber optic exhibited both pendulum and rotational patterns suggesting effects from

wind shear along the ascent path (Fig 3b), which will be explored further in Section. 4.5. After ascent, the rotational motions are dampened and the angle from nadir is reduced to less than 10° (Fig. 3a). For reference, a 10° offset from nadir produces a vertical displacement of about 1.5% at the end of the fiber compared to a nadir profile. The same degree of offset generates a horizontal displacement of about 17% compared to a nadir profile. The displacements may be corrected for by applying the right triangle model to estimate the altitude of all points along the fiber. However, the application of the model depends on the FLOATS dataset and minimum error needed for interpretation of those results. These above geospatial methods provide a framework that can be used to evaluate the quality of future FLOATS temperature profiles.
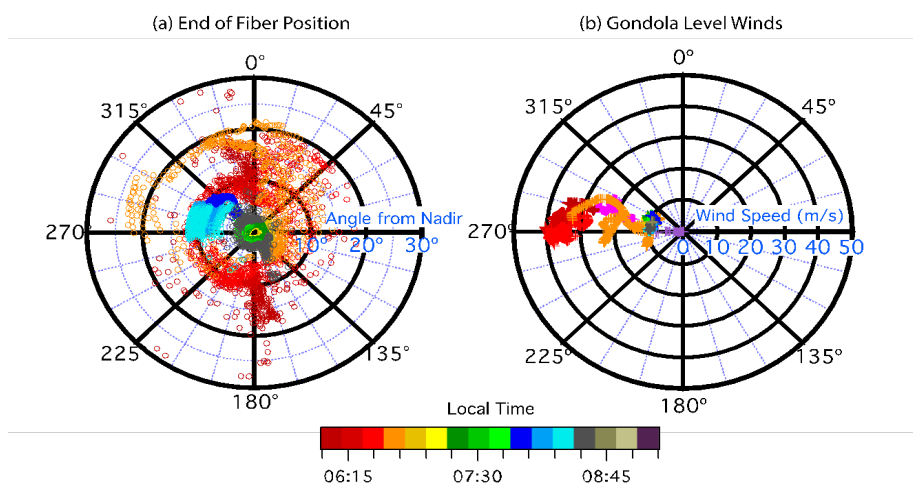
Figure 3. Polar graphs of (a) the end of fiber position angle in degrees with respect to nadir from the gondola and geographic bearing and (b) the wind speed in m/s and wind direction in degrees observed at the gondola level. Markers (rainbow) are colored by the local time (MST)

3.3 DTS Performance

The onboard reference temperature sensors (Fig. 1b) were used to evaluate the performance of the DTS temperature profiles from the ascent and float altitude of WY933. Since the EFU TSEN was damaged only the gondola level iMet-1-RSB temperature coincident to the EFU altitude could be used for the RS4 temperature during the ascent phase. The float altitude profiles were then calibrated using only the internal Reference Sections and RS3. For each reference section, every 1 meter point within that section was used to find the root mean square error compared to its respective sensor as follows:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(T_i - T_{obs})^2}{n}} \qquad (4)$$

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where T_i is the DTS temperature of a given point within a reference section with n observations, and T_{obs} is the reference section temperature.

The average RMSE for each reference section during ascent after the fiber optic was fully deployed, and at float altitude, are shown in Table 1. Generally, the error observed with the DTS observation in RS1

390   and RS2 were less than 0.3° C from all periods of flight and is representative of the minimum error in the measurement. The low error associated with these sections is likely because the sections are used to calculate the calibration parameters C and $\Delta\alpha$ as shown in Eq. 2 and Eq. 3. Also, because the sections are close to the incident laser there is large signal to noise in the Raman backscattering. This is a known characteristic of DTS and the FTR3000 datasheet for example shows a 1.4° C difference in temperature accuracy between

395   measurements at 500 m compared to 2000 m using the manufacturer's calibration. The ascent phase reference sections outside of the gondola were found to have RMSE of 1.15±1.38°C (RS3) and 1.22±0.58°C (RS4) respectively. The comparable RMSE observed with RS3 and RS4 and larger standard deviation observed with RS3 was unexpected and doesn't follow what is known about accuracy as a function of distance down the fiber. Similar RMSE was observed between all ascent profiles and those when the fiber optic was fully

400   deployed. During float the DTS performed better than during ascent with an almost 75% decrease in error observed with RS3 (Table 1). The RMSE error for RS4, however, is unknown because of the damaged EFU TSEN. During the retraction period of the float altitude phase of flight the DTS at RS3 performed poorly with a two order of magnitude increase in RMSE.

Based on the error statistics from the reference sections there are several conclusions that can be

405   applied to the interpretation of the temperature profiles as a whole. First, the Raman backscattering profiles from the fiber optic retraction period cannot be used for temperature retrievals. The reason for the large error observed during retraction is not fully understood, but is thought to be due to damage to the optical core of the fiber optic cable, temperature induced micro-bend losses, or a combination of both. The same error was not observed during the deployment phase, suggesting that the temperature of the fiber optic being

410   spooled/unspooled may have an effect on optical losses. For reference, the WY933 reel was spooled in laboratory conditions and deployed at gondola temperatures greater than -10° C, while the fiber was retracted at temperatures less than -55° C. The effect of spooling/unspooling temperatures may also play a part in the increased RMSE observed with RS3 between the fully deployed ascent and fully deployed float altitude phases. The recently deployed fiber optic may not have reached full temperature stabilization outside of the

415   gondola within the 20 second sampling period and caused the observed differences between the reference temperature and DTS temperature. The similar or greater RMSE observed with RS4 during ascent compared to RS3 suggests that response time of the DTS may be slower than the change in ambient temperature during ascent. This is a reasonable assumption because the average ascent rate of the balloon was 4.3 m/s and therefore there was likely some vertical 'smearing' of the DTS temperature over 20 seconds.

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Table 1: The average and standard deviation of the RMSE of the FLOATS DTS reference section temperature compared to the reference temperature sensors for the ascent and float level profiles.

DTS Profile Type	Reference Section	RMSE ($\mu \pm \sigma$)
Ascent (116 profiles)	1	0.29 ± 0.04
	2	0.29 ± 0.05
	3	1.15 ± 1.38
	4	1.22 ± 0.58
Ascent – fully deployed (41 profiles)	1	0.29 ± 0.03
	2	0.27 ± 0.05
	3	1.41 ± 2.18
	4	1.30 ± 0.69
Float level – fully deployed (179 profiles)	1	0.24 ± 0.04
	2	0.26 ± 0.04
	3	0.35 ± 0.81
Float level – fiber retraction (91 profiles)	1	0.22 ± 0.03
	2	0.24 ± 0.04
	3	12.4 ± 11.9

425   To further evaluate the performance of the FLOATS temperature profiles, full length ascent period profiles are compared to the iMet-1-RSB aboard the instrument gondola. Figure 4 shows the FLOATS temperature profiles averaged into 5 m altitude bins from 6.5 km to 19 km. The number of profile points averaged into each bin presented in Figure 4 is colored by orange gradient on the trace showing that upwards of 55 individual 1 m samples within each altitude bin were included in the ascent average. The standard

430   deviation, shown in grey, indicates that there was little variability in the DTS temperature at a single altitude with an average standard deviation of 0.9° C and a range of 0.3° C to 1.6° C (Fig. 4). The FLOATS ascent average compares well with the radiosonde altitude binned average at the same altitude and follows the same vertical trends. However, there does appear to be decreased vertical resolution observed with the FLOATS profiles corresponding to lower response to fast changes in the environmental lapse rate. This lower response

435   suggests that vertical 'smearing' due to a fast ascent rate compared to the DTS sampling period may be responsible. Using the mean absolute error (MAE) defined as:

$$MAE = \frac{\sum_{i=1}^{n}|T_{obs}-T_{avg}|}{n} \qquad (5)$$

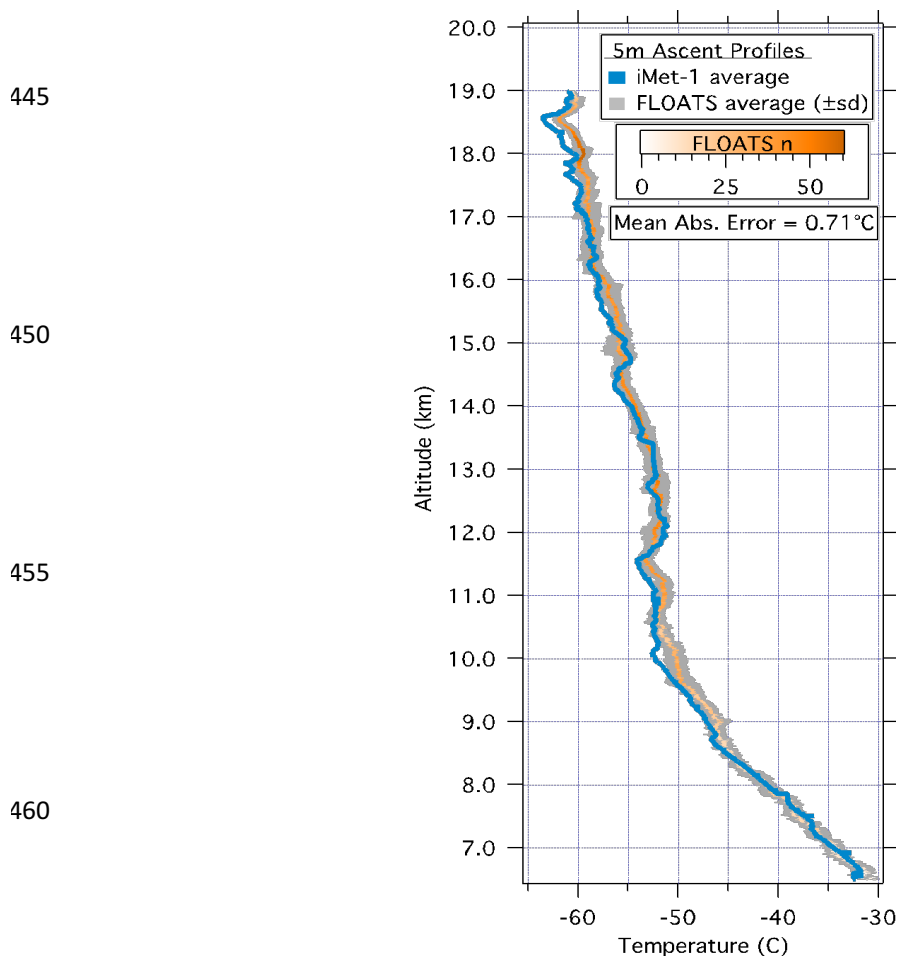
440   where T_{obs} is the average iMet temperature and T_{avg} is the average FLOATS for a given 5 m altitude bin i, and n is the number of altitude bins. The MAE was found to be 0.71° C for the DTS ascent profile compared to the reference temperature profile.

465

Figure 4: Ascent temperature profiles of the gondola level iMet radiosonde (blue line) and the DTS scans averaged into 5 meter bins. The DTS average temperature (orange gradient) is colored by the number (n) of 1m DTS sample points averaged for each 5 m bin. The standard deviation of the 5m DTS bins is shown in grey.

3.4 Float Level Temperatures

The 3-Reference Section calibrated temperatures at the WY933 float altitude can be seen in the curtain

470   plot found in Figure 5a. In the figure FLOATS profile temperatures are displayed as a function of altitude and local time. At the start of float altitude, FLOATS records a relative flat temperature profile near -61° C reaching from ~18 km to ~19.1 km with a cold band centered at 18.5 km. This cold band was observed to have a minimum temperature of -63.0° C and is consistent with the local cold-point temperature of -63.5°C and thermal structure observed in the iMet-1-RSB ascent profile at the same altitude (Fig 5c). Looking at the

475   first 2 minutes of FLOATS measurements at float altitude the average profile was found to have a MAE of 1.0° C compared to the iMet ascent profile. At about 06:55 to 07:05 LT the segment of profile at altitudes greater than 18.55 km began to warm to temperatures between -59° C and -60° C and the lower altitudes in the profile remain at a consistent temperature with an average of -60.8° C (Fig. 6a). Warming at the top half of the FLOATS fiber optic that wasn't observed at the bottom suggests that the instrument was entering a

480   warm layer at those altitudes and that the warming trend wasn't due to solar heating of the cable even as the SZA reached 85° during that period (Fig. 6b). At 07:05 the layer between about 18.5 km to 19.1 km warmed to an average of -58.5° C and the lower layer between about 18.0 km and 18.5 km warmed slightly to an average of -60.1° C. This trend continued until 07:45 local time with an average of -57.8° C in the upper altitude layer and an average of -59.8° observed in the lower altitude layer between those time periods. The

485   temperatures in the upper layer correspond well with the -57.6° C average gondola level temperature reported from the iMet-1-RSB for the period between 07:15 to 07:45 (Fig. 6b). The period between 07:05 and 07:15 was excluded from the gondola level average to remove the assumed biasing due to solar radiative heating of the sensor. After this period a ~2° C average warming was observed in the upper thermal layer from 07:45 to 08:15 and between 18.40 km and 19.1 km (Fig. 6a). Only a slight warming was observed for the lower

490   altitude layer during that time with an average of -59.2° C. As shown in Figure 5a, the fiber optic reel in begins at about 08:15 and after that period the FLOATS temperature profiles become inconsistent compared to the previous profiles probably because of optical distortion. Because of this distortion, the profiles from the reel in period are excluded from any analysis and comparison to the iMet-1-RSB descent profile. The reported descent profile, however, had similar thermal structure to the FLOATS profiles from the period prior

495   to reel in (Fig. 5c). A narrow cold layer was seen at 18.3 km and above 18.4 km a ~700 m warm layer with

a maximum temperature of -52.9° C was reported. A comparison of the average FLOATS temperature profile

2 minutes prior to reel in and the descent profile at the same altitude revealed a MAE of 1.3° C. By contrast

the same FLOATS average had a MAE of 4.0° C compared to the iMet-1-RSB ascent profile. The overall

agreement in thermal structure between the reported ascent and descent profiles and the FLOATS profiles

500   demonstrate that FLOATS aboard a near constant altitude balloon is an effective tool for understanding the

evolution of vertical structure at a high spatial and temporal resolution over a continuous domain.

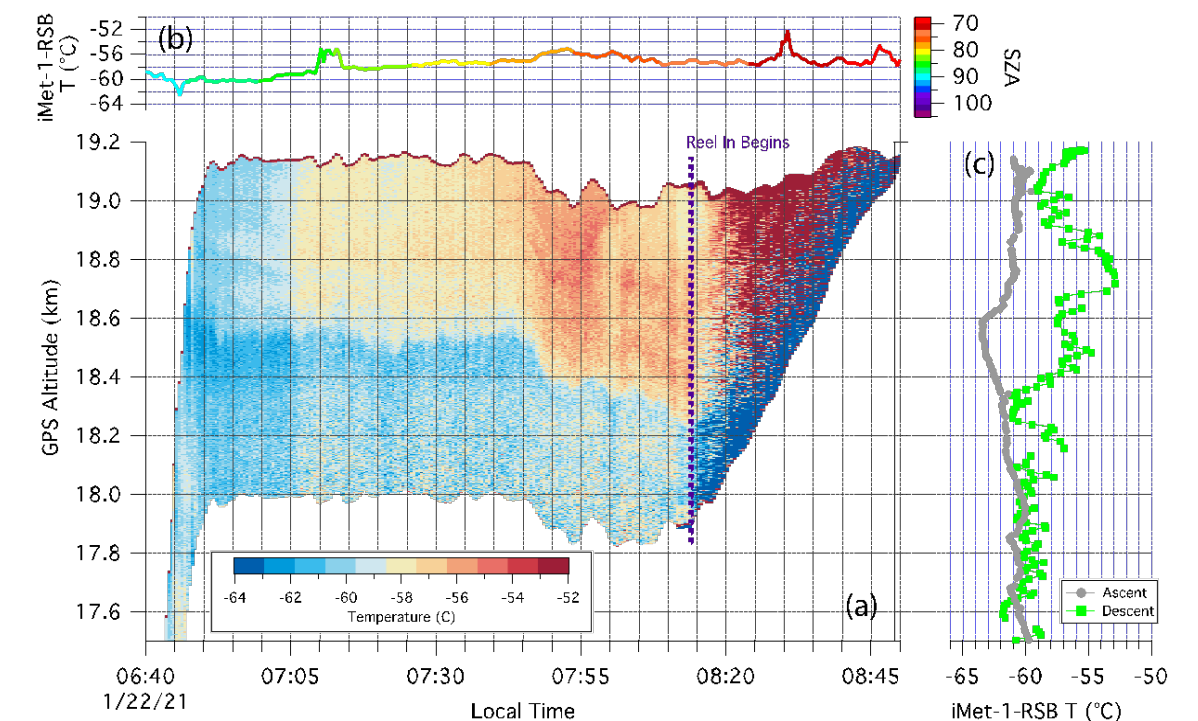



Figure 5: (a) Curtain plot of DTS profile temperatures in °C at or near flight altitude as a function of
altitude and local time. (b) Gondola level temperature in °C as a function of local time and colored by
the altitude adjusted solar zenith angle. (c) The gondola level ascent and descent temperature profiles in
°C as a function of altitude. The time where the fiber optic reel in begins is indicated with a dashed
purple line.

505   **3.5 Comparison with Outside Datasets**

Temperature profiles from outside the WY933 flight including COSMIC-2 and local meteorological

soundings are used to further evaluate the performance of FLOATS. Sounding data was retrieved from the

Wyoming Upper Air website (http://weather.uwyo.edu/upperair/sounding.html) for the Denver, CO (DNR;

72468) and the Riverton, WY (RIW; 72672) stations for January 22, 2021 12 UTC. Level 2 AtmPrf

510 COSMIC-2 temperature profiles for January 20, 2021 to January 24, 2021 were downloaded from the UCAR CDAAC website (https://data.cosmic.ucar.edu/). Because of the low inclination orbit of the COSMIC-2 constellation and subsequent sparse spatial coverage at mid-latitudes only 58 profiles within a ±12° longitude and ±6° latitude range of WY933 were available for the 5-day period based on the perigee point of the radio occultation. Three COSMIC-2 profiles were within a 400 km radius of WY933 within 12 hours of the flight.

515 A profile located at 39.69° N and 106.82° W at 13:00 LT was the closest matching COSMIC-2 profile to WY933. Following similar methods to (Alexander et al., 2008) the COSMIC-2 profiles were also used to generate a 5 day background temperature profile for a ±6° longitude by ±3° latitude grid box centered at 104° W and 40° N. The average of the 21 COSMIC-2 profiles that fit the criteria were used as the background temperature profile for the study region.

520 The temperature profiles from the outside datasets and the FLOATS WY933 flight can be seen in Figure 6, where the geopotential altitudes have been converted to geometric altitude for comparison between the datasets. Generally, the FLOATS average ascent profile compared well with the sounding and best match COSMIC-2 profile. All datasets revealed similar broad thermal structure. A lapse rate tropopause at or near 11 km, then a temperature inversion transitioning to a negative lapse rate up to about 17 km where there was

525 a divergence in vertical structure. Error analysis between the FLOATS ascent profile and outside datasets produce a MAE of 1.34 °C for the full altitude comparison between the FLOATS and COSMIC-2 best match, 1.95° C compared to the RIW sounding, and 3.07° C compared to the DNR sounding. Based on a MAE of 3.23° C between the RIW and DNR soundings the observed error between the FLOATS ascent profile and others is reasonable based on spatial and temporal differences between the datasets.

530 The FLOATS average temperature profile at float altitude also compared well to the outside datasets and is within a similar range of all observations (Fig 6.) Error analysis reported a MAE of 2.40° C, 2.79° C, and 3.23° C for the float level average compared to the COSMIC-2, RIW, and DNR profiles at the same altitude, respectively. The differences between the temperature profiles appear to be related to the FLOATS profile time. The average of the first two minutes from float altitude exhibits a vertical structure similar to

535 the DNR profile with a cold layer near 18.5 km (Fig. 6). Whereas, the average of the last two minutes more closely matched the RIW profile with a warm layer centered at the same altitude. The coincident thermal structure and range of the temperature measurements further validates the FLOATS DTS profiles and provides additional evidence for limited biasing due to solar radiative heating of the fiber optic cable.

Finally, evaluation of the FLOATS DTS profiles compared to the COSMIC-2 background profile

540 shows possible wave related variability in the profiles with altitude. As seen in Figure 6, the flight level

average suggests that WY933 was in an ~2° C warm phase region compared to the COSMIC-2 average. Additionally, differences in the FLOATS profiles compared to COSMIC-2 were observed during different periods of flight. These comparisons suggest that FLOATS data can be used to evaluate wave driven temperature anomalies like those described in Kim et al., 2016 and Chang and L'Ecuyer, 2020 or to evaluate

545 small scale energy states similar to methods described in Alexander et al. (2008).

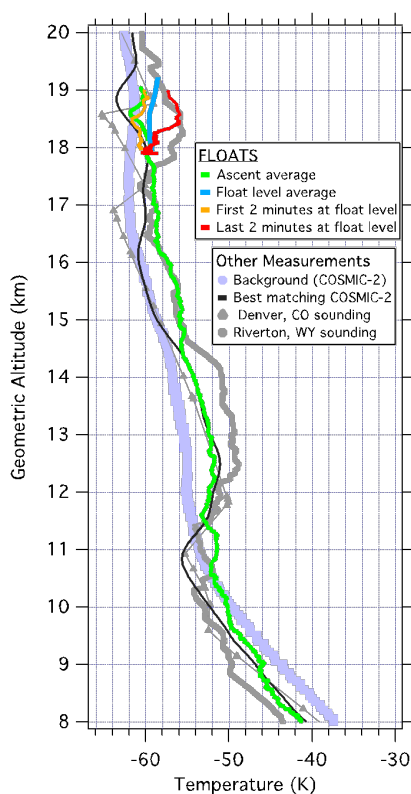



Figure 6: Temperature profiles in °C for the background temperature derived from COSMIC-2 temperature, radio sounding temperatures from Denver, CO (Station 72469) and Riverton, WY (72672) for 22 January 2021 12 UTC and FLOATS DTS. The FLOATS 5 m ascent profile (green), float level average (blue), and average temperature profiles from the beginning (orange) and end (red) of float altitude are displayed.

3.5 Temperature Anomalies and Wave Analysis

570   Here we analyze atmospheric waves present in FLOATS measurements. In this analysis, we will focus on two different parts of the flight: first during the balloon ascent when the EFU underwent a series of oscillations between 06:35 – 06:50 LT, and second at float altitude during the period between 07:05 – 08:10

LT when an upper level warm layer was observed and the balloon float level dropped vertically by ~100 m (Fig. 5a). To provide context for the wave anomalies in the FLOATS WY933 test flight, we use the twice-

575   daily radiosonde profiles at Riverton, WY (RIW), which include T as well as zonal (u) and meridional (v) wind profiles. We choose a 3-day mean of these profiles to define a background that is subtracted, leaving higher frequency, subsynoptic anomalies. The RIW sounding closest in time at 12 UTC 22 January 2021 (Fig. 7a) shows stratospheric wind anomalies (u',v') varying with a 3-km vertical wavelength ($2\pi/m$), and with v' phase leading u' in altitude. These are characteristic of an upward propagating inertia-gravity wave

580   signal. Hodograph analysis (Hirota and Niki, 1985) of the (u',v') signals suggests this is a northeastward propagating inertia-gravity wave with intrinsic frequency (ω) of about 1.5f (where f is the Coriolis frequency), or a wave period of ~11-12 hours. The gravity wave dispersion relation $k^2=(\omega^2-f^2)m^2/N^2$ can then be used to estimate the horizontal wavelength ($2\pi/k$) of ~600 km. The wind anomalies therefore suggest a slow and large-scale wave that is likely present in both the Riverton, WY radiosonde as well as the WY933 balloon

585   ascent and FLOATS profiles.

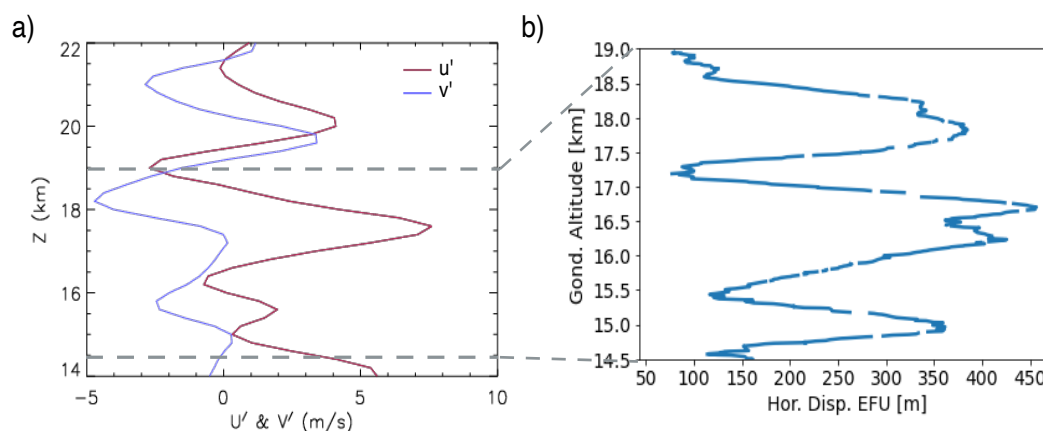



Figure 7: a) Meridional and Zonal wind perturbations as a function of altitude from radiosonde observations in Riverton, WY. b) Horizontal displacement of FLOATS EFU as function of gondola

FLOATS temperature perturbations, T', were calculated throughout the flight as the difference between the 3-day mean T from RIW and the FLOATS profile temperature. Using FLOATS data binned to

590   1 minute temporal resolution and 200 m vertical resolution to match the vertical resolution of the RIW radiosonde observations.

During the ascent phase of WY933 the horizontal displacement of the EFU, at the end of the 1200 m fiber length, exhibits three distinct peaks between ~15 km – 19 km (Fig. 7b). In the context of the WY933 balloon and EFU rising through the 3 km vertical wavelength inertia-gravity wave oscillations, the peaks in the horizontal EFU displacement would occur when the wind difference between the gondola and EFU is largest. This will occur once every half cycle of the inertia-gravity wave, resulting in three peaks in EFU displacement as the balloon rises the 4.5 km distance from 14.5 to 19 km. Therefore, we hypothesize that the oscillations of the EFU position are due to the vertical shear in the inertia gravity wave. FLOATS measured T' during ascent (Fig. 8a) show a warmer layer below 17 km followed by a cooler layer above 17 km. Riverton, WY sonde temperatures (Fig. 6) showed similar +/-2°C temperature variations but with a different phase, cool below 17.5 km and warmer above. This is consistent with the interpretation that the same large-scale inertia-gravity wave is modulating T in both locations, but the phase varies over the ~300km distance between the two sites.

The second period of interest of the wave analysis is characterized by an increase in temperature starting at about 07:05 followed a further increase in temperature at 07:40 at an altitude range of 18.4 km to 19.1 km (Fig. 5 and 8a). To determine if the warming layer is related to higher frequency gravity wave activity, spectral analysis using the S-transform was conducted on the T' profiles (Stockwell et al., 1996), which decomposes the data in time-frequency space similar to a wavelet transform. The spectral analysis (Fig. 8b) shows enhanced spectral power > 0.4 C² for wave period of about 55min and 20min. This suggests the increase in temperature at 07:05 LT can be related with the warm phase of gravity wave with a period of 55 minutes and the further increase in temperature at ~07:40 LT related to a superposition of the 55 minute period gravity wave and a gravity wave with a period of 20 minutes.

This analysis shows the capabilities of FLOATS to detect a variety of gravity waves with differing spatial and temporal scales. As the float time during the test flight was limited to about 2 h the inertia gravity wave with a period of 8 h could not be fully sampled by FLOATS. However, in future long duration flights up to several months (Haase et al. 2018), the ability of FLOATS to sample small vertical and temporal scale structures will become valuable to observe both small- and large-scale waves, extending to global horizontal scales, while fully resolving very short vertical wavelengths that have important effects on cirrus clouds and global circulation (Bramberger et al., 2022), but are difficult to observe from other measurement platforms.

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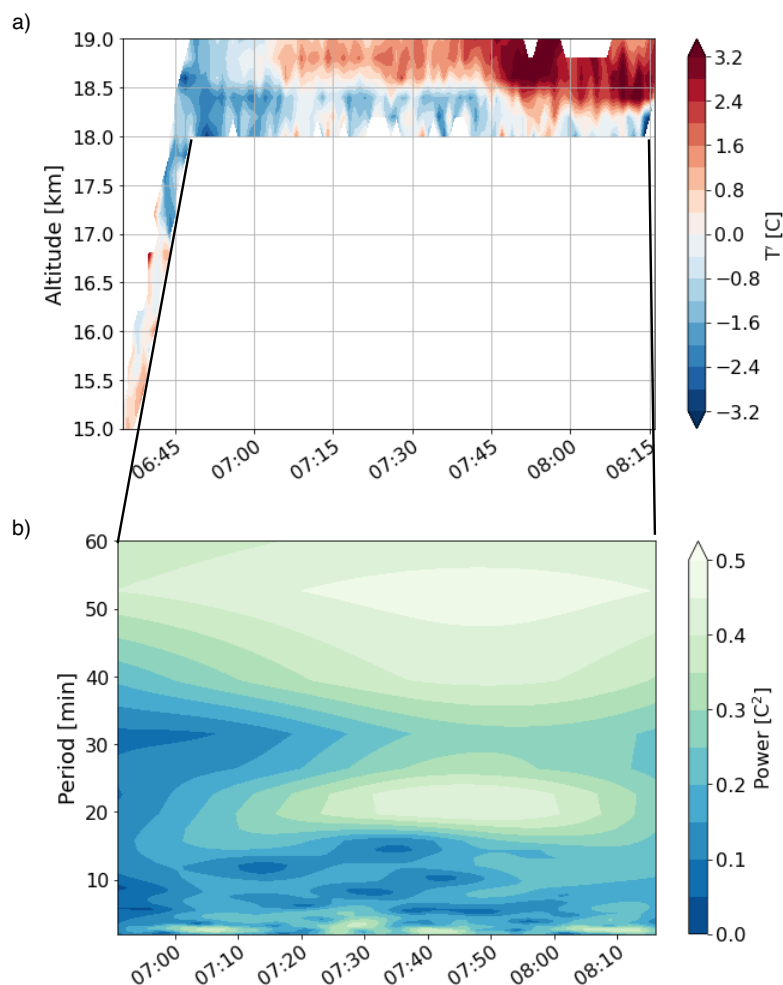
Figure 8: a) Temperature perturbations from FLOATS observed temperature as a function of altitude and local time. B) Spectral power from FLOATS temperature perturbations as a function of wave period and local time, for float level data only.

4 Conclusions

Fiber optic distributed temperature sensing is an under-utilized tool for atmospheric measurements

645   that provides low-cost and good performance temperature measurements at spatial and temporal resolutions not possible with other sensing methods. In the tropical tropopause layer, there is a need for enhanced temperature monitoring to address questions related to vertical transport of material and atmospheric wave propagation within the region. FLOATS is a DTS system designed for up to 2 km vertical temperature profiling in the UTLS aboard drifting constant altitude balloons with a minimum sampling period of 20 s and

650   a vertical resolution of 3 m. The instrument employs a mechanical reeling system, a self-contained end of fiber sub-gondola, and a 4-reference temperature optical system all designed for long duration use within the harsh conditions of the TTL.

       An experiment with the system was conducted aboard a short duration vented balloon flight from Laramie, Wyoming, to validate FLOATS for the Stratéole 2 mission within the TTL. A major motivation for

655   the 19 km altitude flight was to understand the technical performance of the 4-reference section calibration procedure with the fiber optic under stress loads and temperatures typical for the UTLS. Although the end of fiber temperature reference was damaged during launch an adapted 4-reference calibration was validated using the gondola level temperature sensor and produced RMSE values of ≤1.4° C for DTS temperatures compared to the ambient temperature sensor during the ascent phase of flight. These values show good

660   confidence in the FLOATS measurements considering the DTS sampling was integrated over 20 s during the ~4 m/s ascent, and by producing an error of only 0.71° C compared to the gondola level temperature sensor. Evaluation with outside datasets, nearby radios soundings and COSMIC2 measurements, demonstrate similar confidence in the FLOATS measurements. The FLOATS ascent profile was within the range of temperature profiles observed by these other platforms. Float level temperature profiles from the validation flight

665   demonstrate the ability of FLOATS to characterize small scale atmospheric dynamics like gravity waves, and larger scale dynamics like inertial gravity waves at a resolution not possible with other sensing platforms. This study establishes fiber optic distributed temperature sensing as a viable atmospheric measurement platform and FLOATS as a capable and unique balloon-borne temperature sensor for the UTLS.

670   **5 Appendix A – Temperature Retrieval Optimization**

       To retrieve DTS temperature from the thermally complex setup of FLOATS a two-step optimization processing scheme was developed. The method is illustrated in Figure A1, which shows the Raman backscattering ratio as a function of optical distance along the fiber optic cable for a FLOATS profile from

675   the mid-latitude flight described in Sect. 2.5 of the main text. First, the step losses due to the optical unions A and B (Fig. A1), that are positioned between Reference Section 1 (RS1) and Reference Section 2 (RS2), are assumed to be static but unique for each flight configuration. The step loss between the Sections are then estimated by finding the linear fit of $(ln[R(z_2)] + \Delta\alpha_{12}) - (ln[R(z_1)] + \Delta\alpha_{12})$ vs $T(z_2) - T(z_1)$ of all DTS measurements for the flight where z_1 furthest point of RS1 and z_2 is the nearest point of RS2 with respect to

680   optical bench, or the nearest points to the connector, and $\Delta\alpha_{12}$ is the average attenuation of the two reference sections derived from the slope of $ln[R(z)]$ as a function of distance for the two sections. The linear fit of step loss plot can then be used to extrapolate the step loss value for when the two Sections and optical unions are

at the same temperature (i.e. $T(z_2)$- $T(z_1)$ = 0° C). An example of the linear fit and plotting method can be found in the supporting information Figure A2. If $T(z_2)$- $T(z_1)$ is equal to 0° C during a flight then the *(ln[R(z_2)]*

685   *+ Δα$_{z_2}$) - (ln[R(z_1)] + Δα$_{z_1}$)* from those times can be used as the primary method to retrieve the static step loss value of union A and union B for that flight, or as check of the linear extrapolation method described above. The applied step loss correction for union A and union B can be seen in Figure A1 as the light blue *ln(R)* trace.

        The step loss due to the fiber optic rotary joint is more difficult to determine because that region of

690   the instrument contains the rotary joint union, varying lengths of spooled fiber optic cable during flight (which have uncertain micro bend and macro bend losses), and a large temperature transition from inside of the instrument gondola to the ambient air outside the gondola (e.g. ΔT >55°C in the tropics). In Figure A1 this region of the Raman backscattering profile can be seen between the approximate optical distances of 65 m to 110m. The second step in the processing scheme is therefore to estimate the step loss due to the rotary

695   joint and Δα based on a four-reference section optimization. Here we use the optimization scheme discussed in Hausner et al. (2011) Eq. 7 for each 20 s temperature profile, by minimizing the absolute mean bias (MB):

$$MB = \frac{1}{mn}|\sum_1^m \sum_1^n (T_{DTS} - T_{obs})| \qquad (1A)$$

700   where m is the number of reference sections, n is the number of DTS observations within the reference section, T_{DTS} is the temperature at that observation point, and T_{obs} is the externally observed temperature for that reference section. To perform the optimization, Δα and the rotary joint step loss value (unitless) are parameterized into a range of 0.0 m^{-1} to 1.98e^{-6}m^{-1} and -9.0e^{-5} to 2.0e^{-3}. The T_{DTS} is then calculated for each point along the reference section by solving for *T(z)* in Eq. 1 and by using Eq. 2 and Eq. 3. The T_{obs} for RS3 uses

705   the first 10 m of fiber optic cable outside of the gondola and T_{obs} for RS4 uses the 10 m of fiber optic closest to the EFU (Fig. 1b and Fig A1). The T_{obs} for RS3 is obtained from a temperature sensor outside of the gondola. The T_{obs} for RS4 is obtained from the EFU TSEN. An example of an optimized Raman backscattering profile and approximate calibrated temperature can be seen as the purple trace in Figure A1. The benefit of the described dynamic calibration scheme with parameter optimization compared to the use of static parameters

710   is that it accounts for real time changes of the backscattering signal due to strain effects, degradation of the incident laser, or other signal aberrations that could occur during a long duration ballooning mission like Stratéole 2.
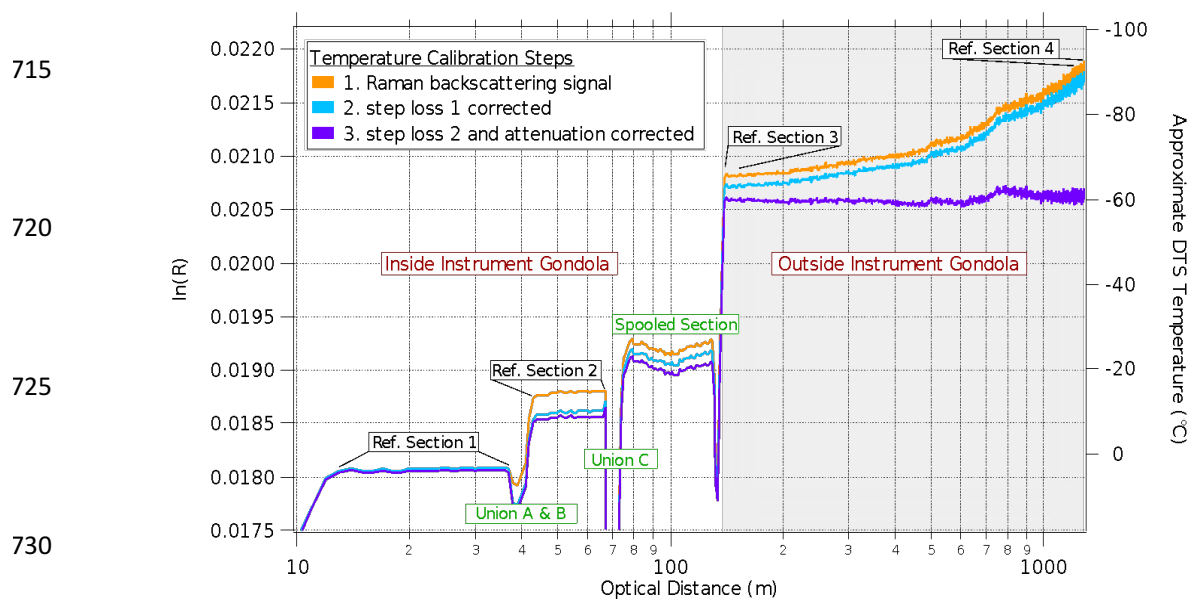
Figure A1: Raman backscattering ratio (left axis) and approximate DTS temperature (right axis) versus optical distance of FLOATS from an example profile with the full deployment of 1167 m of fiber. The raw back scattering signal (orange trace), step loss 1 corrected (blue trace), and optimized back scattering signal (purple trace) are shown. Locations of the uniform temperature reference sections are depicted with black boxes. Insertion loss and unsolvable sections are highlighted with green boxes.
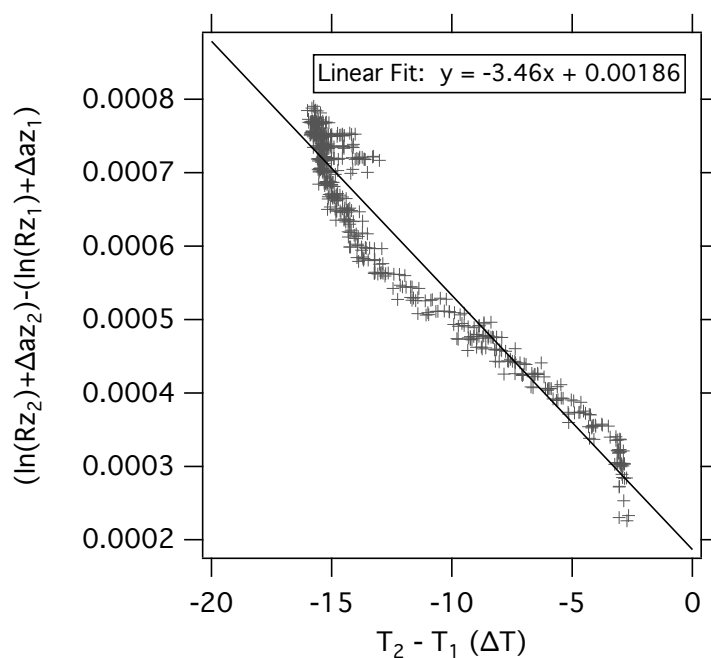
Figure A2: The difference in processed Raman backscattering signal between Reference Section 1 and Reference Section 2 from the WY933 flight versus the difference in temperature between those sections (grey crosses). The linear fit of the data is shown as a black line.

6 Author Contributions

DG designed and built the instrument, led laboratory testing, and drafted this manuscript. Early development and conceptualization of the instrument was completed by LK, SD, and JA. The validation experiment was led by DG and LK, and the Wyoming balloon flight was headed by TD. The gravity wave analysis was conducted by MB and JA. All authors contributed to manuscript editing and revisions.

7 Data Availability

The data is available upon request from the corresponding author.

8 Competing Interests

The authors declare that they have no conflict of interest.

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