Surface Ocean Dispersion Observations from the Ship-Tethered Aerostat Remote Sensing System

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ABSTRACT

Oil slicks and sheens reside at the air-sea interface, a region of the ocean that is notoriously difficult to measure and, therefore, little is known about the velocity field at the sea surface. The Ship-Tethered Aerostat Remote Sensing System (STARSS) was developed to measure Lagrangian velocities at the air-sea interface by tracking the transport and dispersion of hundreds
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of drift cards in the field of view of a high-resolution aerial imaging system. The camera had a field of view of approximately 300 m × 200 m and images were obtained every 15 seconds over periods of up to 3 hours during a series of experiments in the northern Gulf of Mexico in January-February 2016. STARSS was equipped with a GPS and inertial navigation system (INS) that was used to directly georectify the aerial images. A relative rectification technique was developed that translates and rotates the drift cards to minimize the total movement of all drift cards from one frame to the next. Rectified drift card positions were used to quantify scale-dependent dispersion by computing relative dispersion, relative diffusivity, and velocity structure functions. STARSS was part of a nested observational framework, which included deployments of large numbers of GPS-tracked surface drifters from two ships, in situ ocean measurements, and X-band radar observations of surface currents. STARSS operations were supported by weather forecasts from a high-resolution coupled atmosphere-wave-ocean model. Here we describe the STARSS system and image analysis techniques, and present results from an experiment that was conducted on a density front. To the best of our knowledge, these observations are the first of their kind and STARSS-like observations can be adopted into existing and planned oceanographic campaigns to produce a step-change in our understanding of small-scale and high-frequency variability at the air-sea interface.

Keywords: Surface Dispersion, Air-Sea Interface, Langmuir, Aerostat, Gulf of Mexico, Oil Spill, Drift cards, Transport, Particle Tracking

1 INTRODUCTION

In April 2010, the explosion of the Deepwater Horizon (DwH) oil platform in the DeSoto Canyon of the Gulf of Mexico (GoM) resulted in the largest accidental marine oil spill in history (Crone and Tolstoy, 2010). In the aftermath, a great need for transport and dispersion forecasts at the air-sea interface over a large range of spatial (100s of m to 100s of km) and temporal (hours to months) scales became clear (Liu et al., 2011; Mariano et al., 2011). Hydrocarbons were present in a range of environments, from the open ocean to the shoreline, complicating the problem of predicting their motion. Putting aside the complexities of the fate of hydrocarbons in water specifically, even the prediction of the transport of near-surface water masses over such a range of scales and environments has been impeded by a lack of observations of scale-dependent dispersion that span the relevant spatio-temporal scales (Poje et al., 2014). While recent observational campaigns have been devoted to submesoscale transport and mixing (Berta et al., 2015; Coelho et al., 2015; Ohlmann et al., 2017; Poje et al., 2014; Pascual et al., 2017; Petrenko et al., 2017; Schroeder et al., 2012; Shcherbina et al., 2015), relatively few in situ studies (e.g., Matsuzaki and Fujita 2017; Miyao and Isobe 2016) have quantified near-surface velocities at oceanic boundary layer scales (seconds to hours and meters to 100s of meters).

Traditional ocean observation tools (e.g., drifters, ships, and satellites) are limited in their ability to both measure velocities at the air-sea interface, where slicks and sheens of oil reside, and to resolve dispersion at oceanic boundary layer scales. The drifter trajectory data collected during the Grand Lagrangian Deployment (GLAD) in 2012 was successful in improving velocity estimates (Berta et al., 2015; Coelho et al., 2015), data-assimilating models (Carrier et al., 2014; Jacobs et al., 2014), and understanding of turbulence through dispersion statistics (Poje et al., 2014, 2017). However, due to uncertainties in GPS positioning of the drifters (Haza et al., 2014) and the initial drifter separation distances, this technology was capable of accurately sampling only the larger submesoscale and mesoscale features. Haza et al.
Carlson et al. (2014) report that statistics on scales 20-60 times larger than the O(5 m) GPS position uncertainty may be contaminated (i.e., 100-300 m).

Recent developments in modeling and theory have emphasized the importance of the connections between submesoscale fronts, filaments, and eddies and the more isotropic scales of traditional boundary layer turbulence (Taylor and Ferrari, 2009; Hamlington et al., 2014; McWilliams et al., 2015; Smith et al., 2016; Suzuki et al., 2016; McWilliams, 2017). The smaller scales of the submesoscale are also of great interest, because it is on these scales where nonhydrostatic effects first become important (Mahadevan and Tandon, 2006; Hamlington et al., 2014; Haney et al., 2015; Mensa et al., 2015; Suzuki and Fox-Kemper, 2016) and because intense localized restratification occurs intermittently on these scales in large eddy simulations when forced with winds, waves, and/or convective cooling (Mahadevan et al., 2010; Smith et al., 2016; Bachman et al., 2017; Whitt and Taylor, 2017). These interactions between boundary layer turbulence, surface forcing, and submesoscale restratification are not captured in the standard submesoscale parameterizations (Fox-Kemper et al., 2008, 2011). Their effects on near-surface dispersion are therefore also missing from regional models needed to capture larger submesoscale and mesoscale phenomena (Haza et al., 2014; Mensa et al., 2015).

For these reasons, the LAgrangian Submesoscale ExpeRiment (LASER) featured a set of novel observations that attempted to bridge the scales of boundary layer turbulence and the submesoscale. Boundary layer turbulence observations are common from many platforms: the Floating Instrument Platform (FLIP) (e.g., Sutherland and Melville, 2015), Lagrangian floats (e.g., D’Asaro et al., 2014), microstructure profilers (e.g., Sutherland et al., 2014), and moorings (e.g., Prytherch et al., 2013). However, they have not been connected, conceptually or technologically, to the larger scales observed by surface drifters. To fill this gap, the classic tools of messages in bottles and drift cards were brought into the modern era: Continuous quantitative visual monitoring, as in the famous parsnip experiments of Richardson and Stommel (1948), was achieved with visual imaging of buoyant biodegradable objects (bamboo dinner plates) from a ship-tethered aerostat, allowing for a relatively wide field of view and carrying an instrument package to acquire positioning data and high-resolution photography. Here, we present the Ship-Tethered Aerostat Remote Sensing System (STARSS) platform and image analysis methods (section 2), then present results from one of the experiments (section 3). Like most experimental platforms, STARSS did not function perfectly and the relative merits and demerits of the system, with the availability of a range of unmanned aerial systems (UAS) in mind, are considered in the discussion (section 4).

2 METHODS

The Ship-Tethered Aerostat Remote Sensing System (STARSS) was part of a nested sampling strategy employed during the Lagrangian Submesoscale ExpeRiment (LASER) for multiscale sampling of transport and dispersion properties. Several complementary datasets were collected concurrently with STARSS data and aid in their interpretation.

2.1 LASER Experiment

2.1.1 Overview

LASER was carried out by the Consortium for Advanced Research on Transport of Hydrocarbon in the Environment (CARTHE; http://carthe.org) in the northern GoM in January-February 2016 (Fig. 1). The core of the LASER experiment consisted of the deployment of approximately 1000 GPS-tracked near-surface drifters that aimed at resolving the surface velocity field across the submesoscale and
mesoscale (section 2.1.2). Additionally, an unprecedented combination of ship-based sensors (sections 2.1.3–2.1.6), and weather forecasts from a coupled atmosphere-wave-ocean model (section 2.1.7) provided context for the Lagrangian observations. STARSS was flown from the M/V Masco VIII, an offshore supply vessel chartered by CARTHE for LASER (Fig. 2). The R/V Walton Smith accompanied the M/V Masco VIII and recorded oceanographic and meteorological data. The geographic locations in which aerostat flights were permissible were limited by the large expanses of airspace that are dedicated to military training operations in the Gulf of Mexico. Offshore oil and gas installations in the region are serviced regularly by helicopters, which presented an additional logistical challenge. Therefore, STARSS flight operations during LASER were coordinated over a year in advance with the Federal Aviation Administration (FAA), who then alerted the Gulf Coast helicopter companies of our operations and facilitated a Notice to Airmen (NOTAM) for the LASER experiment period (Fig. 1).

2.1.2 Drifter deployments

The unprecedentedly large quantity – over 1000 – of drifters deployed during LASER presented unique design challenges: Thus, a new drifter was developed that was relatively cheap, compact to ship, easy to assemble, and almost entirely biodegradable (Novelli et al., 2017). It consists of a donut-shaped float with the battery and electronics housing in the center, connected with a flexible rubber hose to a four-panel drogue. The drogue is sized so that the drift represents the effect of the integrated currents over the top 60 cm of the water column. The main material is a non-toxic, biodegradable thermoplastic (a type of poly-hydroxyalkanoate or PHA). The drifters were deployed in three large groups and several smaller deployments, including survey lines. The first major deployment (21 January 2016) consisted of 309 drifters, arranged in triplets along a clover-shape. The second major deployment (26-31 January 2016) consisted of 182 drifters that were released in a scheme to reseed the sampling of a front. The third major deployment (7 February 2016) was a grid with 326 drifters. In addition, 25 of the drifters were released during STARRS operations. These drifters provide information of the deeper flow concurrent with the surface measurements taken by STARRS. The drifter floats can also be detected in the STARRS images and used for verification of the georectification. During the experiment, it was discovered that the tether connecting the drogue to the float could break during strong storms. Therefore, significant effort went into identifying the time of drogue-loss (if applicable) for each drifter (Haza et al., 2018). In hindsight, this mishap proved advantageous, as the undrogued floats provided additional data on the currents in the top 5 cm of the ocean.

2.1.3 Oceanographic data

While the M/V Masco VIII had minimal scientific equipment installed to collect basic weather data (see section 2.1.4), its companion vessel, the R/V Walton Smith, was equipped with standard oceanographic instruments. Thus, along-track near-surface temperature and salinity measurements are available from the shipboard flowthrough system.

2.1.4 Air-sea flux measurements

Two meteorological masts were mounted on the starboard and port prows on the bow of the R/V Walton Smith (a catamaran). Each meteorological mast was equipped with three anemometers for vertical profiles (2 RM Young 3D sonic anemometers and 1 Campbell Scientific IRGASON), along with a shielded temperature and humidity sensor. The ultrasonic distance meters (UDMs) were arranged with one sensor on each prow, and three sensors in a triplet configuration on a centerline truss mounted in between the two prows and extending 1 m forward of the furthest edge of the prows. Vessel motion was recorded using a six degrees of freedom inertial motion unit (IMU) that was fastened to a bench in the scientific lab of the
R/V Walton Smith. A GPS and magnetometer measured at 1 Hz and were used for all data processing. All systems were synchronized using a local network time protocol (NTP) server. Raw data were sampled at 20 Hz and the final product was a collection of 10 minute time series for each variable measured. Each 10 minute segment of data passed through several quality control measures to eliminate data that (1) experienced a change in heading >40° during the 10 minute interval, (2) observed wind coming from the aft quadrants of the ship, or (3) experienced any data interruptions that were longer than 30 seconds. All wind data were motion corrected and adjusted to account for vessel translation. Before motion correction, all data were passed through a de-spiking routine to remove outliers. Wind speed, air temperature, relative humidity, and ship heading and motion were measured on the M/V Masco VIII at 10 Hz. These data were subjected to similar quality control procedures as outlined above. The quality-controlled data were averaged to 1 Hz.

2.1.5 Wave buoys

Three spherical wave buoys (30 cm in diameter) were deployed during most STARSS dispersion experiments. Each wave buoy was equipped with an IMU, which consisted of a Yost accelerometer, a gyroscope, and a magnetometer, and a GT31 GPS. The GPS and IMU recorded data at 1 Hz and 10 Hz, respectively. Raw IMU data were motion-corrected following Anctil et al. (1994) and were double integrated to estimate three-dimensional displacements. The horizontal dilution of precision (HDOP) was used to remove raw 1 Hz GPS positions that were recorded during poor satellite reception conditions. GPS data were converted to universal transverse Mercator (UTM) positions and were averaged over one minute intervals.

2.1.6 X-band radar

An X-band marine radar was mounted on the R/V Walton Smith at a height of 12.5 m. Here, we briefly summarize the operating principles behind techniques to estimate surface currents from a vessel-mounted X-band radar. Marine X-band radar backscatter from the sea surface is controlled by Bragg scattering, i.e., it depends on the presence of cm-scale roughness elements. Marine radars are capable of imaging long (>15 m) surface waves through the interplay of tilt modulation, hydrodynamic modulation, and shadowing (Nieto Borge et al., 2004). Marine radar near-surface current mapping exploits the wave signal within a radar image sequence. The wave signal obeys the linear dispersion relationship

$$\omega = \sqrt{g k \tanh (kh)} + \mathbf{u} \cdot \mathbf{k}$$  \hspace{1cm} (1)

where $\omega$ is the angular frequency, $\mathbf{k}$ the wavenumber vector with magnitude $k = |\mathbf{k}|$, $h$ the water depth, $g$ the acceleration due to gravity, and $\mathbf{u}$ the current vector. A three dimensional (3D) fast Fourier transform (FFT) is used to convert a radar image sequence from space-time to wavenumber-frequency coordinates. In the resulting 3D spectrum, the wave signal is located on the so-called dispersion shell (Young et al., 1985), which is Doppler shifted in the presence of a current. The near-surface current is determined through an iterative best-fit technique that adjusts $\mathbf{u}$ to minimize the wave signal’s distance from the dispersion shell (Senet et al., 2001).

The marine radar used during LASER was developed at Helmholtz Zentrum Geesthacht, Germany. It is based on a standard 12 kW X-band radar operating at 9.4 GHz with a 2.25 m horizontal transmit and horizontal receive (HH) polarized antenna, a pulse repetition frequency of 2 kHz, and an antenna rotation period of 2 s. It was modified to become a coherent-on-receive Doppler radar (Braun et al., 2008). It yields
the raw backscatter intensities (and phase information) in polar coordinates with a 7.5 m bin size, $\approx 1^\circ$ azimuthal resolution, and 13 bit pixel depth.

The near-surface current analysis is performed in circular areas of $\approx 0.7$ km$^2$ that were evenly distributed over the radar field of view (with up to 40% overlap between neighboring boxes). The marine radar currents have an accuracy better than 4 cm s$^{-1}$ (Lund et al., submitted). Vessel motion and azimuthal offsets in the radar image heading were corrected using methodology described in Lund et al. (2015).

2.1.7 Coupled model

Daily forecasts from the coupled model were an essential part of the operational planning process as the overall success of the experiment depended heavily on the ability to adapt both ship and aerial operations to changing weather conditions and sea states. The coupled model used in this study is the Unified Wave INterface - Coupled Model (UWIN-CM; Chen et al. 2013; Chen and Curcic 2016, 2017), which is designed as a multi-model system portable for transition to the next generation fully-coupled regional and global models. The model has been used to study the role of Stokes drift for surface transport (Curcic et al., 2016), impacts of atmospheric forcing on ocean transport in the Gulf of Mexico on diurnal and seasonal scales (Judt et al., 2016), as well as impacts of coupling on boundary layer structure (Zhu et al., 2016) and storm surge prediction (Dietrich et al., 2018) during Hurricane Isaac (2012). Here, the model components consist of the Weather Research and Forecasting model (WRF; Powers 2017) for the atmosphere, the University of Miami Wave Model (UMWM; Donelan et al. 2012) for the ocean waves, and the HYbrid Coordinate Ocean Model (HYCOM; Wallcraft et al. 2009) for the ocean circulation. Haza et al. (2018) describe the configuration of the coupled model used in support of LASER in more detail.

Coupled model forecasts were generated from 1 January–30 March 2016 and all fields were output at spatial and temporal resolutions of 4 km and 1 hr, respectively. These forecasts were critical in planning ship, aerostat, and aircraft operations around strong atmospheric fronts that impacted the northeast GoM every few days (Judt et al., 2016). These fronts generated winds that exceeded 20 ms$^{-1}$ locally, and wave heights that exceeded 4 m. Seven cold fronts passed over the LASER study area between 15 January and 1 March 2016, during which time ship, aerostat, and aircraft operations were suspended. The coupled model products that were most relevant for planning aerostat operations were wind speed and direction, wave height, visibility, and cloud base. A network of National Oceanographic and Atmospheric Administration (NOAA) National Data Buoy Center (NDBC) observations and NOAA coastal stations (http://www.ndbc.noaa.gov/) were used both in ship guidance with regard to real-time weather and wave conditions, as well as for verification of the coupled model. The STARSS deployment on 30 January 2016 (section 3) was performed at a time when the winds were calm ($U_{10} < 10$ ms$^{-1}$) and wave heights were small ($H_S < 0.5$ m).

2.2 STARSS

STARSS was designed to resolve the spatiotemporal scales relevant to the patches and filaments of oil observed during the Deepwater Horizon spill (see, e.g., Figure 5a in Lumpkin et al. 2017). STARSS observations were intended to link the oceanic boundary layer turbulence scales to the submesoscale and mesoscale. The operational requirements for the STARSS platform were the ability to observe near-surface dispersion on spatial scales of O(100 m $\times$ 100 m) and over time periods of minutes to hours in winter-time, open-ocean conditions in the northern GoM. Additionally, STARSS experiments were designed to minimize the number of drifting sensors that needed to be retrieved to maximize the use of ship time.
Existing oceanographic instrumentation and techniques could not satisfy these operational requirements in an open ocean setting. For example, differential GPS (DGPS) and real-time kinematic (RTK) GPS (Suara et al., 2015) can produce position estimates with accuracies \(O(10\, \text{cm})\) and \(O(1\, \text{cm})\), respectively, but accuracy degrades with distance from base station measurements. Furthermore, most DGPS and RTK GPS sensors log positions internally, requiring each unit to be retrieved to download data. Other coastal sensors that are typically used to estimate Lagrangian trajectories, like high frequency (HF) radar (e.g., Carlson et al. 2010), cannot resolve the spatial and temporal scales of interest at distances that exceed 100 km from land. Similarly, satellite remote sensing has sufficient spatial and temporal resolution to investigate submesoscale dynamics (Delandmeter et al. 2017; Qazi et al. 2014; Marmorino et al. 2017; Vanhellemont and Ruddick 2014) but currently lacks the necessary temporal resolution to track dispersion due to boundary layer turbulence. Frequent cloud cover is an additional limitation imposed on passive satellite imagery.

Drift cards were selected as an indicator for dispersion of buoyant tracers. Drift cards and drift bottles have been used to study surface Lagrangian transport for well over a century (Garstang 1898). In the past, drift cards typically provided only information about initial and final locations (e.g., Williams et al. 1977; Levin 1983), though in rare cases they have been used to quantify short-term transport (Yeske and Green 1975). The drift cards used during LASER were 28 cm diameter organic bamboo dinner plates. Bamboo plates were chosen because they were easily and cheaply available for purchase in large quantities and because they are biodegradable. They were subjected to extensive tests in the SUrge STructure Atmospheric INteraction (SUSTAIN) facility and in coastal waters near the Rosenstiel School for Marine and Atmospheric Sciences (RSMAS) of the University of Miami. These tests revealed that the bamboo plates floated in the upper few cm of the water column for periods in excess of 6 hr without a change in buoyancy or loss of structural integrity and that the plates were not subject to appreciable windage. The natural color of the plates provided sufficient contrast with surface ocean waters and, as a result, plates could be detected easily in test images. A subset of the plates were painted with natural, non-toxic paint by students in Miami-area schools as part of a CARTHE outreach program and to test whether such color differentiation could help in the linking step of the trajectory reconstruction (see section 2.4.4).

Thus, an aerial platform with the ability to maintain its position over a patch of bamboo plates (hereafter referred to as simply ‘plates’) approximately 100 m \(\times\) 100 m in area and track their dispersion over periods up to 4 hr would be required. Manned aircraft (including fixed-wing, rotary wing, and airships/blimps) can fly below cloud bases and can adapt their altitude to achieve a desired spatial resolution (Klemas 2012). Manned aircraft have been used to study submesoscale dynamics (Bruno et al. 2013) and small-scale features (Marmorino et al. 2009), jellyfish patches (Magome et al. 2007), the evolution of dye plumes (Clark et al. 2014; Sundermeyer et al. 2014), air-sea interactions (Blanc et al. 1989; Trokhimovski et al. 2000), and surface currents (Dugan and Piotrowski 2012; Dugan et al. 2014). UAS have become important tools in oceanographic research (Brouwer et al. 2015; Whitehead and Hugenholtz 2014; Whitehead et al. 2014; Klemas 2015; Reineman et al. 2016) and were initially considered during the planning stage. However, planning began in 2013 and LASER was carried out in January-February 2016, before the FAA instituted regulations for non-recreational use of UAS in the National Airspace System (NAS). The open-ocean requirement, combined with the low-cost requirement, prohibited the use of manned aircraft. An aerostat was selected for ease of regulatory compliance, persistence, high lift capacity, and stable flight characteristics with the intention of producing a scalable and accessible platform to promote rapid scientific advancement through observations of oceanic boundary layer turbulence.
Like drift cards, tethered aerostats and balloons have a long history: They have been used as an aerial imaging and reconnaissance platform for over 100 years (Brewer, 1902; Crawford, 1924; Vierling et al., 2006) and have also seen extensive use in studies of the planetary boundary layer (see Vierling et al. 2006 for a review). Tethered aerostats and balloons have been used at sea and in coastal areas to provide situational awareness during oil spill exercises (Hansen, 2015; Jacobs et al., 2015), to study melt ponds on sea ice (Derksen et al., 1997), to measure toxin levels during in situ oil burning operations during the DwH spill (Aurell and Gullett, 2010), to study surf-zone dynamics (Bezerra et al., 1997), to quantify macro-debris on beaches (Nakashima et al., 2011) and on the sea surface (Kako et al., 2012), to monitor marine mammals (Flamm et al., 2000), to study shoreline changes (Eulie et al., 2013), and to track floating buoys on the surface of the ocean (Miyao and Isobe, 2016). While Miyao and Isobe (2016) and Kako et al. (2012) used a ship-tethered balloon to track drifting buoys and marine debris, respectively, their overall scientific goals and their methodology differed from those of LASER and STARSS. Specifically, Miyao and Isobe (2016) and Kako et al. (2012) used a blimp-style balloon that was only suitable for flights in light winds to track O(10) drifting objects. STARSS was designed to track O(100-1000) drifting objects over a range of wind speeds and sea states.

Modern aerostats are equipped with a sail that keeps the nose of the envelope pointed into the wind and also causes tether tension to increase with wind speed. As a result, aerostats exhibit relatively stable flight characteristics even in wind speeds over 10 m s⁻¹. However, adverse weather, in terms of limited visibility, limits the use of aerostats. Federal regulations governing aerostat flights in the NAS are outlined in Part 101, subpart B of the Code of Federal Regulations (see http://www.ecfr.gov). In short these regulations are: a maximum altitude of 150 m (500 ft), minimum clearance of 150 m below any cloud base, a minimum of 4.8 km (3 miles) visibility, and the use of an automatic emergency deflation device. No licenses or certifications are required for aerostat operators.

STARSS was built around a large (4 m diameter, 38 m³), helium-filled Skydoc model 20 aerostat with a lift capacity of 30 kg (Fig. 2A). STARSS was equipped with a 50.6 megapixel (8688 x 5792 pixels) Canon EOS 5DSR Mk III digital single lens reflex (DSLR) camera that was paired with a Canon 17-40 mm lens. At an altitude of 150 m dimensions of a nadir-looking image correspond to 318 m x 212 m (assuming a 35 mm sensor with 17 mm lens). A battery grip was used to extend the battery life. Two 512 GB memory cards were installed on the camera. The weight of the camera, lens, battery grip, and motion unit (described below), as well as the data cables prevented the use of a gimbal. Camera settings were controlled using gphoto2 (http://www.gphoto.org/) calls in a Python script that ran on an Odroid C-1 single board computer. The Python script controlled the interval between images and copied each new image to a 256 GB USB drive and to the ground station. Thus, images were saved in three locations (camera memory card, USB drive, and ground station computer) to ensure preservation of data in the event of a system failure or a crash. Images were acquired every 15 seconds, though infrequent errors occasionally increased the time between successive images to 30-90 seconds. A Ubiquiti Networks 5 GHz WiFi bridge connected the STARSS onboard computer to the ground station computer and allowed images to be viewed in near-real-time. The ground station operators could adjust shutter speed and aperture settings during the interval between images. Additionally, near-real-time imagery allowed the operators to keep STARSS in position over the drift card patch (Fig. 2B). The onboard instruments were powered by a 24 V sealed lead acid battery pack and a custom power distribution board that was capable of powering the components for periods of approximately 4 hr. STARSS instruments are shown in Fig. 2A.

Flights in an open-ocean environment prevent the use of fixed ground control points for georectification. An Inertial Labs inertial navigation system (INS) was mounted adjacent to the camera with the intention of
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using the Latitude, Longitude, altitude, pitch, roll, and heading output by the INS to perform absolute, or direct rectification (see section 2.4.2). The INS processed raw position and altitude measurements from a NovaTel global navigation satellite system (GNSS) antenna, pressure data, and accelerations and rotation rates from a micro-electrical-mechanical systems (MEMS) IMU using a proprietary extended Kalman filter (EKF). This specific INS was selected as a compromise between cost and accuracy (MEMS-based sensors are significantly cheaper, though much less accurate, than fiberoptic gyro IMUs). Unfortunately, the INS did not function as advertised due to initialization errors. The INS also lacked an event trigger, hindering subsequent efforts to synchronize the imagery with the INS data. Approximate absolute rectification was performed, followed by a relative rectification (see section 2.4.3).

2.3 STARSS dispersion experiments during LASER

Ten STARSS dispersion experiments were conducted over five nonconsecutive days in late January and early February 2016. A typical STARSS experiment consisted of inflation, launch, ascent to 150 m altitude, drift card release, and image acquisition until the majority of drift cards spread out of the field of view (FOV) of the camera or were influenced either by the wind shadow of the ship or by water displaced by the ship’s propellers during repositioning maneuvers. An electric winch was bolted to the deck of the M/V Masco VIII and was used to control the ascent/descent and maximum altitude of the aerostat. All flights were conducted during daylight hours. Focal lengths of 17 mm, 21 mm, and 23 mm resulted in nadir-looking FOVs that ranged from 318-235 m to 212-157 m. Drift cards were either released by the M/V Masco VIII or by a small workboat launched from the R/V Walton Smith. Two drift card deployment patterns were employed: a dense, small patch of drift cards and a grid-like array (Fig. 2C,D). The advantage of patch deployments is the short deployment time. However, the proximity and occasional overlap of drift cards complicate particle tracking. Therefore, patch releases are more amenable to cloud dispersion analysis (e.g., Okubo 1971), whereas the gridded deployments permit more detailed quantitative analysis based on particle tracking velocimetry (PTV, see section 2.4.4) but require coordination between STARSS operators and the small boat crew.

2.4 Image Processing

The first three steps in the image processing workflow are the same for both patch and grid deployments. First, lens distortion was removed using Agisoft Photoscan (an affordable photo processing software package). Second, drift cards were detected in the imagery (section 2.4.1). Third, the images were rectified (sections 2.4.2-2.4.3). Grid deployments employ a fourth step to link the drift cards and create trajectories (section 2.4.4). Additionally, the plate detection method was slightly modified for detecting individual plates in grid deployments versus groups of plates in patch deployments, as individual plates often could not be identified in patch deployments.

2.4.1 Detection

The key to identifying plates, either individually or as patches, is the color differentiation from the mostly blue background of the ocean surface and bright sun glitter. Each color image (8688 × 5792 pixels × 3 colors) resolves each 28-cm diameter plate with approximately 8 pixels across. Custom algorithms were developed to detect only plates, while rejecting sun glitter, white-caps, boats, and boat wakes. The M/V Masco VIII was located at the top of each image and was, therefore, easy to remove. The small work boat moved around in the FOV during the initial stages of the experiment and was manually edited out. Sun glitter was problematic in many instances and complicated plate detection. Even imagery acquired at low sun angles included sun glitter due to reflection of sunlight by surface gravity waves (Mount 2005). During
the experiments, an effort was made to position the aerostat relative to the plates and the sun in a way that separated the majority of the plates from the majority of the sun glitter. Therefore, most of the sun glitter could be masked out before plate detection. Sun glitter also tends to be closer to white in color than the plates, which can be exploited in a color filter. Finally, sun glitter is ephemeral and plates identified in one image without a corresponding plate in the subsequent images can be flagged as false positives and removed.

When plates are sufficiently separated in space to be resolved as individual circular shapes in the image, a shape filter can differentiate plates from non-circular sun glitter. For the grid deployments, a shape filter is then applied by convolving each of the RGB color components with a shape kernel (Fig. 3A,B). The convolution kernel mimics the size and shape of a plate: A 2D image, with values set to 1 within a radius from its center equivalent to a plate radius (4 pixels for full-resolution images), set to -1 outside this inner circle and within an annulus of width 2 pixels, and set to 0 everywhere else, is subjected to a 2D Gaussian smoothing filter with standard deviation 3 pixels. The result is used as the convolution kernel (Fig. 3A,B).

The next step is color-filtering. Relative to the open-ocean seawater, whose hues are dominated by blue, and the sun glitter, whose colors are close to pure white, the plates are characterized by yellow, red, and magenta colors. This property is exploited in the conversion of the three RGB color components into a single intensity value, using the function

\[ F_c = (r - g)^2 + (g - b)^2 + (b - r)^2 \]  

(2)

where \( r, g, \) and \( b \) are color components of each pixel (Fig. 4A,B).

For the patch deployments, it is sometimes helpful at this stage to perform a noise filter to eliminate sun glitter. This can be done, e.g., with a bandwidth or a Wiener filter; here the MATLAB implementation wiener2 is used with a 200 × 200 window. Knowing the approximate number of plates released and the approximate number of pixels per plate, one can estimate the total number of plate pixels. A binary image is created by setting the brightest pixels to 1 and others to 0 (Fig. 4C). The best threshold value depends on the particular experiment, but tends to be around 0.05% or 0.025%.

The last step is to identify the approximate plate centers. This is done following the method of Crocker and Grier (1996), in an implementation based on that by Blair and Dufresne (http://site.physics.georgetown.edu/matlab/). After all local maxima are found within a local neighborhood of approximate plate size, the collection is thinned with a minimum imposed separation of one plate radius. The center position is then refined as the intensity-weighted centroids of the pixels within the local neighborhoods of the local maxima. For patches, this procedure yields a nearly uniform distribution of identified plates within each patch. In some applications, it is preferred to deal with these bright areas in the image as a single patch instead of as a collection of “plates” whose number is highly dependent on the chosen exclusion radius. In these cases, the MATLAB functions bwconncomp and regionprops can extract the properties of the individual contiguous areas, including their centroids and their areas, which are estimates of the number of plates within each patch.

### 2.4.2 Absolute rectification

Absolute rectification, or direct georectification, uses the horizontal position, altitude, orientation (pitch, roll, and heading), and camera parameters (sensor size and resolution and lens focal length) to assign a geographic location to each pixel in the image (Mostafa and Schwarz 2001). Here we summarize the basic
principals of direct/absolute georectification of low-altitude aerial imagery as they relate to an unstabilized camera suspended from an aerostat.

Since the camera was mounted on an aerostat, which was tethered to a heaving, surging, and swaying ship, the camera was always in motion (translating, and rotating about all three axes). The position, altitude, and orientation data recorded by the INS were collected with the intention of using them to directly georectify the images. However, the magnetometer on the INS malfunctioned and incorrect heading data were recorded. Other variables output by the EKF used by the INS, i.e. horizontal position, altitude, pitch, and roll, depend on the accuracy of all the input data and, therefore, may have been affected as well. Figure 3C shows a diagram of the aerostat and camera relative to its field of view and the variables required to directly georectify aerial imagery.

Ideally, one can calculate the absolute position of each plate in an image given complete information about the camera motion. First, in pixels relative to the center of the image \((x_i, y_i)\) plate coordinates are converted to look angles at the camera \((\alpha_x, \alpha_y)\):

\[
\alpha_x = \arctan \left( \frac{\cos(\alpha_y) x_i l_x}{N_x f} \right) \tag{3}
\]

\[
\alpha_y = \arctan \left( \frac{\cos(\alpha_x) y_i l_y}{N_y f} \right) \tag{4}
\]

\(l_x, l_y\) are sensor dimensions (36 mm × 24 mm for the full-frame sensor in the Canon EOS 5DSR Mk III), \(N_x, N_y\) are image dimensions in pixels (8688 × 5792), and \(f\) is the focal length of the lens (17 mm – 21 mm).

These angles, after adjustment for camera pitch \((\theta_p)\), roll \((\theta_r)\), and heading \((\theta_h)\) are then converted to position relative to the camera \((\vec{x}_r)\), which is in turn converted to absolute position \((\vec{x}_a)\).

\[
x_r = \frac{h_c \tan(\alpha_x + \theta_r)}{\cos(\alpha_y + \theta_p)} \tag{5}
\]

\[
y_r = \frac{h_c \tan(\alpha_y + \theta_p)}{\cos(\alpha_x + \theta_r)} \tag{6}
\]

\[
\vec{x}_a = R(\theta_h) \vec{x}_r + \vec{x}_c \tag{7}
\]

where \(h_c\) is camera altitude, \(x_c\) is camera position, and \(R(\theta_h)\) is the 2D rotation matrix.

### 2.4.3 Relative rectification

Camera motion information may be unavailable, incomplete, or inaccurate. When this is the case, it is still possible to perform a “relative” rectification, finding positions of plates relative to the centroid of the collection of plates (Fig. 4D). Relative rectification builds on the assumption that the plates move only small distances between consecutive frames and that large apparent motion of the entire field of plates is due to camera motion. Since images were collected every 15 s, this assumption is reasonable. Note, however, that relative rectification removes large-scale coherent motion of the group of plates. Therefore, positions obtained through relative rectification can be used to analyze relative dispersion but not absolute dispersion.
The process translates and rotates the field of plates such that the total movement of all plates from one frame to the next is minimized. Even when absolute rectification is possible, this relative rectification may be used to improve the performance of the plate linking algorithm (see section 2.4.4).

Given plate positions \( \{ \mathbf{x}_i(t) \} \) at time \( t \), the following minimization determines translation \( \mathbf{T} \) and rotation \( \theta \) to be applied to plate positions \( \{ \mathbf{x}_i(t + \Delta t) \} \) in the next image from time \( t + \Delta t \):

\[
\min_{\theta, \mathbf{T}} \sum_{j=1}^{N(t+\Delta t)} \min_{\mathbf{y}_j(t)} |R(\theta)\mathbf{y}_j(t + \Delta t) + \mathbf{T} - \mathbf{y}_i(t)|
\]

(8)

where \( N(t) \) is the number of plates in the image at time \( t \).

For the inner minimization of (8), we used the MATLAB nearest neighbor search function \textsc{knnsearch}. For the outer minimization of (8), we used the MATLAB function \textsc{fminsearch}, which searches for local minima using the simplex search method of \cite{Lagarias1998}. Specifying a reasonable start value for the search is important. The initial value of \( \mathbf{T} \) is taken to be the translation that maps the center of mass of the field of plates \( \{ \mathbf{x}_i(t + \Delta t) \} \) to the origin. The center of mass of \( \mathbf{x}_i(t) \) is also at the origin and its major axis aligned with the x-axis. If necessary, the initial value for \( \theta \) can be chosen as the smaller of the two angles such that the primary eigenvector of the position covariance matrix \( C(t + \Delta t) \) aligns with the x-axis. The covariance matrix is

\[
C(t) = \begin{bmatrix}
\langle x_i x_i \rangle(t) & \langle x_i y_i \rangle(t) \\
\langle x_i y_i \rangle(t) & \langle y_i y_i \rangle(t)
\end{bmatrix}
\]

(9)

where averaging \( \langle \cdot \rangle \) is over all the plates at time \( t \). However, for plate dispersion experiments with a preferred direction of motion, like the front described in section 3, this rotation is not necessary.

Despite our best efforts, some sun glitter may be falsely detected as “plates”. Unlike real plates, which persist from frame to frame and move relatively short distances, sun glitters are ephemeral and change depending on waves, clouds, and camera orientation. Therefore, distances between sun glitters from one frame to the next tend to be larger than distances traveled by plates. Because the experiments were set up to minimize plates in areas of strong sun glitter, glitters also tend to be farther away from plates. Thus, the false positions can, to some extent, be removed with a distance threshold to the closest plate. In order to avoid including sun glitters in the minimization itself, the summation in (8) can be re-written to exclude the \( M \) largest “plate” distances, where \( M \) is chosen to be some small fraction of the total number of plates \( N \). We used a distance threshold of 3.4 m and fraction \( M/N = 0.1 \).

### 2.4.4 Linking and particle tracking

Once the rectified plate positions in each frame have been determined, plate trajectories can be constructed by linking individual plates between frames. The linking procedure creates one-to-one associations (links) between plates from frame to frame such that the total distance between plates in consecutive images is minimized \cite{Malik1993, Chenouard2014}. While both the relative rectification and linking procedures minimize total distance between plates, they differ in that rectification transforms the plate fields (as described in section 2.4.3) while linking does not, and linking produces one-to-one associations between plates while relative rectification does not. We used a MATLAB linking algorithm called “Simple Tracker” by Jean-Yves Tinevez (https://www.mathworks.com/matlabcentral/fileexchange/34040-simple-tracker).
Linking performance degrades when the non-dimensional spacing \( P = \frac{\Delta x}{u \Delta t} \) becomes small or as position errors due to uncorrected camera motion become large relative to displacement \((u \Delta t); [\text{Malik et al. 1993}]\). While the Simple Tracker has some ability to deal with data gaps when a plate is not detected for a frame but reappears in the next frame, the trajectories derived with this method for the sample grid deployment nonetheless tended to be relatively short, with an average time span of 52 min, compared to the total length of the experiment, which was approximately 170 min. On average, plate spacing was \( \Delta x \approx 3.4 \) m, the time between images was \( \Delta t = 15 \) s, and the average velocity was \( u \approx 0.022 \) m s\(^{-1}\), which results in average \( P \approx 10 \). However, \( P \) values can be significantly smaller, because maximum velocities may reach \( u \approx 0.22 \) m s\(^{-1}\), and plate spacing \( \Delta x \) decreases to less than 0.5 m as the plates cluster together. Plate velocities were calculated by forward differencing of plate positions along trajectories. In order to detect and eliminate erroneous velocities due to incorrect links, each velocity which differs by more than 2 standard deviations from the average velocity in its neighborhood is eliminated from the statistics. We used the default 6.8 m for neighborhood radius.

### 2.4.5 Dispersion metrics

The evolution of the patch of drift cards is quantified by computing the dispersion of the patch of plates, the relative dispersion of pairs of plates, diffusivity, and velocity structure functions. Dispersion ellipses, \( \sigma^2 \), are fit to the patch of plates in each image for comparison with the results of [Okubo (1971)]. Ellipse-fitting is not affected by the time interval between images or the number of plates detected and simply computes the variance along the major and minor axes of the patch of plates [Okubo (1971)]. If \( \sigma_a \) and \( \sigma_b \) denote the variances of the distribution of plates along the major and minor axes, respectively, then

\[
\sigma^2 = 2\sigma_a\sigma_b \tag{10}
\]

Indication of the presence of coherent structures comes from the anisotropy of the flow field and is revealed by anisotropy in the dispersion rates. \( \sigma_a \) and \( \sigma_b \) are, therefore, computed separately, and the ratio \( \frac{\sigma_a}{\sigma_b} \) is used to identify incidences of anisotropic dispersion.

While eq. (10) provides a relatively simple method to quantify the dispersion of a patch of plates, it does not provide any information about the motions of individual plates inside the patch. Trajectories of individual plates (see section 2.4.4), on the other hand, can be used to compute the relative dispersion and velocity structure functions by examining pairs of initially proximal plates. Relative dispersion is computed as

\[
\sigma_D^2 = \langle (r_1(t) - r_2(t))^2 \rangle \tag{11}
\]

where \( r \) is the position vector and plate pairs are indicated by subscripts. The relative dispersion provides a measure of the separation of initially proximal drift cards at a given time [LaCasce 2008] and is commonly used when analyzing large numbers of trajectories of virtual particles computed from numerical ocean model (e.g., [Haza et al. 2014]) or HF radar velocity fields (e.g., Carlson et al. 2010), and in limited cases when sufficient numbers of drifter observations exist (e.g., LaCasce and Ohlmann 2003; Poje et al. 2014).

Following Okubo (1971) we compute diffusivity \((K)\) from dispersion

\[
K = \frac{\sigma^2}{4t} \tag{12}
\]
Plate trajectories also permit the computation of velocity structure functions

\[ S^n(r) = \langle \Delta u^n \rangle \quad (13) \]

where the order of the structure function, separation scale, and velocity are indicated by \( n \), \( r \), and \( u \), respectively.

3 RESULTS

On 30 January 2016, a front was detected in the marine X-band radar data (Fig. 5), and was selected as a suitable target for a STARSS experiment. The STARSS dispersion experiment took place approximately 130 km southeast of the Mississippi River Delta in a depth of approximately 140 m. The X-band radar provided live visualization of the position of the front (Fig. 5), which extended from the northeast to the southwest (top right to bottom left in the backscatter image; Fig. 5). It was characterized by enhanced backscatter that separated two distinct surface current regions. On the west side of the front (left side of the image) the surface water was cooler and fresher (Fig. 6) and currents were relatively strong (0.4 ms\(^{-1}\)) and directed toward the southwest (Fig. 5). On the east side of the front (right side of the image), surface waters were warmer and saltier (Fig. 6) and currents were weaker (0.2 ms\(^{-1}\)) and directed to the west-southwest (Fig. 5). The front extended some distance as evidenced by the number of drifters that were trapped in the frontal convergence zone (yellow arrows in Fig. 5). Surface drifter trajectories viewed over a much larger area also show convergence along what appears to be a front and transport to the southwest over a 48 hour period (Fig. 7). Some of these drifters were observed by aerostat operators on the bridge of the M/V Masco VIII during the dispersion experiment, along with patches of sargassum and freshwater vegetation.

A patch of plates was released on the front by a small work boat and was imaged by STARSS for nearly 4 hr, though the analysis presented here is limited to a 170 min segment. Three wave buoys were deployed in the patch of plates and drifted with the plates throughout the experiment. The wave buoys show a general drift to the southwest at an average speed of approximately 0.15 ms\(^{-1}\) (Fig. 8). Significant wave heights were generally small (<1 m) and the dominant wave period was approximately 4-5 s (Fig. 8). Wind speeds recorded on the M/V Masco VIII ranged from 3 ms\(^{-1}\) - 10 ms\(^{-1}\). The Langmuir number (see equation 4 in Thorpe 2004) was approximately 0.01 throughout the experiment, which is typical of the open ocean and indicates that the development of Langmuir circulation was possible.

The GPS on the aerostat also shows a general drift of the patch to the southwest (Fig. 9A) though the path of the aerostat is more complex, when compared to the wave buoys, due to the frequent repositioning maneuvers required to keep the patch of plates in the FOV and out of sun glitter. The INS data show that the altitude varied from 100 m to a brief excursion up to 160 m (Fig. 9B). Pitch varied between -10° to +20° and the preference towards positive values was likely due to ‘nose-up’ orientation caused by the sail on the aerostat (Fig. 9C). Roll was mostly negative and varied from -15° to 0° (Fig. 9D). The preference towards negative roll values likely reflects uneven loading on the instrument frame. The heading data suggest that the aerostat was slowly turning in circles, which it was not (Fig. 9E). The erroneous heading data resulted from INS initialization on a moving ship.

The STARSS images were rectified using a combination of absolute and relative rectification. First, absolute rectification (section 2.4.2) was performed using the horizontal position, altitude, pitch, and roll. Given the lack of accurate heading data and precise synchronization between the camera and the INS, two relative rectification (section 2.4.3) passes were used. Between 250-290 individual plates were detected in
the imagery, which enabled plate positions to be linked (section 2.4.4). However, changes in illumination and camera settings resulted in two gaps in the rectified image sequence where insufficient contrast between the ocean surface and the plates led to poor performance of the detection algorithm (see section 2.4.1).

The rectified imagery shows that the shape of the patch of plates varied considerably during the 170 min experiment (Fig. 10 and Supplementary Video 1). About 10 min after deployment it contracted (Fig. 10B) and approximately 30 min later it stretched into an elongated streak (Fig. 10C). The length and width of the streak varied over the next 90 min. Approximately 120 min after deployment, the patch of plates started to stretch rapidly, forming a long, narrow streak (Fig. 10D,E). The length of the streak increased until the 150 min mark. In the last few minutes of the experiment the front appears to break down and the plates spread rapidly both along and across the front (Fig. 10F). After this time, many of the plates either left the FOV or were influenced by the M/V Masco VIII.

Dispersion ellipses and the average relative dispersion of pairs of plates show considerable variability over the 170 min experiment (Fig. 11A). The smaller magnitude of the average relative dispersion reflects the separation scales of pairs of plates while the dispersion ellipses scale with the entire patch of plates. Negative dispersion was observed early on, followed by exponential and super-Richardson dispersion towards the end of the experiment. The ratio of major and minor dispersion ellipses show anisotropic dispersion throughout the experiment (Fig. 11C) with two peaks that corresponded to the rapid spreading along the front (Supplementary Video 1). The spreading event observed in the final 30 min of the experiment corresponded to the breakdown of the frontal feature, as indicated by the increase in variance in the cross-front direction (Fig. 11B-C).

Similarly, diffusivity exhibited large temporal variability. The initial diffusivity of O(1 m$^2$s$^{-1}$) declined to O(10$^{-2}$ m$^2$s$^{-1}$), reached a minimum of O(10$^{-3}$ m$^2$s$^{-1}$), and then rapidly increased to O(10$^{-2}$ m$^2$s$^{-1}$) during the final stages of the 170 min experiment (Fig. 11D). While dispersion and anisotropy increased around the 2000 s mark, the diffusivities remained relatively stable, which indicates that while the patch spread rapidly along the front its area remained relatively constant in time.

4 DISCUSSION

4.1 STARSS Performance

STARSS satisfied the overall objective of quantifying small-scale, surface ocean dispersion in an open ocean environment, as evidenced by the results of a dispersion experiment that was conducted along a density front in the northern Gulf of Mexico. The results of this experiment will be discussed in section 4.2. STARSS met its design requirements (see section 2.2), acquiring high-resolution images of hundreds of bamboo plates at 15 sec intervals over periods of up to 4 hr. The use of biodegradable bamboo plates limits environmental impact and simplifies logistics, as the number of drifting sensors to be retrieved was minimal. STARSS was safely deployed and retrieved from an offshore supply vessel. One of the main drawbacks of STARSS was its large helium envelope, which required a relatively large number of helium cylinders to be stored onboard. The large envelope provided approximately 30 kg of lift but the combined lift and drag required a custom electric winch though when wind speeds exceeded 10 m$s^{-1}$ the winch lacked the torque required to reel in the aerostat. Developing a miniaturized version of the STARSS instrument package would reduce the size of the aerostat required, which would reduce the winch requirements, the amount of helium required for inflation, and potentially make operations from smaller boats possible. Small boat operations could simplify logistics while significantly reducing costs. A smaller boat would also have less of an impact on the dispersion of patch of plates.
The weight of the Canon 5DSR, battery grip, lens, and INS prevented the use of a gimbal. While the image quality and resolution of the Canon 5DSR are exceptional, analysis of half-resolution images produced identical results when compared to full-resolution images. A smaller and lighter stabilized mirrorless camera could be used in future studies. Even a stabilized camera will be subject to heave, sway, and surge due to wind gusts and ship motion transmitted through the tether. INS initialization problems and the lack of an event trigger for image time synchronization required the development of custom image rectification techniques. The development and implementation of these techniques significantly increased time required to analyze the data. Future studies will use devices with event triggers for precise image time synchronization, such as the low-cost Emlid Reach RTK global navigation satellite system (GNSS) receiver (http://emlid.com/reach/). MEMS IMU heading accuracy, however, will likely continue to be a source of error in absolute rectification, especially for a slow-moving aerostat-based system. Drifting control points, like those employed by Miyao and Isobe (2016), could be used. However, if highly convergent features, like fronts, are present then any initial spatial configuration will likely collapse onto the front, thereby limiting the utility of drifting control points in rectifying the imagery.

Since STARSS development began UAS flight capabilities and cameras have improved dramatically. UAS flights would allow the tender vessel to stay well clear of the patch of bamboo plates. UAS can also provide a turn-key aerial imaging system that could reduce the amount of time spent on development and testing. Most commercially available UAS, however, were developed for cinematography and agricultural monitoring and, therefore, may require some modifications before they are suitable for use at sea. Research-related UAS operations are considered non-recreational by the FAA and require a commercial remote pilot certificate. Additionally, the University-National Oceanographic Laboratory System (UNOLS) is developing regulations for UAS flights from their vessel. While the cost of UAS continues to decrease and functionality increases, aerostats offer a safe and stable aerial platform that is relatively easy to operate. Complete power loss on STARSS had no effect on the flight characteristics of the aerostat while power on a rotary-wing UAS would result in complete failure of the entire system. Integration of UAS imaging and communications systems into a STARSS-like system could provide the convenience of ‘plug-and-play’ hardware and software with the stability of an aerostat. The imaging system could also be expanded to include thermal infrared and multispectral cameras.

4.2 STARSS Dispersion Results

The plate detection algorithms were able to distinguish between bamboo plates and ephemeral features like sun glitter and white caps (see section 2.4.1). The use of painted plates had no discernible effect on detection success. Aerial images of plates were rectified using a combination of absolute rectification (see section 2.4.2) and relative rectification (see section 2.4.3) methods. Dispersion ellipses (eq. 10) quantified the spread of entire patch of plates and the relative dispersion (eq. 11) quantified the separation between individual pairs of plates.

The STARSS observations presented here extend observational estimates of scale-dependent diffusivity down to the scale of 5-10 m (Fig. 12A) and the magnitudes of the diffusivities agree with other observations at similar spatiotemporal scales (Li, 2000; Carlson et al., 2010; Matsuzaki and Fujita, 2017). However, scale-dependent diffusivities reveal complex behavior at short scales (3-10 m) during the first 80 minutes of the experiment (Fig. 12A), which does not obey any kind of power law. This corresponds to a time period when the patch of plates was small, changed shape rapidly, and often took on complex shapes (Fig. 10 and Supplementary Video 1). Explaining this complex behavior is difficult as wind forcing and Langmuir circulation could have been present in addition to frontal convergence. During the last 70 minutes of the
experiment, as the patch of plates elongated into a streak, diffusivity exhibited a clear dependence on spatial scale (Fig. 12A,B), however, the slope during this period was steeper than Richardson’s 4/3 law (Richardson, 1926). STARSS diffusivity values at the largest scales resolved compare well in magnitude, if not in slope, with the smallest scales reported by Okubo (1971), suggesting that similar diffusivity can be expected at these scales. This agreement is striking when considering that Okubo (1971) analyzed the three-dimensional spread of dye releases, which are known to behave differently than near surface 2D motion (Mensa et al., 2015). The super-Richardson behavior was observed as the patch of plates spread rapidly along the front and when the front broke down at the end of the experiment. The second order velocity structure function exhibits scaling consistent with a Richardson-Komolgorov cascade of energy (Fig. 12C). The second order velocity structure function, however, considers relative velocities between individual particles and the apparent disparity between the super-Richardson scaling obtained from the dispersion ellipses could reflect the different spatial scales of motion. The overall dispersion of the patch of plates differed from the relative motions of individual plates. In fact, small-scale eddy-like motions are traced out by individual plates within the patch (Supplementary Video 1). The disparity in scaling observed between dispersion ellipses and the second order velocity structure function cannot currently be explained, but analysis of the other 9 experiments may aid in understanding dynamics at these scales.

5 SUMMARY AND CONCLUSIONS

Here we demonstrate the capability of STARSS to observe small-scale transport at the air-sea interface by tracking hundreds of drifting bamboo plates. This paper focuses largely on the development of STARSS and presents results from a single experiment that measured dispersion over spatial and temporal scales of a few meters to approximately 200 m and seconds to hours, respectively. These observations are the first of their kind and fills a critical knowledge gap about how the ocean transports material at the sea surface and at small spatiotemporal scales. With current advances in UAS we can expect improved performance in terms of size, weight, and power (SWaP) as well as in camera resolution and position accuracy. Thus, STARSS can be easily integrated into existing and planned field campaigns to enable diffusion and dispersion estimates to be obtained throughout the world’s oceans. In addition to improving our response tactics to oil spills, these results can aid in understanding boundary layer turbulence in general.

6 NOMENCLATURE

• STARSS - Ship-Tethered Aerostat Remote Sensing System
• GPS - Global Positioning System
• DwH - Deepwater Horizon
• GoM - Gulf of Mexico
• GLAD - Grand LAgrangian Deployment
• CARTHE - Consortium for Advanced Research on Transport of Hydrocarbon in the Environment
• SST - Sea Surface Temperature
• LASER - LAgrangian Submesoscale ExpeRiment
• FLIP - FLoating Instrument Platform
• UAS - Unmanned Aerial Systems
• M/V - Marine Vessel
• R/V - Research Vessel
CONFLICT OF INTEREST STATEMENT

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

AUTHOR CONTRIBUTIONS

DFC, TO, GN, CG, CH, MB, MC, ER, and LB aided in the development, construction, and testing of STARSS. DFC, TO, GN, CO, JM, SM, HH, MB, and MR participated in the research cruise aboard the M/V Masco VIII. DFC, HC, BFK, JM, EF, HH, and ADK Jr. developed image analysis algorithms. BL and JH provided X-band radar data. SM and BH provided meteorological and wave buoy data. MC and SC
provided coupled model forecasts. All authors contributed to overall experimental design, interpretation of results, and editing of the manuscript.

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**FIGURE CAPTIONS**
Figure 1. The Gulf of Mexico with the STARSS area of operation, as established by agreement with the Federal Aviation Administration and Gulf Coast Helicopter operators, outlined in magenta. A MODIS Aqua chlorophyll-α image that was acquired on 10 February 2016 reveals a feature-rich submesoscale environment in the area of interest.
Figure 2. [A] STARSS consists of large aerostat (1), an emergency deflation device (2), a 5 GHz WiFi bridge (3), a NovaTel GNSS antenna (4), a 50.6 megapixel Canon 5DSR Mk III DSLR and INS (5), handling lines for launch and recovery (6), a sail (7), and a tether (8). The onboard computer and batteries were stored in a waterproof case on the top of the instrument frame (not visible). [B] An aerial image of a STARSS dispersion experiment. STARSS (1) is positioned over a patch of bamboo plates (2) and is tethered to the tender vessel (M/V Masco VIII; 3). [C] A grid deployment. [D] A patch deployment.
Figure 3. [A] Cross-section of the kernel along the x-axis showing the step function in blue and the Gaussian smoothed shape in red. [B] Kernel of the shape filter used to identify individual drift cards. [C] Schematic diagram of the relevant quantities used to rectify STARSS imagery. Here, $\theta_p$, $\theta_r$, $h_c$, $(x, y)_c$, and $(x, y)_c$ correspond to pitch, roll, heading, altitude, camera position, and image center, respectively. See equations [7] in section 2.4.2.
Figure 4. [A] A raw RGB image excerpt showing the drift card patch. [B] A grayscale image produced after the color filtering step (see equation 2 in section 2.4.1) clearly separates the patch of plates from the background and removes sun glitter. [C] The binary image (plates = 1 and background = 0) that results after the thresholding step. [D] The rectified patch of plates, with the major axis oriented along the x-axis due to lack of heading data (see Fig. 9E).
Figure 5. Panels A-D show the shape and orientation of a sharp density front during the STARSS dispersion experiment on 30 January 2016 in normalized marine backscatter intensity (greyscale) measured from a scientific X-band marine radar (see section 2.1.6) that was installed on the R/V Walton Smith. The backscatter has been corrected for range decay. Surface currents (black arrows), surface drifter trajectories (yellow arrows) and the ship track (blue) are also shown during the averaging period for each frame. The black arrows in the image corners indicate image heading, mean ship heading, and wind direction (counterclockwise from top right).
Figure 6. Sea surface temperature [A], salinity [B], and density [C] recorded by the thermosalinograph on the R/V Walton Smith. The starting location of the STARSS dispersion experiment is indicated by the pink triangle.
**Figure 7.** Trajectories of LASER surface drifters deployed in the region on [A] 29 January, [B] 30 January, and [C] 31 January reveal the scale of the front sampled by STARSS. The tails correspond to the previous 6 hr positions and the green line corresponds to the R/V Walton Smith’s position.
Figure 8. [A] Trajectories of three wave buoys that were deployed in the patch of drift cards show a general drift to the southwest during the 170 min experiment. The X and Y axes are scaled according to the average starting location of the wave buoys, which is located at the top right of the panel. [B] Drift speed of each buoy. [C] Significant wave height (SWH) and [D] dominant wave period (DWPd). [E] Wind speed measured from the M/V Masco VIII.

Figure 9. [A] STARSS position as measured by the onboard INS (relative to starting point). [B] STARSS altitude as measured by onboard INS. [C] STARSS pitch as measured by onboard INS. [D] STARSS roll as measured by onboard INS. [E] Erroneous STARSS heading as measured by onboard INS. Heading errors resulted from the manufacturer’s initialization procedure, which was not suitable for a moving ship.
Figure 10. Snapshots of rectified plate positions and ellipses at [A] 0 min, [B] 12 min, [C] 30 min, [D] 125 min, [E] 141 min, and [F] 170 min. Supplementary Video S1 shows the plate positions at each time step.
Figure 11. [A] Cloud dispersion, $\sigma^2 = 2\sigma_a\sigma_b$ of the patch of plates (blue dots) and average relative dispersion of pairs of plates (pink dots) plotted as a function of time on a log-log scale. The red dashed line and the black line represent exponential ($\sigma^2 \sim e^t$) and Richardson ($\sigma^2 \sim t^3$) dispersion regimes, respectively. [B] The major and minor axes of the dispersion ellipses are denoted by dark blue and cyan colors, respectively. [C] The dispersion ratio $\sigma_a/\sigma_b$. [D] The diffusivity ($\sigma^2/\Delta t$) computed from dispersion ellipses as a function of time.
Figure 12. [A] STARSS scale-dependent diffusivities during LASER computed from dispersion ellipses. [B] STARRS results are color coded according to time since deployment. In [B], Richard scaling ($K \propto \sigma^{4/3}$) is shown as a solid black line, the results compiled by Okubo (1971) as black triangles, surface drifter results from Poje et al. (2014) as pink ‘x’, and large eddy simulation results of Mensa et al. (2015) as red ‘+’. [C] Second order velocity structure function computed from linked trajectories of plates during three segments of the 170 min experiment. The black line in [D] corresponds to $r^{2/3}$. 