

SCI-DEM: A Method for Generating Digital Beach Surfaces from Tide and Waterline Timeseries

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Abstract

We present SCI-DEM, a method for deriving Digital Elevation Models (DEMs) of intertidal beach surfaces, profiles and beach widths from time-series waterlines using low-cost coastal CCTV cameras and modelled water levels. SCI-DEM builds on two established components: a waterline extraction method built on a semantic segmentation model, and a camera-pose-estimated homography, used to georeference each waterline. The SCI-DEM-specific contribution is the spatiotemporal aggregation of the resulting waterline time series: over a two-week moving window, waterlines are cleaned, intersected with fixed cross-shore transects, tagged with modelled water elevation (astronomical tide plus sea-level anomaly), and fit with shape-constrained monotonic regression under automated quality control; profiles passing quality control are combined into intertidal DEMs, mean-high-water (MHW) shoreline contours, and per-transect beach-width estimates. We validate SCI-DEM against RTK-GNSS beach-profile surveys at two camera deployments in Southern California, Torrey Pines and Oceanside Harbor South Jetty, and demonstrate its beach-width product at a third, Ehukai Beach Park (Hawaii), a microtidal beach with no survey programme. At all three sites an independently produced CoastSat satellite-shoreline record is shown alongside the camera series. Camera-derived and surveyed profiles agree to a mean absolute vertical residual of 0.09 m (1 October 2024), 0.15 m (20 May 2025) and 0.10 m (6 October 2025) at Torrey Pines and 0.11 m (1 October 2024) and 0.18 m (6 October 2025) at Oceanside Harbor South Jetty. The resulting beach-width time series reproduce the in-situ MHW crossings to within 3.0 m at Torrey Pines and 2.2 m at Oceanside Harbor South Jetty, and follow the same seasonal trends as the tidally corrected CoastSat record. SCI-DEM is currently running on over 60 live cameras. The method offers a cost-effective route to continuous, high-temporal-resolution beach-profile and beach-width monitoring that complements (and densifies) episodic physical surveys.

Keywords: shoreline detection; digital elevation model; beach morphodynamics; coastal video; intertidal zone; monotonic regression

1 Introduction

Accurate monitoring of beach morphodynamics informs coastal-erosion assessment, climate-change adaptation, and management of the nearshore environment. Roughly a quarter of the world’s sandy shorelines are eroding [Luijendijk et al., 2018], and projected sea-level rise threatens the beach area that shields coastal communities and infrastructure [Vitousek et al., 2017, Ranasinghe, 2016]. The spatiotemporal resolution at which beach profiles can be measured directly bounds the questions such data can address.

The traditional reference for beach-morphodynamics monitoring is topographic GPS survey, which achieves high vertical and horizontal accuracy but at low temporal and spatial resolution [Pardo-Pascual et al., 2005]. Airborne lidar [Sallenger et al., 2003] and unmanned aerial vehicle (UAV) photogrammetry [Turner et al., 2016, Casella et al., 2020] extend spatial coverage at centimetre-to-decimetre vertical accuracy, but each sur-

vey is a snapshot whose repeat interval is set by operating cost. At the other end of the trade-off, satellite optical imagery now supports multi-decadal shoreline records at global coverage [Vos et al., 2019a, Turner et al., 2021], with open toolkits such as CoastSat [Vos et al., 2019b] making the extraction routine. The performance of satellite-derived shorelines is site-dependent, with reported horizontal errors of 3.7–13.5 m [Pardo-Pascual et al., 2024], revisit cadence prevents instantaneous beach-profile reconstruction, and the correction of each instantaneous waterline to a reference contour requires a beach-face slope that must itself be estimated [Vos et al., 2020]. Water-level effects are the dominant error source in a recent multi-algorithm benchmark [Vos et al., 2023]. Between a twice-yearly survey of centimetre accuracy and a near-daily satellite record of metre-to-decametre accuracy there is no operational method that delivers profile-grade measurements at sub-weekly cadence.

Between these extremes sits the *waterline method*: if

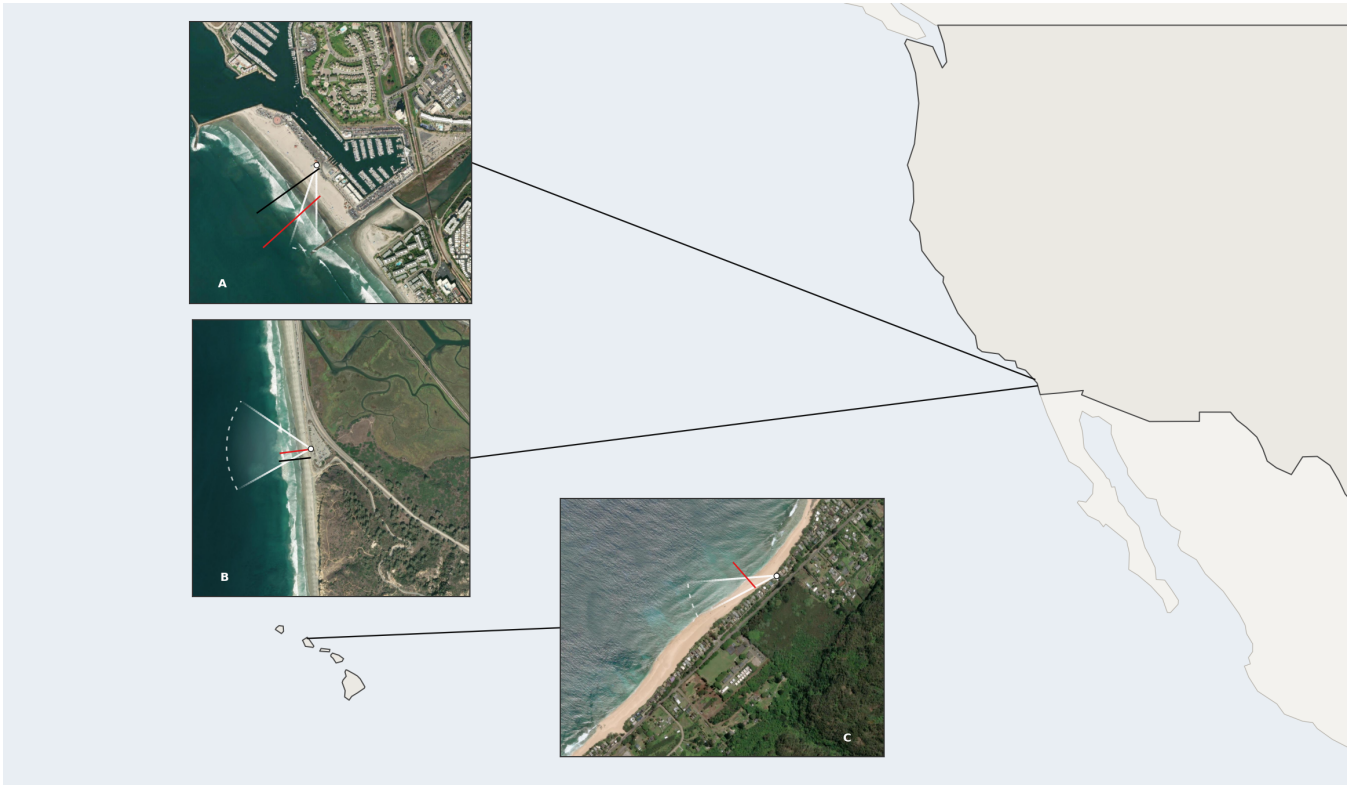


Figure 1: Study sites. **(A)** Oceanside Harbor (OS-1070); **(B)** Torrey Pines (TP-0520); **(C)** Ehukai Beach Park. The overview map locates the Southern California and Oahu deployments; satellite insets show the local camera context at each site. The white marker and wedge in each inset are the camera position and its horizontal field of view at the calibration zoom (64° at Torrey Pines, 19° at Oceanside, 23° at Ehukai), drawn to a nominal 390 m: the cameras view to the horizon, so the dashed arc is a drawing range, not a coverage limit. The black and red lines in each inset are the SANDAG and SCI-DEM transects, respectively.

the elevation of the waterline is known at the moment it is observed, each waterline is an elevation contour, and a set of waterlines spanning the tidal range can be assembled into a digital elevation model (DEM) of the intertidal zone. The principle was demonstrated with satellite radar three decades ago [Mason et al., 1995] and has since been applied to satellite composites and shore-based radar [Sagar et al., 2017, Bishop-Taylor et al., 2019, Bell et al., 2016]. Fixed video cameras are its natural platform: a stationary camera observes the shoreline continuously, over the full range of tidal levels, at cadences bounded only by the capture rate. Plant and Holman [1997] first estimated intertidal topography from time-exposure video images, Aarninkhof et al. [2003] quantified and corrected the water-level biases of video-detected shorelines, and Uunk et al. [2010] automated the workflow at a single site; subsequent work has broadened detection techniques from colour classifiers to neural networks [Vousdoukas et al., 2011, Valentini et al., 2017, Soloy et al., 2021, Montes et al., 2023].

Per-site calibration and supervision have kept this thirty-year-old idea from operating at network scale. Coastal video systems such as Argus [Holman and Stan-

ley, 2007] are georeferenced through surveyed ground-control points and photogrammetric calibration workflows [Simarro et al., 2017, Bruder and Brodie, 2020], shoreline detectors are tuned or manually reviewed per site [Montes et al., 2023], and each installation is a scientific instrument attended by experts. Repurposing consumer-grade camera infrastructure, as CoastSnap did for fixed smartphone stations [Harley et al., 2019], also requires calibration, detection, cleaning, and quality control to run unattended.

We present SCI-DEM, which addresses the temporal and spatial resolution gap between the in-situ survey and the satellite record; a method for producing intertidal beach DEMs from the video-derived shoreline streams of an operational surf-camera network, with shoreline contours and beach-width time series extracted at a chosen reference elevation, here taken as mean high water (MHW). SCI-DEM takes its inputs as: waterlines produced by the extraction method of Reinwald et al. [2026b], georeferenced by a camera-pose homography calibrated against ground control points (Section 2.4.2) and a water-level estimation. What SCI-DEM contributes, and what this paper evaluates, is the spatiotemporal aggregation of the resulting wa-

terline time series: waterlines are intersected with fixed cross-shore transects, fit with shape-constrained monotonic regression under automated per-transect quality control, and combined into intertidal DEMs, MHW contours, and per-transect beach widths with attached uncertainty. The method runs unattended on more than 60 live cameras at a daily cadence with a two-week aggregation window, improving the two in-situ survey records per year to circa 365 measurements per year at camera-equipped sites. SCI-DEM is validated against episodic in-situ beach-profile surveys at two camera deployments in California and demonstrated at a third in Hawaii; at all three, a CoastSat satellite-derived shoreline record is shown alongside the camera series as an independent observation of the same beach. The remainder of the paper describes the methodology (Section 2), reports validation results (Section 3), and closes with an outlook on extensions (Section 4). Appendix A shows the complementary satellite-derived shoreline methods used to support the validations.

2 Methodology

2.1 Study sites

SCI-DEM is evaluated at three camera deployments (Figure 1). Torrey Pines and Oceanside Harbor South Jetty (Southern California) have repeated RTK-GNSS beach-profile surveys from the San Diego Association of Governments (SANDAG) [San Diego Association of Governments, 2025], against which the method is validated. Ehukai Beach Park (Oahu) has no survey programme; it is included to demonstrate the beach-width product at a highly dynamic microtidal beach with a different camera geometry, and no accuracy claim is made for it. At all three sites a CoastSat satellite-derived shoreline record (Section 2.3) is shown alongside the camera series. The sites span micro- to mesotidal conditions and varying camera locations and angles.

2.2 In-situ beach profiles

Ground-truth beach morphology at Torrey Pines and Oceanside Harbor comes from the SANDAG Shoreline Monitoring Program, which conducts twice-yearly RTK-GNSS cross-shore profile surveys along fixed transects [San Diego Association of Governments, 2025]. We use transect TP-0520 for Torrey Pines and OS-1070 for Oceanside Harbor. The SCI-DEM historic data covers three survey dates for Torrey Pines and two for Oceanside Harbor. Each profile records elevation (relative to MLLW) versus cross-shore distance from the transect origin. Near the low-tide end of each profile the SANDAG surveys switch from terrestrial RTK-GNSS to boat-based bathymetry without a marker in

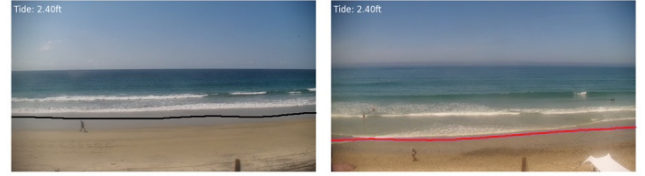


Figure 2: Averaged 1 Hz waterlines at Torrey Pines in October 2024 (black) and May 2025 (red), both at a water level of 0.73 m (2.40 ft) and a common camera perspective. Each extracted waterline traces the elevation contour equal to the water level at capture, so at a matched water level in calm conditions the difference between the two is morphological.

the data, which bears on the profile residuals at low elevations (Section 3.1).

The RTK-GNSS surveys are the only reference of known accuracy used here; they check the absolute elevations of the camera-derived surface at specific points in time. Beach width and profile are compared against in-situ data by shifting the SCI-DEM measurements to the origin of the in-situ survey transect (Section 2.6).

2.3 Satellite-derived shorelines

At all three sites a satellite-derived shoreline record is shown alongside the SCI-DEM beach widths, extracted with CoastSat [Vos et al., 2019b] from Sentinel-2 and Landsat 8–9 imagery, run unsupervised with the toolbox’s automated quality control, intersected with the validation transect, and tidally corrected to the site MHW contour with the beach-slope method of Vos et al. [2020]. The two are independent remote-sensing observations of the same beach; the satellite record is not a reference, and no accuracy claim is made for either method against the other. Its configuration, a worked example scene, the differences between the two records and their sampling density are given in Appendix A.

2.4 SCI-DEM derived shorelines

SCI-DEM produces georeferenced waterline time series from 1 Hz coastal CCTV, then aggregates them into intertidal DEMs before extracting the MHW contour to track the shoreline position. Throughout, a *waterline* is the instantaneous land/water boundary in a frame or a 10 minute average waterline and the *shoreline* is the MHW contour extracted from the aggregated surface.

2.4.1 Waterline extraction

Waterline positions are taken from the 1 Hz waterline extraction method of Reinwald et al. [2026b], which delineates the land/water boundary in each frame from a semantic segmentation model. SCI-DEM consumes

those waterlines as given; the extraction itself is described and evaluated in that paper.

Each ten-minute video segment is processed as a batch: 600 1 Hz waterlines are temporally averaged into a single representative average waterline, which suppresses short-term oscillations from breaking waves in a manner analogous to the time-exposure (Timex) methods of Harley et al. [2019].

Figure 2 shows representative average waterline outputs at Torrey Pines on two dates sharing a common mid-tide water level.

2.4.2 Homography and georeferencing

Each averaged waterline is georectified with a tide-adaptive homography. A pinhole camera model (Eq 1 P) is fitted per camera to surveyed ground control points collected with an RTK-GNSS surveyor at Oceanside Harbor and a mobile phone at Torrey Pines, giving the intrinsic (Eq 2 K) and extrinsic matrices (Eq 3 R and t). The sea surface is treated as a horizontal plane at the water level anchored to the waterline and horizon (Section 2.5). Thus, at a known elevation Z , the pinhole model yields a homography from image coordinates (Eq 1 u, v, Z) to real-world coordinates that can be used to georectify waterlines.

$$\begin{bmatrix} u \\ v \\ w \end{bmatrix} = P \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix} = K [R | t] \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix} \quad (1)$$

$$K = \begin{bmatrix} f_c & 0 & c_h \\ 0 & f_c & c_v \\ 0 & 0 & 1 \end{bmatrix} \quad (2)$$

$$[R | t] = \begin{bmatrix} r_{11} & r_{12} & r_{13} & t_x \\ r_{21} & r_{22} & r_{23} & t_y \\ r_{31} & r_{32} & r_{33} & t_z \end{bmatrix} \quad (3)$$

In Eq 1, (X, Y, Z) are world coordinates in meters, east and north of a local reference point and elevation, and $(u/w, v/w)$ is the corresponding pixel position in the image. In K , f_c is the focal length in pixels and (c_h, c_v) is the principal point, the pixel at which the optical axis meets the image, fixed at the image center. R rotates the world axes into the camera axes and is set by the camera azimuth, tilt and roll. The translation is $t = -RC$, where C is the camera position in world coordinates. The fit solves for seven parameters: the three components of C , the three rotation angles and f_c .

Calibration quality was checked by reprojecting the surveyed ground control points through the fitted model and comparing them with their surveyed positions, giving a mean horizontal error of 1.4 m at Torrey Pines and 0.43 m at Oceanside Harbor. GCP surveys were completed at low tide, covering the top beach and

intertidal zone to provide as much information to the fit as possible. It is expected that georectification error is a function of distance from the camera and camera height and so the accuracy of the rectification is dependent upon where the waterline is measured in the scene which can change over seasons. The difference in horizontal error between the two GCP collection methods is attributed to the GPS accuracy of the RTK-GNSS surveyor compared to a mobile phone.

2.4.3 Waterline aggregation and DEM construction

The SCI-DEM-specific processing aggregates georeferenced, water-level-tagged waterlines from a two-week window ending on the report date. Over this window each ~ 10 -minute video segment contributes one georeferenced waterline and its total water elevation, sampling the intertidal zone across a representative range of water levels. The aggregation is a per-transect, monotonically shape-constrained variant of the classic video *waterline* method: as the tide rises and falls, each detected waterline traces an elevation contour whose elevation equals the water level at capture [Montes et al., 2023].

Cleaning. 10-minute average waterlines are excluded when the video recording is flagged as degraded by the SCI-VIS visibility classifier [Reinwald et al., 2026a], or when the waterline is self-intersecting due to poor segmentation. The remaining waterlines are clipped to the bounds of the pre-defined transects for each camera.

Transect intersections and tide-conditioned cleaning. The intersections of the waterlines with the pre-defined transects are computed, recording the cross-shore distance from the transect’s landward origin and the intersection lat/lon position; where a waterline crosses a transect more than once it is considered corrupted and dropped from the analysis. Elevation is attributed to each waterline from Section 2.5. Outliers are removed within six tide quantile bins using a Tukey $1.5 \times \text{IQR}$ rule on cross-shore distance, so genuine tidal movement is not confused with scatter at a fixed water level.

Monotonic profile fitting. For each transect the cleaned (elevation, distance) samples are fit under a physical monotonicity constraint: as water level decreases the waterline can only retreat seaward, so cross-shore distance is a non-increasing function of elevation. The fit proceeds by isotonic regression, followed by smoothing of the isotonic curve, and finally a piecewise-linear refit with 0–6 complexity-penalised breakpoints whose turning points summarise the profile shape (Figure 3b). Automated metrics—tidal coverage, coverage of the reference contour (MHW), fit RMSE, residual

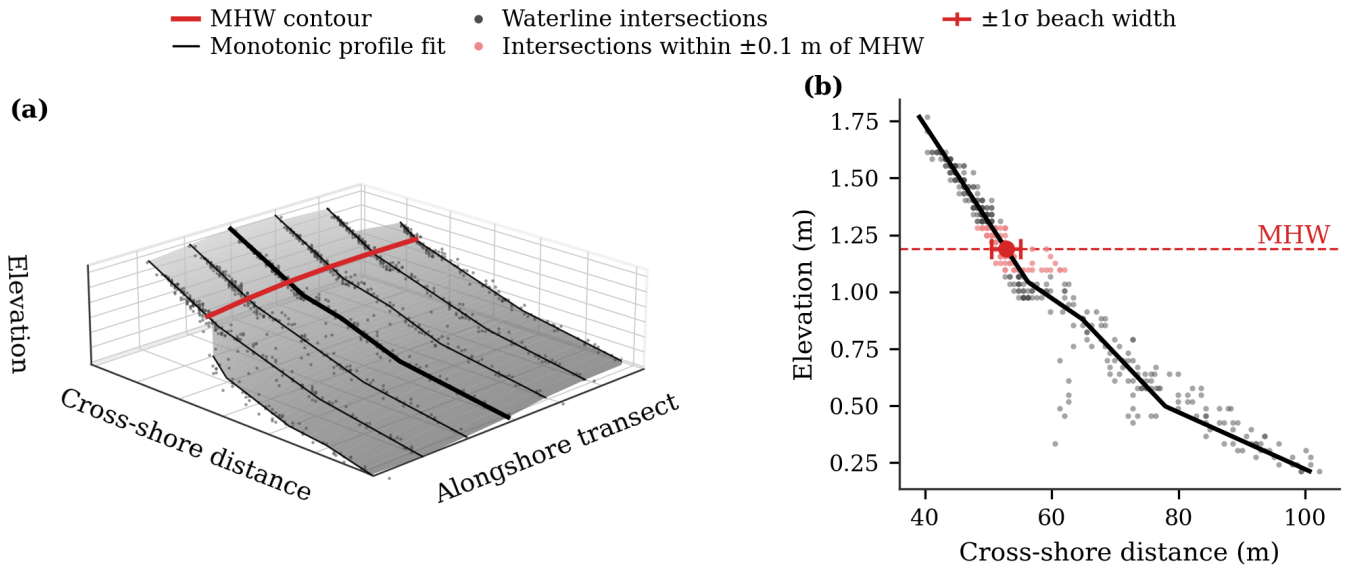


Figure 3: The aggregation of a single two-week window at Torrey Pines. **(a)** The seven consecutive alongshore transects that passed the fit quality checks. Each transect shows the monotonic profile (black) fitted through the waterline–transect intersection points (gray, every second one drawn); the surface is swept between adjacent fits at matched elevation, and the MHW contour (red) is the constant-elevation line from which the beach width is reported. Tick labels are omitted because (a) illustrates the construction; the two horizontal axes share one scale and elevation is exaggerated ten times. **(b)** The transect drawn with the heavier line in (a), with all 412 of its intersections. The fit follows the scatter over the full tidal range while cross-shore distance decreases monotonically with elevation. The red dot is the beach width, the fitted distance at the MHW elevation (dashed). The 82 intersections within ± 0.1 m of MHW are drawn in light red; the red bar is the $\pm 1\sigma$ beach-width uncertainty of 2.3 m, the standard deviation of their cross-shore distances about the fit.

spread near that contour, and perpendicular distance to the fit—assign each transect a pass or fail quality flag; only passing transects contribute to the reported surfaces.

Beach width, MHW contour, and surface DEM.

The beach width on a transect is the fitted profile’s cross-shore distance at the site’s MHW reference contour (Section 2.5), interpolated inside the fitted range or edge-extrapolated and clamped to the observed distance range when the contour lies just outside it. The crossing points on adjacent transects form the MHW shoreline contour used for beach-width monitoring. An uncertainty is attached to each width as the standard deviation (1σ) of the measured waterline intersections whose water level lies within ± 0.1 m of the reference contour, so it expresses the scatter of the observed waterline at the elevation at which beach width is defined (Figure 3b).

A surface is created with straight constant-elevation bands between each of the fitted profiles and projected onto a regular lon/lat grid. This surface can then be used to interpolate along any given transect within the camera field of view for monitoring or validation. Figure 3 shows the whole construction for one Torrey Pines window.

The two products degrade differently as tidal range

shrinks. At microtidal sites, such as those in Hawaii, the intertidal zone is so narrow that the water level sweeps too little of the beach face to resolve a profile, and the elevation–distance fit approaches a vertical line. Beach width survives this limit: a near-vertical fit still locates the reference contour in cross-shore distance, so width remains recoverable at sites where the profile itself does not. This limit is therefore dynamic and is dependent on both the slope of the beach and the tidal range.

After experimenting with different window sizes, this two-week window reflects a trade-off between sample density (enough tidal range to span the intertidal zone) and temporal resolution (short enough to capture rapid morphodynamic response to storms or nourishment events).

2.5 Water-level estimation

Both the satellite-derived shorelines (Section 2.3) and SCI-DEM (Section 2.4) require an instantaneous water-surface elevation at each waterline observation so that cross-shore positions can be compared on a common vertical datum or, for SCI-DEM, used directly as the elevation coordinate in profile fitting.

Tide prediction. The astronomical predicted tide for each ten-minute average waterline is derived from NOAA tidal harmonic constituents at nearby tide gauges and rounded to the nearest 0.1 m. Torrey Pines uses the La Jolla (Scripps Pier) station [NOAA National Ocean Service, Center for Operational Oceanographic Products and Services, 1991b]. Oceanside Harbor and Ehukai Beach Park use the San Clemente and Haleiwa subordinate stations, whose predictions are time and height offsets from the San Diego [NOAA National Ocean Service, Center for Operational Oceanographic Products and Services, 1978] and Honolulu [NOAA National Ocean Service, Center for Operational Oceanographic Products and Services, 1991a] reference stations, taken from NOAA tide-prediction tables as distributed in the XTide harmonics database [Flater, 2021]. The same source is applied to both the camera-derived and the satellite-derived shorelines in Appendix A, so the two share a vertical reference by construction. Tide is expressed in metres relative to the local tidal MLLW datum of the assigned station and so no vertical conversion was required to compare with the in-situ survey elevations.

Sea-level anomaly. The astronomical tide z_{ast} is augmented with daily sea-level anomaly (SLA) z_{sla} from the Copernicus Marine Service global altimeter L4 product at the nearest grid point to the site centroid (for these cases <5 km from the site), which adds the meteorological contribution to the observed waterline. The SLA correction is an order of magnitude smaller than the tidal signal — a decimetre-scale offset (0.05–0.16 m) against a tidal range of 1.7–1.9 m for these validation cases — but on shallow beach faces even an offset of this size can contribute significantly to the beach-width estimate, so it is not negligible at the accuracy being validated. The *total water level* is

$$z_{\text{twl}} = z_{\text{ast}} + z_{\text{sla}} \quad (4)$$

Remaining elevation errors are therefore attributed to unestimated surge and wave set-up, which are assumed to average out over the two-week aggregation window.

Reference contour. The target contour z_{ref} is each site’s mean high water (MHW) level, taken as the average high-tide elevation over the site’s 2023–2024 tide time series. The same value of z_{ref} is used for SCI-DEM (Section 2.4.3) and for the satellite-derived shorelines (Appendix A), referenced to the same local tidal datum as that site’s tide time series, so z_{ref} and z_{twl} share a common vertical reference: 1.19 m at Torrey Pines, 1.20 m at Oceanside Harbor, and 0.39 m at Ehukai Beach Park. These MHW elevations are derived from the tide series rather than taken from published NOAA/NOS datums, so that the same procedure can be applied at sites without a published datum.

Application. In SCI-DEM, z_{twl} is attached to each retained waterline and propagated through transect intersection and monotonic profile fitting, so each cross-shore sample lies on an elevation contour equal to the water level at capture. For satellite shorelines, the same z_{twl} feeds the slope-based contour normalisation in Equation (A1), mapping each instantaneous shoreline observation to the reference elevation used for beach-width comparison.

2.6 Transect alignment for validation

The SCI-DEM validation transect and the in-situ survey transect are in slightly different locations at both sites with surveys (Figure 1). The camera transects are positioned for the camera field of view, whereas the survey lines run seaward from fixed origins established by the survey programme, so the two origins do not coincide: the in-situ origin lies 39 m alongshore of the camera transect at Torrey Pines and 95 m at Oceanside Harbor. Cross-shore distances measured on the two lines are therefore not directly comparable. The two are brought to a common origin with a single constant offset. The in-situ survey origin is projected onto the SCI-DEM transect and its along-transect distance from the SCI-DEM origin is read off, positive seaward (+8.0 m at Torrey Pines; −80.2 m at Oceanside Harbor, where the origin lies landward of the SCI-DEM origin). Subtracting this offset from every SCI-DEM cross-shore distance re-references it to the in-situ origin, so beach profiles can be compared directly. The shift is applied to every distance measured on the SCI-DEM transect—the elevation-surface samples compared with the surveyed profiles (Section 3.1), the MHW crossing that defines the beach width, and the CoastSat intersections on that transect (Appendix A)—and changes only the coordinate at which a value is read: elevations, profile shape and the width uncertainty are untouched. A constant shift assumes that the elevation contours run perpendicular between the camera transect and the in-situ transect. This could contribute to perceived errors in the results where there is a material beach change between the transects.

3 Results

SCI-DEM is validated at the two surveyed deployments (Figure 1; Section 2.1): camera-derived elevation surfaces against episodic in-situ beach profiles, with particular attention to the mean high water (MHW) contour at which beach width is defined, and beach-width time series against the in-situ MHW crossings. The Ehukai Beach Park series is shown alongside as a demonstration, and the CoastSat record at all three sites is compared in Appendix A.

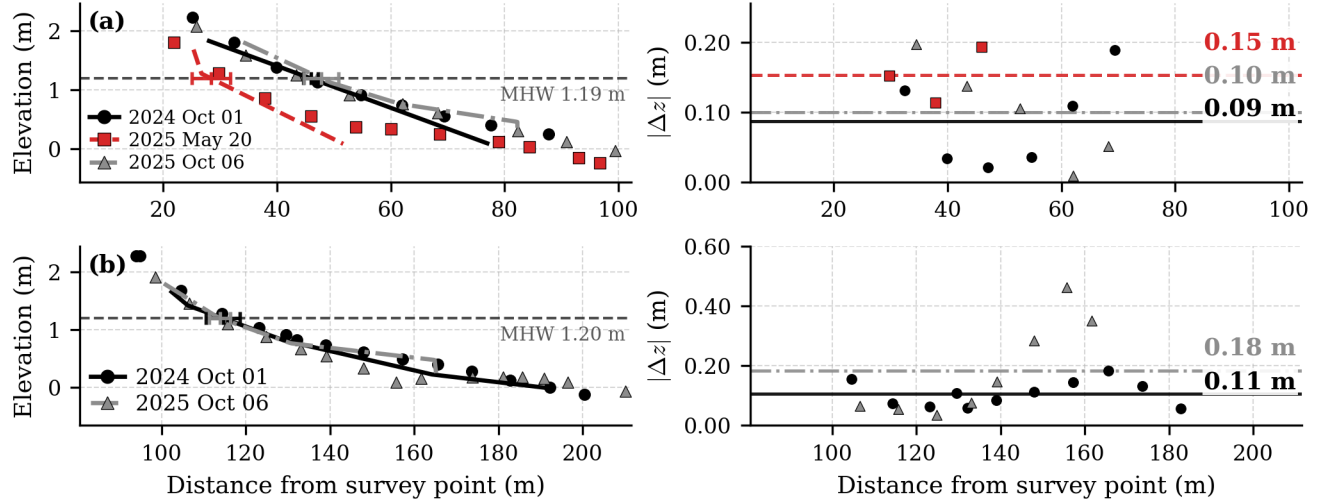


Figure 4: Beach-profile validation at the two sites with survey data, one row per site: (a) Torrey Pines, three survey dates; (b) Oceanside Harbor, two survey dates. *Left*: in-situ beach profiles (markers) and aligned SCI-DEM elevation surfaces (lines); the dashed line is the site’s MHW reference contour at which beach width is defined—1.19 m and 1.20 m on each site’s local tidal datum. The horizontal error bar on the MHW line is the $\pm 1\sigma$ cross-shore spread of the waterline intersections lying within ± 0.1 m of that contour over the lagged 14-day aggregation window. *Right*: the corresponding absolute vertical residual $|\Delta z| = |z_{\text{in-situ}} - z_{\text{SCI}}|$ at each overlapping survey sample, in the same colours, with horizontal lines and labels giving the per-survey mean. Note that the residual scale differs between sites.

3.1 Beach profile validation

Figure 4 overlays the surveyed profiles with the SCI-DEM elevation surfaces (left column) alongside the corresponding absolute vertical residuals (right column). The comparison is restricted to the cross-shore range over which the fitted SCI-DEM profile and the survey overlap. Ehukai Beach Park has no survey programme and does not enter the validation (Section 2.1).

At Torrey Pines (Figure 4 a), in-situ and SCI-DEM profiles agree closely across the intertidal zone, with the tightest correspondence at higher elevations; mean vertical residuals are 0.09 m (October 2024), 0.15 m (May 2025), and 0.10 m (October 2025). Importantly, the SCI-DEM accurately reproduces the seasonal and annual beach width change captured by the bi-annual survey programme. It should also be noted that this camera pose calibration was solved using GCPs from a mobile phone. Rectification errors would show in the results as constant bias in the SCI-DEM profiles, which is not present, indicating that the mobile phone GCP fit is performant enough to capture these profiles.

The horizontal error bars drawn at the MHW reference contour in Figure 4 give the cross-shore uncertainty on the MHW shoreline position on each survey date, namely the 1σ spread of the waterline intersections observed within ± 0.1 m of MHW (Section 2.4.3). At Torrey Pines the beach-width uncertainty is ± 1.3 m, ± 3.4 m and ± 3.0 m in October 2024, May 2025 and October 2025 respectively, and ± 4.0 m and ± 2.5 m at Oceanside Harbor in October 2024 and October 2025.

The beach width at MHW is therefore resolved to a few metres in the cross-shore. Measured against beach widths that vary by tens of metres between seasons (Section 3.2), a spread of this size leaves the seasonal signal well resolved.

Oceanside Harbor (Figure 4 b) shows mean residuals of 0.11 m (October 2024) and 0.18 m (October 2025), in line with Torrey Pines. This is a more challenging site for georectification due to the waterlines being over twice as far from the camera compared to Torrey Pines, as well as being more obliquely angled. In October 2025, residuals are below 0.08 m from 107 m to 133 m, the stretch spanning the MHW crossing at 114 m, and grow seaward of it, to 0.15 m at 139 m and 0.46 m at 156 m near the low-tide end of the profile. This residual growth toward the low tide is likely an artefact of distance from the camera, since small pixel displacements yield large real-world distances as the waterlines move closer to the horizon in pixel space, which is the vanishing point of the planar homography. Due to the 95 m distance between the comparison transects, it is also possible that this low tide gully exists along the in-situ transect but not along the SCI-DEM transect. The October 2024 profile shows no such growth: its residuals stay below 0.19 m over the whole 105–183 m overlap, including the low-tide end.

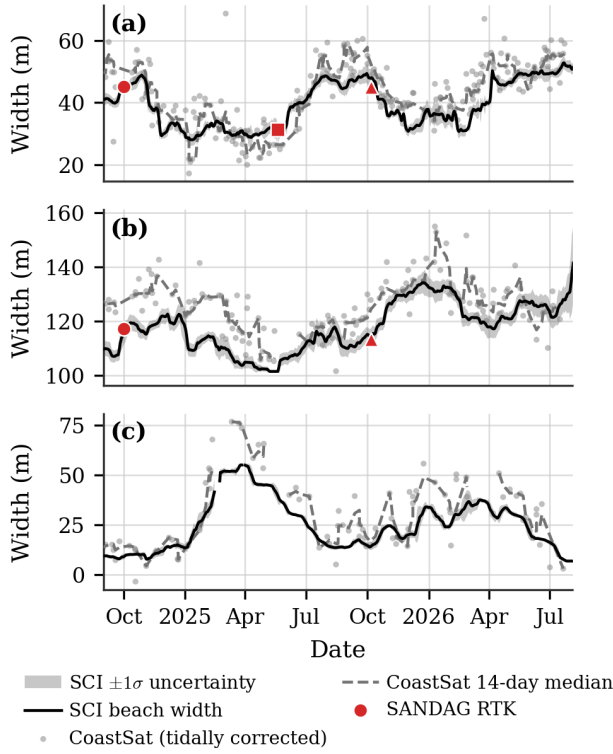


Figure 5: Stacked beach-width time series at the three sites (shared time axis from September 2024). (a) Torrey Pines; (b) Oceanside Harbor; (c) Ehukai Beach Park. Black line: SCI-DEM MHW beach width, with the grey $\pm 1\sigma$ band of waterline intersections near that contour. Red markers: in-situ RTK crossings at the site reference contour, with the marker shapes of Figure 4 (circle October 2024, square May 2025, triangle October 2025). Faded grey dots: the independent CoastSat record, individual shorelines tidally corrected to the same contour by the slope method of Equation (A1) (Appendix A). Dashed grey line: the median of those CoastSat shorelines over a trailing 14-day window, matching the SCI-DEM aggregation window so the two are smoothed comparably; it is drawn only between overpasses less than 28 days apart, so breaks in it mark intervals with no usable scene.

3.2 Beach-width time series

Figure 5 shows the continuous beach-width time series at the three deployments. Each panel shows SCI-DEM beach width on the site’s validation transect, with an uncertainty band of $\pm 1\sigma$ of the waterline intersections falling within ± 0.1 m of the MHW contour (Section 2.4.3). In-situ RTK crossings are drawn at the two surveyed sites and the tidally corrected CoastSat record at all three; the SCI-DEM and satellite cross-shore distances, both measured on the camera transect, are shifted to the in-situ survey origin where one exists (Section 2.6).

At Torrey Pines (Figure 5a) the SCI-DEM MHW beach width lies within 3.0 m of the three in-situ RTK crossings (+0.7, -3.0 and +2.8 m, positive seaward), and at Oceanside Harbor (Figure 5b) within 2.2 m of the two crossings (-2.2 and +1.1 m); in every case the measured in-situ beach width is within the $\pm 1\sigma$ uncertainty band (Section 3.1). Ehukai Beach Park (Figure 5c) has no survey programme; its series demonstrates the beach-width product at a microtidal beach with a different camera geometry and carries no accuracy claim. At all three sites the camera and CoastSat records follow the same seasonal trends; the differences between the two records and their sampling density are reported in Appendix A.

4 Conclusion and outlook

We have described SCI-DEM, a method for producing intertidal beach DEMs and beach-width time series from video-derived waterlines, modelled water levels, and shape-constrained profile aggregation. Validation against in-situ beach profiles at two camera deployments (Section 3) shows agreement across the intertidal range, tightest at the mean high water (MHW) contour used for beach-width extraction (Figure 4), and beach-width time series that reproduce the in-situ RTK crossings (Figure 5). At those sites and at a third, unsurveyed deployment in Hawaii, the camera series and an independent CoastSat record follow the same seasonal trends (Appendix A).

The value of the method is in temporal resolution and unattended operation at network scale: SCI-DEM is currently running on more than 60 live cameras, producing continuous beach-profile and beach-width time series at a daily cadence. This densifies the intermittent physical-survey record by orders of magnitude without the large compromise in accuracy that is the case with satellite derived shorelines. The natural next directions are (i) expanded multi-site profile validation against additional survey programmes, (ii) characterisation of the geometry-dependent low-tide error across a range of camera elevations and viewing angles, (iii) quantification of the segmentation-error contribution separately from the georeferencing and water-level estimation errors, (iv) alerting on rapid morphodynamic change (e.g., post-storm response), and (v) training site-specific predictive models on the outputs to forecast morphodynamic change.

Author disclosure

B. Freeston, a co-author of this paper, is the named inventor on US Patent 10,891,481 B2 (Freeston [2021]), assigned to Surfline/Wavetrak, Inc., which discloses the broader automated ocean-sensing framework within which SCI-DEM was developed.

Data and code availability

The validation reference data (SANDAG beach-profile surveys) is publicly available from SANDAG’s Shoreline Monitoring Program (<https://www.sandag.org/projects-and-programs/environment/shoreline-management/monitoring-program>). The camera imagery, per-camera segmentation and homography configurations, and derived DEMs are proprietary to Surfline/Wavetrak, Inc. and are not publicly released. The methodology described in this paper is sufficient for independent re-implementation against a comparable camera deployment.

A Satellite-derived shoreline comparison

A.1 Shoreline extraction and tidal correction

CoastSat is used to extract shorelines (the toolbox’s term for the instantaneous water boundary in a scene) from multiple satellite sources at each site; each is intersected with the validation transect and tidally corrected to the site’s MHW reference contour (Section 2.5) using an estimated beach slope, giving a cross-shore beach width comparable with the SCI-DEM product.

Shoreline extraction. Satellite-derived shorelines are extracted with CoastSat [Vos et al., 2019b] from Sentinel-2 (Level-1C) and Landsat 8–9 (Collection 2, Tier 1, the tier recommended for time-series analysis) top-of-atmosphere imagery. Detection and quality control are fully automated, with no manual review of individual scenes: scenes with more than 50% cloud cover or a georeferencing accuracy poorer than 10 m are discarded, shorelines are not mapped within 300 m of cloud pixels, detections are confined to a 100 m buffer around a digitised reference shoreline, sand objects below 1000 m² and shoreline segments shorter than 500 m are rejected, and transect intersections pass CoastSat’s quality-controlled intersection routine (25 m alongshore window) followed by Otsu-threshold and physical-implausibility despiking. CoastSat’s cloud-mask correction is additionally enabled at the two Californian sites, where bright sand was visibly being masked as cloud. Running CoastSat unsupervised in this way is established practice at regional scale [Graffin et al., 2023, Tiede et al., 2023] and is how the toolbox is characterised in the satellite-derived shoreline benchmarking intercomparison [Vos et al., 2023]; it also means neither side of the comparison is hand-curated, since SCI-DEM likewise rejects observations only by automated rule (Section 2.4.3).

Transect intersection. Each waterline is intersected with the site’s validation transect, recording the cross-shore distance from the transect origin at the crossing nearest the landward end. Because satellite-derived waterlines are observed at instantaneous water levels that rarely coincide with the reference contour, each intersection is tidally corrected to a common elevation (Equation (A1)).

Slope estimation. The beach-face slope β is estimated per site with the spectral method of Vos et al. [2020], applied to the tide-only signal (excluding the non-tidal surge residual, which would only add noise to the tidal frequency the method targets). The method’s frequency-grid resolution parameter (assumed sampling interval, in days) is set per site to the ceiling of that site’s median inter-image interval: 2 days at Torrey Pines and 4 days at Oceanside Harbor and Ehukai Beach Park. On a slope search grid of resolution 0.005, this converges to $\beta = 0.050$ at Torrey Pines and Oceanside Harbor, and yields $\beta = 0.051$ at Ehukai Beach Park via a published fallback source.¹

Tidal correction. Following the linear beach-slope method of Vos et al. [2020], the observed shoreline distance d at total water level z_{twl} is corrected to the reference contour z_{ref} via

$$d_{\text{corr}} = d - \frac{z_{\text{ref}} - z_{\text{twl}}}{\beta}. \quad (\text{A1})$$

Corrected distances are shifted to the in-situ survey origin with the same offset as the SCI-DEM widths (Section 2.6); water levels z_{twl} are computed as described in Section 2.5.

Figure A1 makes the preceding steps concrete on a single overpass at Torrey Pines, and places the resulting satellite shoreline beside the SCI-DEM MHW contour for the aggregation window containing it.

A.2 Differences between the two records

Median cross-shore differences, CoastSat minus SCI-DEM, are 3.9 m at Torrey Pines over 226 coincident days, 10.3 m at Oceanside Harbor over 161 and 6.5 m at Ehukai Beach Park over 88, positive where the satellite shoreline lies seaward of the camera shoreline. At each site the seasonal range of beach width is larger than the 3.7–13.5 m horizontal error reported for satellite-derived shorelines [Pardo-Pascual et al., 2024]. At Ehukai Beach Park the CoastSat waterlines are often seaward-biased because bright whitewater from waves

¹At Ehukai the spectral estimate does not converge; the published slope of Vos [2026] for its `usa_HI_0023` site is used instead, disclosed as a fallback rather than an independently derived estimate.

Sentinel-2
14 October 2024

CoastSat shoreline extraction

Shorelines on the validation transect

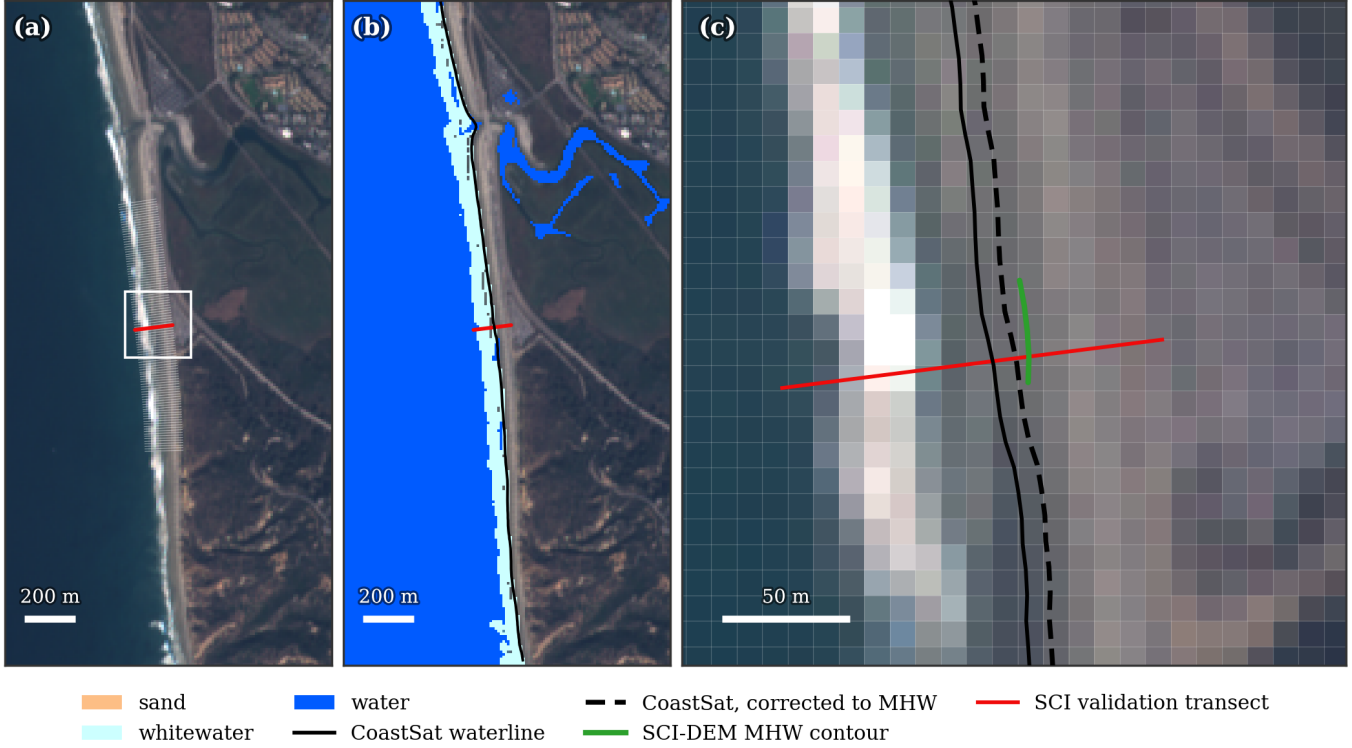


Figure A1: An overview of how satellite-derived shorelines (using CoastSat) were compared with SCI-DEM at Torrey Pines. (a) The full Sentinel-2 scene in true colour, with the validation transect in red and the box marking the extent of (c). (b) The same scene under CoastSat's pixel classification, with the extracted shoreline overlaid. (c) The validation transect at pixel scale. The satellite observes an instantaneous waterline (solid line), which Equation (A1) moves onto the SCI-DEM MHW shoreline (dashed line). Only the corrected line is comparable with SCI-DEM; the solid line is the raw observation.

breaking on the offshore reefs shifts the detected water boundary seaward; this is visible as the offset in Figure 5c.

A.3 Sampling density of the satellite and camera records

The density of the CoastSat markers in Figure 5 varies markedly between sites and through time, which bears directly on how much of the record either method can resolve. A satellite-derived shoreline requires a cloud-free overpass that also survives the quality control of the detection and tidal-correction steps, so the sampling of the resulting series is limited by the revisit interval and the local cloud conditions. To quantify the data availability for a lagged 14-day window, and to compare against the SCI-DEM data availability, the aggregation window was stepped across the full time series at each site and a count of how many data points are available for aggregation was made (Table A1, Figure A2): usable CoastSat scenes on the satellite side, and on the camera side the number of distinct days contributing rewinds to the SCI-DEM aggregation win-

dow. Every calendar day is evaluated for both, not only the days carrying an observation, so intervals with no usable scene and days on which the aggregator produced no window are counted rather than skipped.

Even at Torrey Pines, the best-sampled site by CoastSat, the median 14-day satellite window holds only 4 scenes and the total valid scenes amount to only 31.5% of what a daily sensor would deliver. The scene availability issue is particularly prevalent at Ehukai Beach Park, where the median window holds only 2 scenes and 75% of aggregation windows would have fewer than two scenes to average over. With so few data points to aggregate, there is not enough data to average out the uncertainty in the waterline estimation from the satellite-derived beach widths.

The right-hand panel of Figure A2 is the same measurement made on the camera record. Its distribution shows the median window at every site draws on all 14 days. Each ~10-minute daylight segment yields one waterline (Section 2.4.3), so a window is built from hundreds of waterline observations spread across a representative range of water levels, rather than from whichever few tide stages a cloud-free over-

Table A1: Number of data points in a trailing 14-day window at each site, for each method, evaluated on every day of the time series. The coverage columns express the mean count as a percentage of a hypothetical complete record — one observation every day, and therefore 14 in every window.

Site	CoastSat				SCI-DEM		
	Scenes in record	Median per window	Empty (%)	Coverage (%)	Median days per window	Empty (%)	Coverage (%)
Torrey Pines	221	4	3.2	31.5	14	0.0	98.7
Oceanside Harbor	134	3	7.0	19.4	14	0.0	100.0
Ehukai Beach Park	87	2	16.0	12.5	14	0.0	99.9

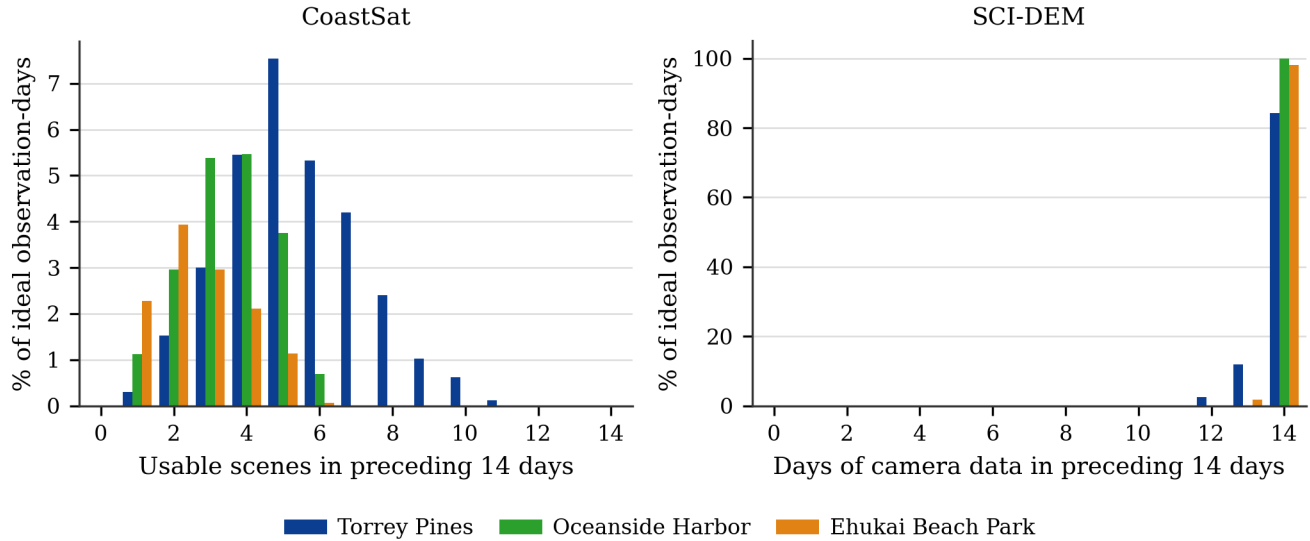


Figure A2: Number of data points in a trailing 14-day window, one colour per site: *left*, usable CoastSat scenes; *right*, days of camera data in the corresponding SCI-DEM aggregation window. Both panels are evaluated on every day of the record and share the same count axis. Bar heights are normalised against a complete record of one observation per day (14 per window) rather than against the observations that exist, so each bar gives the share of that ideal volume.

pass happened to catch. The satellite-derived shore-
lines nonetheless follow the same long-term trends as
the SCI-DEM series (Section A.2).

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