

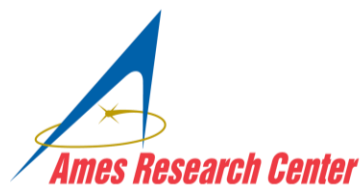
# Dataset Documentation

## FROST:

Features Relevant to Ocean Worlds Surface Terrain



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# 1 Introduction

We present FROST – Features Relevant to Ocean Worlds Surface Terrain, an analog dataset. FROST provides examples of possible terrain features, geometry, and appearance at the 1-10cm scale on ocean worlds/icy moons such as Europa, Enceladus, and Pluto. The motivation for collecting this dataset was a lack of available high-resolution digital models suitable for development of surface missions to these bodies, including use for simulation of mechanics, sampling, and imaging. NASA field opportunities to Death Valley, California and the Atacama Desert, Chile were leveraged in order to observe and record analog sites.

## 2 Data Collection Process



**Figure 1. 3D terrain information is collected using a survey LIDAR scanner on a tripod.**

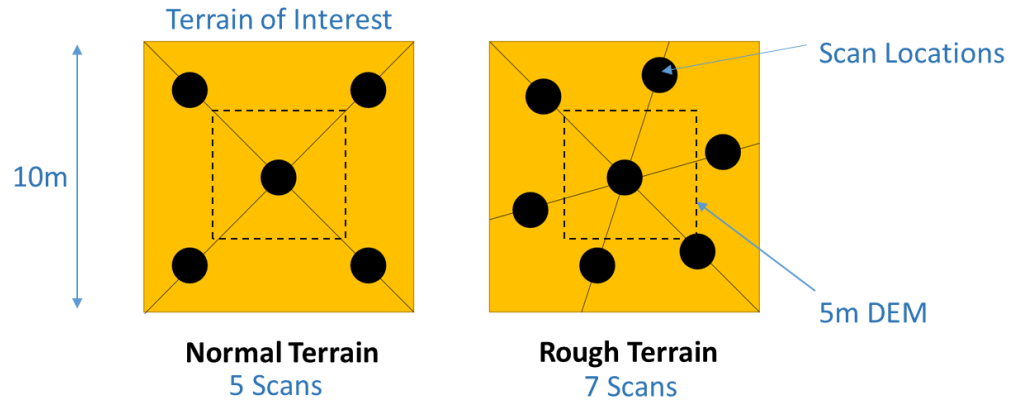
The process to collect 3D data of terrain involves scanning patches of terrain with a survey LIDAR scanner (FARO M70) mounted on a tripod in a fixed pattern. A target area of interest of 10m x 10m area is first identified and cordoned off. A pattern of 5 or 7 scans is selected for each area based on the roughness (vertical relief) of the features in that area. Rough areas require more scans to faithfully model occlusions around features. We use the scan patterns as guides, but do not attempt to position the tripod with high repeatability due to the erratic nature of the ground.

Each scan produces a “cloud” of about 10 million points, with about 80% of points typically lying in the target area. We use scan parameters of 1/4 angular resolution and 2X averaging<sup>1</sup>. The

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<sup>1</sup> We encourage the reader to review the FARO M70 documentation for the technical definition of these parameters

scanner also has a co-located color camera which collects panoramic imagery of the scene to colorize the point clouds.



**Figure 2. Illustration of process for framing an area of interest, placing scan locations, and extracting the high-density central 5m x 5m section.**

Multiple scans are registered and aggregated into a single point cloud using the FARO scene software. We take the central 5m x 5m square patch of the target areas to crop the point cloud. This central area has a uniform high density of measurements that is appropriate for the desired spatial resolution. A digital elevation model (DEM) and orthoimage are created representing this 5m x 5m patch. Please refer to the Data Products section for more information on how these are created.

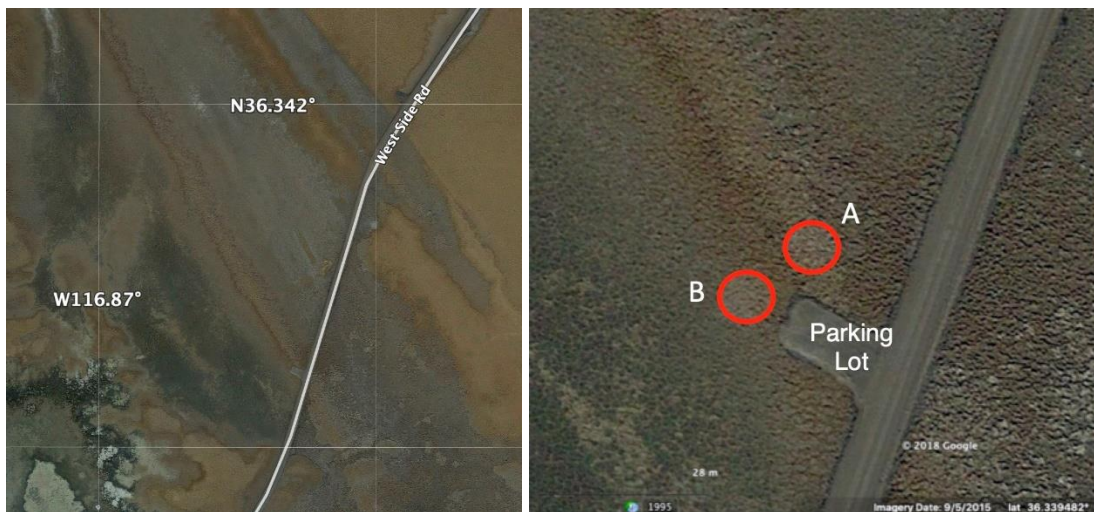
# 3 Terrain and Environment Information

Data was collected at the Devil's Golf Course site in Death Valley and the Yungay site in the Atacama Desert. A total of 11 scenes were collected across 4 unique sites. Patches collected span a range of salt, soil, and rock feature distributions.

## 3.1 Field Site: Devil's Golf Course, Death Valley

Devil's Golf Course (DGC) is composed of growing salt structures emerging/growing at varying stages of growth. This is evident from clearly observable color variations captured in the satellite imagery provided by Google Earth.

### 3.1.1 DGC Location 1 – “Parking Lot”



**Figure 3. Satellite views of the “Parking Lot” location. [Map data: Google, Maxar Technologies]**

Satellite view of this location indicates a surface supporting three different color textures. Within this broad marker we selected two regions, “Terrain D1A” and “Terrain D1B”, the former of which is representative of the grey colored terrain of the larger (10 km<sup>2</sup>) surrounding region. Terrain D1B was chosen due to its relatively darkened surface color compared to A. Note both locations are on the valley floor (-85m). North points to top of page.

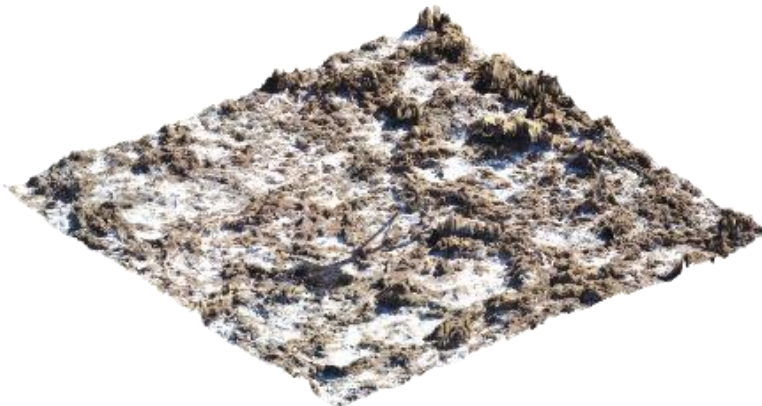


### Terrain D1A



**Terrain D1A:** Salt efflorescence with crystalline pinnacle structures 20-50 cm across. Some structural clustering observed surrounded by patches of relatively muted pinnacle development. Structures are highly porous and, in some places, show fractal overhang (not captured here). Exposed side of pinnacles appear wind eroded with some exhibiting scalloped surface textures oriented in the S-SE direction, aligned with the valley. Wind-shielded undersides of overhanging structures (not shown) are more jagged. Materials exhibiting white hues correspond to new salt growth and are relatively dry. Underneath 2-5 mm of darker surfaces reveals materials with higher moisture content. Textural quality of structures in this terrain is ubiquitous across the immediate surrounding region (at least 10km<sup>2</sup>).

### Terrain D1B



**Terrain D1B:** Salt efflorescence with crystalline pinnacle structures with maximum horizontal scale of ~20 cm and vertical scale ~10cm. Flatter muted stretches (0.5-1.5 m scale) characterized by putative cellular boundaries with budding crystalline structures. Higher standing pinnacles also preferentially manifest themselves at cellular boundaries. Whiter hue surfaces primarily contain new crystalline growth while more infrequent darker surfaces contain materials of

relatively high moisture underneath only 2-3 mm of the surface. Flatter reaches appear more eroded compared to nearby higher standing structures. By comparison, the structures in this zone appear less developed than those in Terrain D1A.

### 3.1.2 DGC Location 2 – “Salacious Crumb”

This region is characterized by flat, greyish-colored flat dry ponding zone with no relief, which we call “Salacious Planitia” (SP). The region was selected because the presence of the road (Westside Road, “WR”), located on its southern border, influences the manner in which freshly emplaced rain runoff ponds and, subsequently, the character of emergent salt efflorescence to develop on either side of WR. Four zones were selected surrounding SP maximizing variety of textural appearance from this satellite imaging.



**Figure 4. Satellite views of the “Salacious Crumb” location. [Map data: Google, Maxar Technologies]**



### Terrain D2A



**Terrain D2A:** Salt efflorescence with crystalline pinnacle structures. Two categories of pinnacles occur with smaller (5cm) scale relatively fresh structures with comparatively raised larger 5-10cm vertical scale. This particular zone exhibits size segregation with its one half-side, showing smaller units that are white (fresh), boundary separated from its other half-side supporting greyer-tanner more raised structures. Individual pinnacles that appear to merge into one another to form the rim of 20-40cm scale putative cellular structures. The centers of cells are generally relatively flattened and appear like pits, with occasional presence of fresh salt growth within. The emergent structures appear more mature compared to those found in Terrain D2B.

### Terrain D2B



**Terrain D2B:** Salt efflorescence with crystalline pinnacle structures. Two categories of pinnacles occur with smaller (5cm) scale relatively fresh structures with comparatively raised larger scale 5-15cm scale, the latter of which are found along raised ridgelines. All structures show relatively low porosity and little to no fractal overhang. Ridgelines appear as broken-up surface units. Cellular structuring indicate preferred locations of salt growth. Greyish units contain more moisture beneath 2-3mm of surface compared to tan units which are practically dry. Dark units

exhibit intricate climb-like pinnacle growth compared to tan units, which show rounding. Centers of cells relatively planar and tend to support fresh salt growth (very white features). Very little (if any) fresh salt growth is observed on pre-existing growth on or near cell boundaries. Raised ridgeline may have been initiated by off-road vehicle.

### Terrain D2C



**Terrain D2C:** Salt efflorescence with crystalline pinnacle structures. Found within a raised section of SP (north or WR). Mostly muted terrain is white colored (relatively fresh) pinnacle structures with typical horizontal scales  $\sim$  30-35 cm and rising only 5cm. Moisture level is high beneath 2-3 mm of surface. Note proximity to nearly flat and relatively high moisture content of SP. Surface textures show small scale (few cm) wind-eroded ridging aligned with prevailing S-SE orientation of the valley. Structures exhibit relatively low porosity with low frequency of fractal overhangs (cf., Terrain D2D). Along edge of scene prominent ridgeline can be seen about 1 m across and raised about 0.5 m where enhanced crystallization is observed to congregate.

### Terrain D2D



**Terrain D2D:** Salt efflorescence with crystalline pinnacle structures. Relatively dark colored crystalline growth is relatively wet compared to the more muted tan colored terrain found interspersed in the zone. Darker complexes also show a high degree of fractal overhang, and also in places exhibiting intricate outwardly spiraling spindly 1-5 cm growth. This zone's fractal overhang and high porosity is not observable in this DEM reconstruction and, in places, appears as 90 degree vertical cliffs. Stretches of darkened material are interspersed with relatively eroded tan colored textures like seen in previous zones. Gross features are generally 20 cm across and about 5-10cm high.

### 3.1.3 DGC Location 3 – “Badwater Basin”

Badwater Basin region is located 15km south of locations 1 and 2 and is found at the end of Salt Road. The locations to study (A+B) were chosen based on analysis of satellite images. One relatively darkened zone (A) and one relatively light zone selected (B). Satellite imagery indicates B supports hexagonal structures.



Figure 5. Satellite view of “Badwater Basin” location. [Map data: Google, Maxar Technologies]



### Terrain D3A



**Terrain D3A:** Salt efflorescence with relatively high-standing and porous crystalline pinnacle structures. Material is primarily dark (relatively wet) interspersed throughout with patches of fresh salt growth (white). Generally large amplitude growth (~20-50cm in vertical and 60-100 cm in horizontal) fill in relatively muted intergrowth “valleys” which are themselves more rolling in character compared to the flattened parts of the hexagonal zones of Terrain D3B. Fresh/nascent salt crystals (2-3cm in size) preferentially expressed on higher standing parts of structures – fewer found in valleys. Ridgeline scalloping like seen in Terrain D3B is less evident here. New salt growth exhibits more randomly structured texturing.

### Terrain D3B



**Terrain D3B:** Salt efflorescence with crystalline pinnacle structures with prominent hexagonal mesoscale structures. Region is relatively white and appears mottled with fresh salt growth. Overall structures are relatively low amplitude (<10cm) with individual secondary structures (2-5cm) growing atop primary mounds. High standing (15-20cm) growth is also observed and although these are less frequent they tend to exhibit scalloped ridging aligned with the valley’s S-SE orientation. Hexagonal patterning (~1m) shows preferential salt growth along its rims rising

up to 5cm over the mean level of the interior of the hexagon. Occasional stand-alone small axisymmetric mounds of fresh (very white – high albedo) salt growth found in otherwise flat interiors of hexagons. Spires of salt growth found either in very center of hexagons or along rims with annular stretches showing little or no growth.

## 3.2 Field Site: Atacama Desert, Chile

### 3.2.1 Atacama Location 1 – Yungay

Terrain Y1A



Terrain Y1B



### Terrain Y1C



### 3.3 Summary of Location GPS Coordinates

Terrain Name	Latitude	Longitude
<b>Death Valley 1 – Parking Lot</b>		
D1A	36.339376	-116.867822
D1B	36.339289	-116.868015
<b>Death Valley 2 – Salacious Crumb</b>		
D2A	36.329583	-116.875649
D2B	36.329482	-116.875558
D2C	36.330486	-116.875698
D2D	36.32927	-116.87539
<b>Death Valley 3 – Badwater Basin</b>		
D3A	36.28586	-116.82571
D3B	36.286346	-116.825432
<b>Atacama</b>		
Y1A	-24.079562	-69.926080



<b>Y1B</b>	-24.080482	-69.927491
<b>Y1C</b>	-24.080182	-69.927409

\*Note: GPS measurements have an accuracy of 3 meters

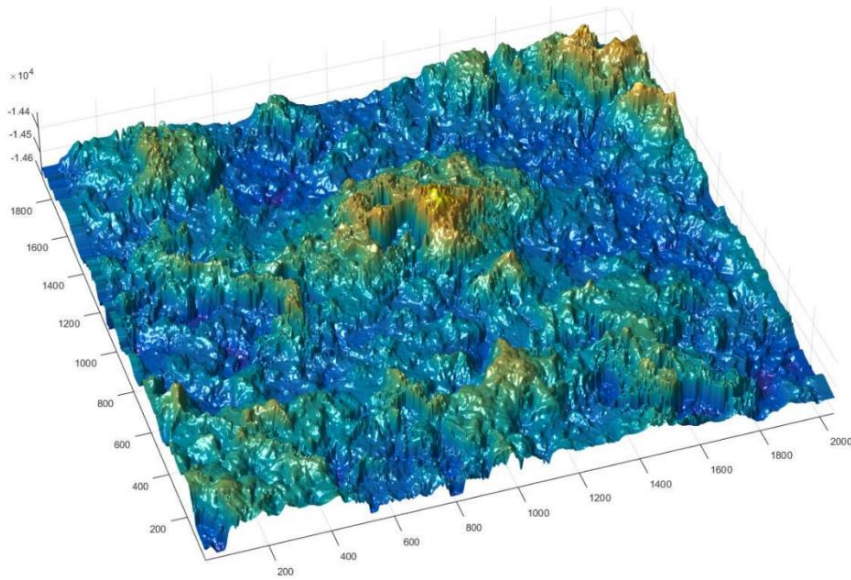
## 4 Data Products

Each terrain contains a DEM (floating point TIFF format), a registered orthographic color image (8-bit PNG format), and the raw point cloud (Matlab matfile). This data can be easily manipulated in most programming environments, but we provide information for Matlab in the table below. The DEMs and orthoimages are at 2048 x 2048 pixel resolution covering a 5m x 5m area, giving a **spatial resolution of 2.44mm between postings**. This resolution was chosen because it is a convenient value that is similar to the LIDAR's factory-calibrated range error of 3mm.

	File Type	Data Format	Units of Data Values	Matlab Import Command
<b>DEM (geometry)</b>	Floating Point TIFF	2048 x 2048 single	Meters	imread() or Tiff obj
<b>Orthoimage (color)</b>	RGB PNG	2048 x 2048 x 3 uint8	(0-255)	imread()
<b>Point Cloud (geometry + color)</b>	Matfile v7.3 / hdf5	N x 6 double	<XYZ, RGB>	load() or matfile obj

### 4.1 Processing Details

We use a multi-scale process to produce the terrain model that has been experimentally found to give the best tradeoff between noise and preservation of artifacts. The DEM and color orthoimage are created by taking the stitched point clouds, cropping them using the 5m bounding box, and projecting orthographically onto a voxel grid. The z-coordinate of the DEM aligns with the gravity vector collected by the LIDAR sensor.



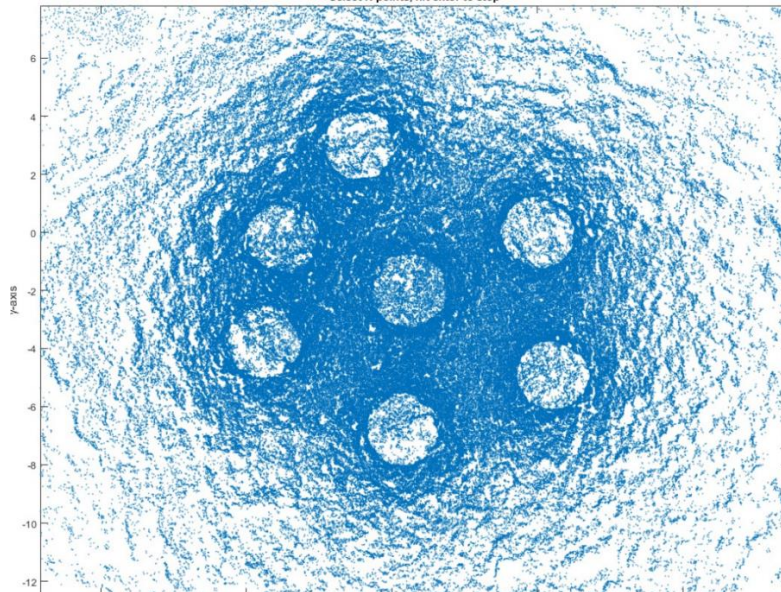
**Figure 6. Example of a DEM provided colored by height.**

Points are binned into voxel locations by spatial (x-y) coordinates using the Matlab library function `accumarray()`. The median value of the point elevations is selected as the voxel height (z), while the median value of each color channel is independently selected for RGB color. Median filtering is selected to reduce the effect of outliers on voxel data. Any holes in the DEM are filled using Euclidean distance, K-nearest neighbor interpolation, with  $K = 3$ . This process is repeated with voxel grids of dimension  $2048 \times 2048$  and  $1024 \times 1024$ . The final DEM is a weighted average of both these models at the higher resolution. Using a weighted average of two resolutions reduces association artifacts that result from binning at only a single resolution.



**Figure 7. Example of a DEM rendered with color orthoimage data.**

As they are created together, the DEM and color orthoimage are precisely registered. We provide the DEMs and color image as 32-bit floating point TIFF and 8-bit RGB PNG images respectively. The elevation values of the DEM are in units of meters and the color tuples are uint8 types in the range 0-255. **It is the user's responsibility to ensure that the DEM is scaled with the appropriate grid resolution of 2.44mm between postings** (or 5.0m specified for the X and Y dimension).



**Figure 8. Both the cropped and raw point stitched clouds for each terrain are provided. The intrinsic measurement density as well as the tripod occlusion zones are visible in this example.**

We provide the point clouds due to the known limitations of orthographic projection in creating a 2.5D DEM from a 3D point cloud, such as artifacts from overhangs and occlusions. You can use this point cloud to create your own 3D voxel or mesh representation with better preservation of features. The point cloud is stored in a matfile v7.3 (hdf5) and is a double (64-bit) matrix of dimension [N x 6]. N is variable the number of points in the point cloud and the 6 columns are [X, Y, Z, R, G, B] attributes. The cartesian coordinates are in units of meters and RGB channels range from 0-255.

## 4.2 Discussion of Possible Errors

The range/geometry data provided can include errors, primarily due to two reasons: (1) the conical measurement from a LIDAR beam and (2) orthographic projection of point measurements onto a watertight DEM. This is particularly prominent in terrains with large vertical changes or complex concave features - small concavities can be smoothed over and overhangs could turn into cliffs. Since each terrain is created by alignment of scans from multiple views using optimization, slight misalignment could cause “ghosting” of features, meaning that they are

duplicated or fuzzy. Point cloud noise that is not successfully removed from multi-scale and median filtering may show up as 1-pixel “spikes” in the DEM.

The color data is susceptible to multiple types of artifacts. Because the imagery is taken using ambient illumination, over which we have no control, artifacts may arise from combining multiple scans. The photography from each scan is affected by auto exposure and white balance which can change subtly according to the perspective and is not radiometrically calibrated. The time of data collection for five scans is approximately 1 hour, so the sun angle can change appreciably near dawn and dusk. The shadowing of the sensor and tripod are visible in some scans.

We advise the user to be cognizant of these technical limitations when using the data.

### **4.3 Dataset Extras**

The raw, uncropped point clouds are also provided that have been stitched directly from the scans. This data is provided as-is, so that the user may study a wider region or create new data products, without guarantee of data density or accuracy.





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# FROST Dataset

Features Relevant to Ocean Worlds Surface Terrain

[\[Attribution\]](#) [\[Acknowledgements\]](#) [\[Support\]](#) [\[Download Primary Dataset\]](#) [\[Download Extras\]](#)

## Summary

We present an analog dataset that provides examples of possible terrain features, geometry, and appearance at the 1-10cm scale on ocean worlds/icy moons such as Europa, Enceladus, and Pluto. The motivation for collecting this dataset was a lack of available high-resolution digital models suitable for development of surface missions to these bodies (circa 2019), including use for simulation of mechanics, sampling, and imaging. We took advantage of NASA field opportunities to Death Valley, California and the Atacama Desert, Chile in order to observe and record analog sites.

Data was collected at the Devil's Golf Course site in Death Valley and the Yungay site in the Atacama Desert. Areas of interest were preselected from satellite views with final terrain selections made in person. A high-resolution laser scanner (with built-in color camera) was used to survey each area with a multi-view scan pattern to minimize occlusions. The highest resolution centroid of each survey's point cloud was then cropped to create 5m x 5m digital elevation models (DEMs) of terrain at 2.5mm resolution. A total of 11 scenes were collected across 4 unique sites. Patches collected span a range of salt, soil, and rock feature distributions.



**Keywords:** Dataset, ocean world, icy moon, 3D, LIDAR, DEM, point cloud, terrain, lander, Europa, simulation, robotics

**Changelog:**

## Attribution

The FROST Dataset was produced through the work of the OceanWATERS simulation team in the [Intelligent Systems Division](#) at the NASA Ames Research Center.

### Citation:

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## Acknowledgements

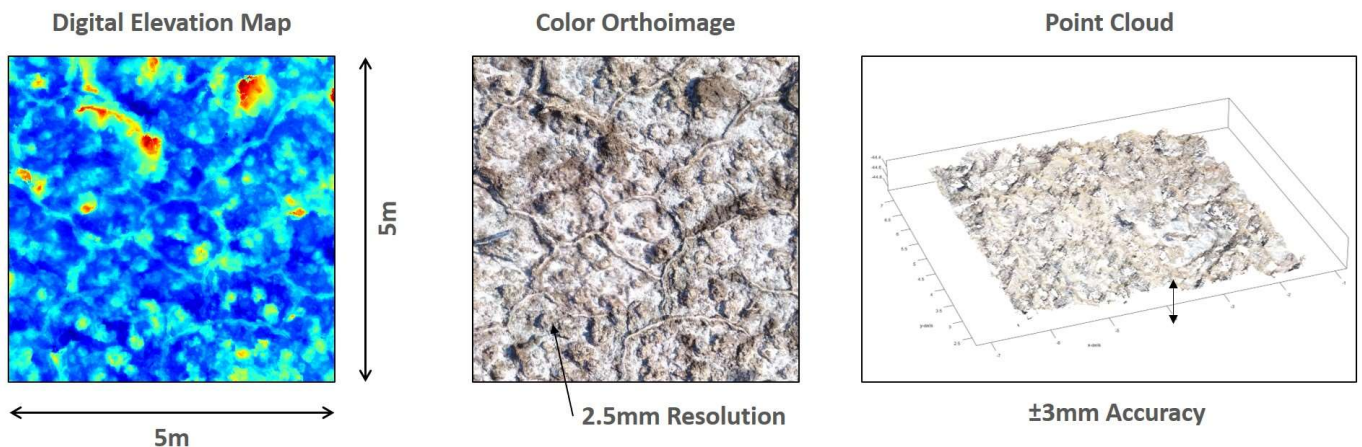
This work was funded by the Planetary Exploration Science and Technology Office in the NASA Science Mission Directorate as a part of the development of the OceanWATERS simulator.

We would also like to thank Thomas Stucky and the rest of the OW team for advice and support.

## Support and Documentation

**Download** the complete dataset documentation [[.pdf](#)].

Each terrain contains a DEM (TIFF format), a registered orthographic color image (PNG format), and the raw point cloud (Matlab mat file). The DEMs and orthoimages are at 2048 x 2048 pixel resolution covering a 5m x 5m area, giving a spatial resolution of 2.5mm between postings. This resolution was chosen because it is a convenient value that is similar to the LIDAR's intrinsic range error (3mm). We provide the point clouds due to the known limitations of orthographic projection in creating a 2.5D DEM from a 3D point cloud, such as artifacts from overhangs and occlusions. You can use this point cloud to create your own 3D voxel or mesh representation, for example.



For questions about the dataset, contact: Dr. Uland Wong <uland **dot** wong **at** nasa **dot** gov> or Dr. Orkan Umurhan <orkan **dot** m **dot** umurhan **at** nasa **dot** gov>.

## Primary Dataset

**Download** the entire dataset here [[.zip](#), 11.5 GB] or download individual parts below.



## Death Valley Location 1 - "Parking Lot"

Terrain D1A



Terrain D1B



**Description:** Satellite view of this location indicates a surface supporting three different color textures. Within this broad marker we selected two regions, "Terrain D1A" and "Terrain D1B", the former of which is representative of the grey colored terrain of the larger (10 km<sup>2</sup>) surrounding region. Terrain D1B was chosen due to its relatively darkened surface color compared to A. Note both locations are on the valley floor (-85m).

**Download:** [.zip]

## Death Valley Location 2 - "Salacious Crumb"

Terrain D2A



Terrain D2B



Terrain D2C



Terrain D2D



**Description:** This region is characterized by flat, greyish-colored flat dry ponding zone with no relief, which we call "Salacious Planitia" (SP). The region was selected because the presence of the road (Westside Road, "WR"), located on its southern border, influences the manner in which freshly emplaced rain runoff ponds and, subsequently, the character of emergent salt efflorescence to develop on either side of WR. Four zones were selected surrounding SP maximizing variety of textural appearance from this satellite imaging. [Map data: Google, Maxar Technologies]

**Download:** [.zip]



### Death Valley Location 3 - "Badwater Basin"

Terrain D3A



Terrain D3B



**Description:** The Badwater Basin region is located 15km south of locations 1 and 2 and is found at the end of Salt Road. The locations to study (A+B) were chosen based on analysis of satellite images. One relatively darkened zone (A) and one relatively light zone selected (B). Satellite imagery indicates B supports hexagonal structures.

**Download:** [.zip]

### Atacama Desert Location 1

Terrain Y1A



Terrain Y1B



Terrain Y1C



**Description:** Data was collected in the Atacama desert south of Yungay. Three samples were taken constituting rough salt growth (A), smooth growth (B) and no growth(C).

**Download:** [[.zip](#)]

## Dataset Extras

### Uncropped Scans of Terrain

**Description:** The raw point clouds from the laser scans cover a large area (>30m from each scan point), 5 or more scans from each location are registered to create a unified point cloud, of which a central 5m x 5m square is cropped. This download link provides the all of the uncropped scan data in an as-is manner. Because of the measurement density fall-off with range, a spatial resolution of 2.5mm is not guaranteed.

**Download:** 16 MB [[.zip](#)]

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Curator: Intelligent Robotics Group

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