PRE-STORM DUNE VOLUME & THEIR RELATION TO DUNE BREACH LOCATIONS IN MANTOLOKING, NJ, DURING SUPERSTORM SANDY

By

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ABSTRACT OF THE THESIS

PRE-STORM DUNE VOLUMES & THEIR RELATION TO DUNE BREACH LOCATIONS IN MANTOLOKING, NJ, DURING SUPERSTORM SANDY

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On October 29th, 2012, Superstorm Sandy breached the dune system in the Borough of Mantoloking, New Jersey, in particular locations. In this thesis, LiDAR-based morphological pre-storm data of the specific borough on the barrier island are analyzed.

This assessment was carried out by segmenting the dune system perpendicular to the shoreline starting from north at Curtis Point Drive to further south at Carrigan Place. Multiple cross sections were created in order to identify the location and elevation of the dune crest. To enhance and better understand the results with respect to height, the volumes of dunes were calculated as well. The latest, year-2010 LiDAR data was used as the baseline to perform the analysis, and the Quick Terrain Modeler Version 8.0.0 was used as an exploitation tool.

Morphometric parameters estimated from the LIDAR data, explain the

presence of a general relationship between the initial breaching and the dune morphology. Results show that the initial breaching probably occurred where the complex was low either in height or volume and therefore the overwash from the storm surge removed nearly the entire dune complex.

A more consistent construction and/or better maintenance program could possibly help make the dune system more uniform along the shoreline and help diffuse the energy and reduce the total damage. A regular monitoring of the morphometric parameters of a dune system using LiDAR could also provide an “early warning” to the process of shoreline management.

Acknowledgements

This thesis would not have been possible without the support and encouragement of many people who generously contributed their time and knowledge.

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To professors: Jie Gong and Steven Medlar for serving on my thesis committee and providing valuable comments and suggestions. Special thanks are also extended to Dr. Jie Gong for his help with introduction of LiDAR data and software.

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1. Introduction

At the end of October 2012 the most destructive, costly and deadliest Hurricane of the Atlantic Hurricane Season was recorded. Post-Tropical Cyclone Sandy made landfall on October 29th, 2012 near Brigantine on the coastline of New Jersey, almost a year after Hurricane Irene. Sustained winds from landfall of Sandy were reported at an intensity of 50 to 64kt (about 60 to 75 miles per hour). Then the cyclone turned toward to west-northwest and gradually weakened while moving to southern New Jersey, northern Delaware and southern Pennsylvania.

Sandy's storm surge in addition to the large beating waves destroyed large portion of New Jersey shoreline. The extent of the catastrophe along the coastline and especially the one occurring in Monmouth and Ocean Counties was unprecedented. The aftermath of Sandy was thousand of house washed away from their foundation, whole communities inundated under water and debris and boardwalks totally destroyed. The destruction in the community of Mantoloking features the severity of the storm surge and waves across the New Jersey coastline. Three inlets were cut across the barrier island, showing this way the power of the storm surge.

Mantoloking is a borough in Ocean County, New Jersey and it is situated on the Barnegat Peninsula, a barrier island that separates the Atlantic Ocean and the Barnegat Bay. Figure 1 shows the exact location of the Borough in Google maps. Sediment composition is fine to medium fine quartz sand and now after the Superstorm a considerable amount of debris, from the storm surge, has mixed with the sand.

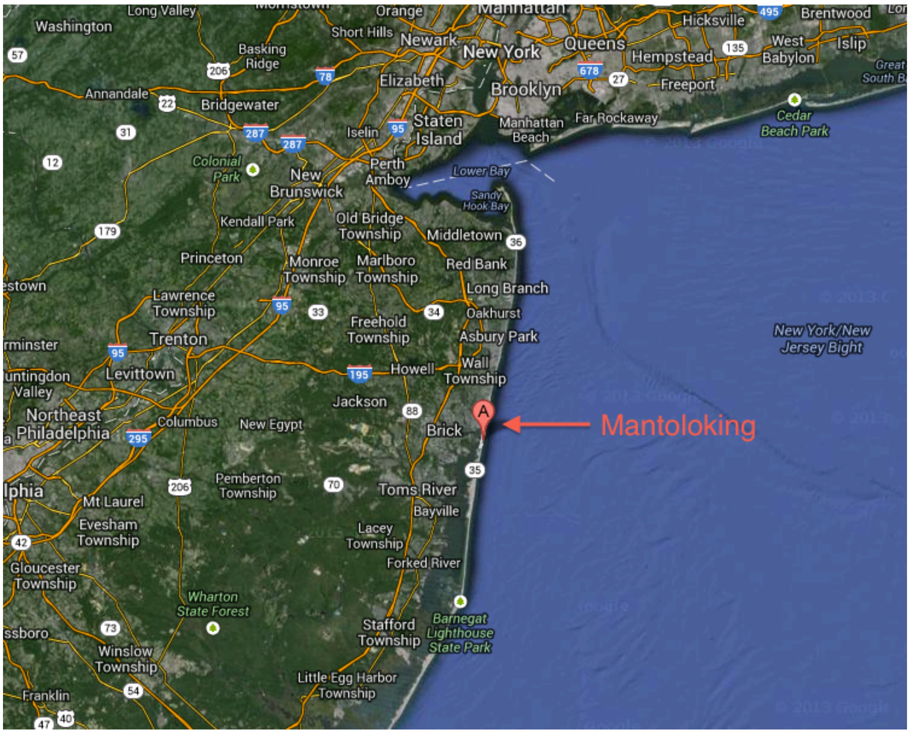

Figure 1: Location of Mantoloking, NJ, Source: Google Maps

The foredune system is an essential natural form of protection against storm damage to rest of the barrier island and especially for the borough of Mantoloking. The foredune system while protective it can be quite susceptible to storm surge and waves especially at areas where lower elevations or discontinuities exist.

The sand dune system in Mantoloking was breached at particular locations. The post-storm aerial image of the New Jersey coastal town shows that at the Mantoloking Bridge (Herbert Street) a new inlet was cut across the barrier island, connecting the Atlantic Ocean and the Barnegat Bay. A couple feet north form this breach, at 1117 Ocean Avenue a smaller was observed as well, while further north at Lyman Street one more breach was observed.

The aim of this research is to examine spatial variation of the height and volume of the pre-storm dune system and to identify a possible linkage between the weak points of the dune system and the breach locations. Figures 2 and 3, show the before and after aerial image of the Borough of Mantoloking.

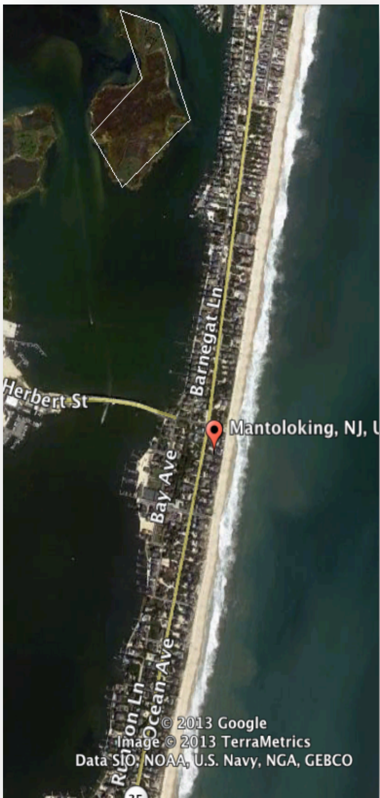

Figure 2: Pre-Storm Aerial Photo of the Borough of Mantoloking, Source: Google Earth

Figure 3: Post-Storm Aerial Photo of the Borough of Mantoloking, Source: NOAA Remote Sensing Division

2. Background on Dunes

2.1 Sand Dunes

Dunes are hill-like sand formations created by wind or water flow. They form when sand particles are transferred into a protected area behind an obstacle. Dunes exist both in coastline and inland. Inland dunes are related with ancient lake or sea levels. There are several different types of dunes based on their size and shape. Every sand dune has a windward or seaward slope, a crest, a slip face and leeward slope. A common formation of a dune is a mound with a longer side wind or seaward and a shorter side leeward (USGS, 1997)

Different shapes of sand dunes are (USGS, 1997)

- Crescentic or transverse: most common forms of dunes created from a principal wind. They are considered wide instead of long arrangements.
- Linear: Straight dunes, often in parallel ridges.
- Reversing: Dunes created from winds, which reverse periodically.
- Star dunes: Shaped as pyramid and the have three or more sides.

Types of dunes are (USGS, 1997):

- Coastal Dunes: Products of the ambient coastal processes and vital part of the beach–dune system.
- Sub-aqueous Dunes: Dunes formed by strong currents beneath the water. Common in ocean, rivers and estuaries.

- Lithified Dunes: Compacted and hardened dunes.

This thesis, research focuses on coastal dunes and their geomorphological features so a better understanding of their characteristics and how the perform under erosion will be gained.

2.1.1 Coastal Sand Dunes

A dune according to the New Jersey Department of Environmental Protection is defined as:

"A dune is a wind or wave deposited or man-made formation of vegetated or drifting wind blown sand, that lies generally parallel to, and landward of the beach, and between the upland limit of the beach and the foot of the most inland dune slope. Dune includes the foredune, secondary and tertiary dune ridges, as well as man-made dikes, where they exist. Formations of sand immediately adjacent to beaches that are stabilized by retaining structures, and/or snow fences, planted vegetation, and other measures are considered to be dunes regardless of the degree of modification of the dune by wind or wave action or disturbance by development. A small mound of loose, wind blown sand found in a street or on a part of a structure as a result of store activity is not considered to be a dune."

The definition is included in the Coastal Resource and Development Policies (N.J.A.C. 7:7E-1.1).

Coastal dunes are considered a vital component of coastal and flood defenses. They are the ecological transition between the beach and the protected area behind them. For the purpose of coastal engineering and management, coastal dunes, beaches and offshore bathymetry are considered an integrated coastal system.

As it is mentioned in the definition, different types of dunes exist within a coastline. However, the most important geomorphological feature is the foredune (Figure 4).

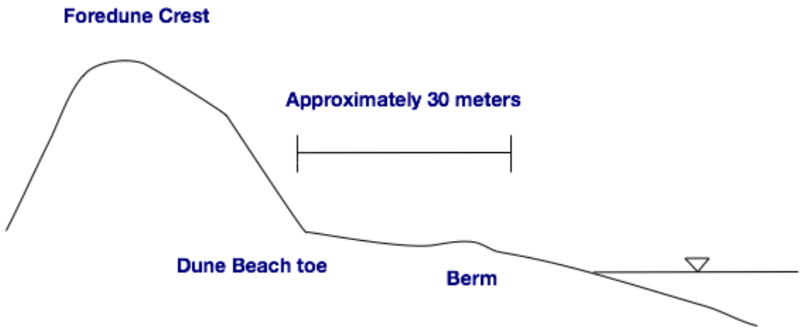

Figure 4: Coastal Foredune

Foredune is the first dune inland and above the beach line, which changes constantly with the storm intensity. It interacts dynamically with winds, waves and currents, and therefore it is in a constant exchange of sand with the beach and offshore system. This dune-beach profile is the basic sand-sharing system. Changes in energy level and in mobilization of sand from the one portion to another can change the status of the beach-dune-bathymetry system. In a classic closed system each element periodically stores and loses sand in a trade of sediment. The following Figure 5 describes the stages of exchange of sand in a dune system.

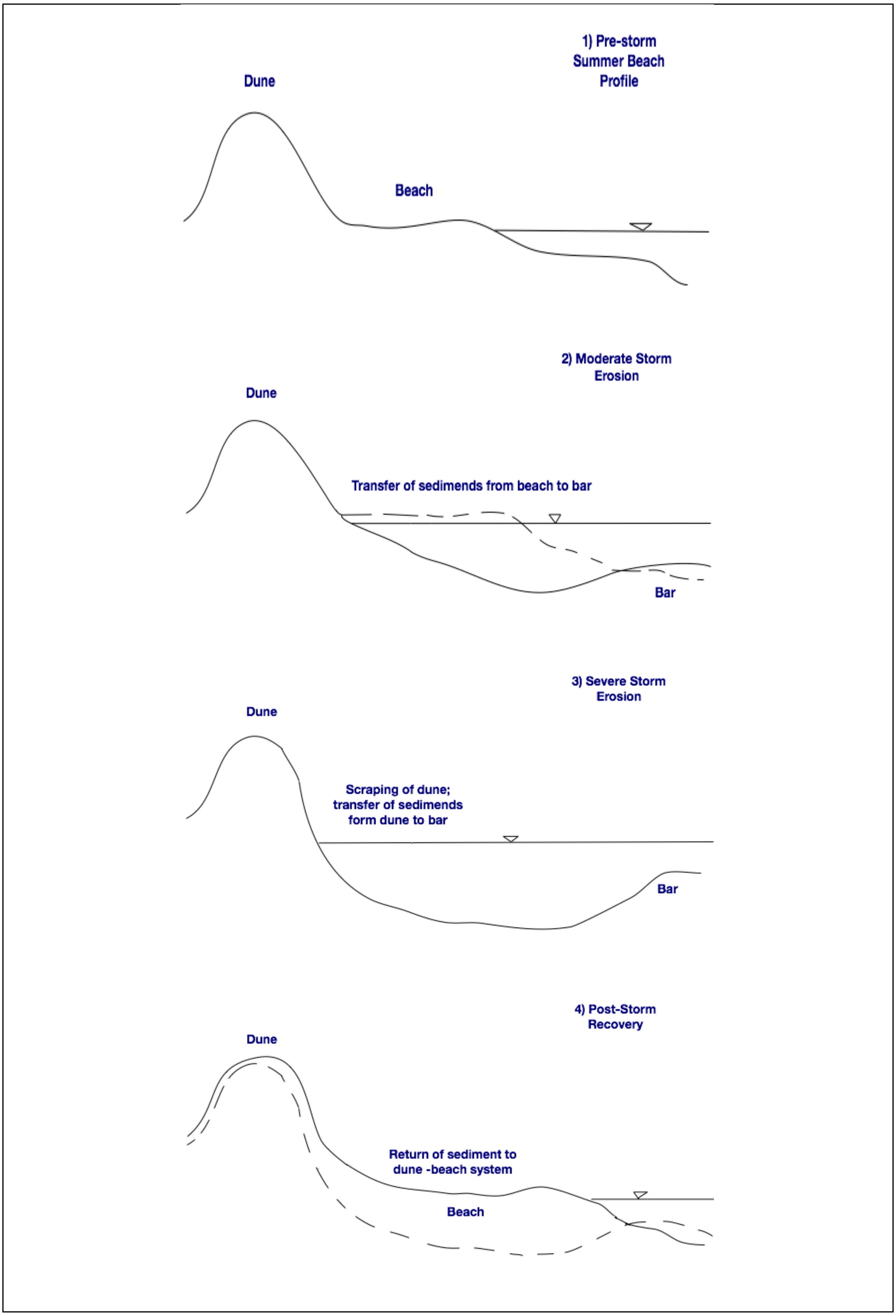

Figure 5: Stages of Dune-Beach System Sand Sharing With Offshore, (Modified from (Psuty & Ofiara, Coastal Hazard Management, 2002))

Some of the most important characteristics are described below:

Characteristics of a Coastal Dune

1. Dune Height

The height of a dune depends on the erosion rate, the weather conditions, vegetation, human interaction and accessibility of sand. In New Jersey the mean height is approximately 8-15ft above the beach (Psuty & Ofiara, Coastal Hazard Management, 2002). Hamer, Cluster and Miller,(1992) reported that under ideal circumstances of sufficient quantities of sand, vegetation cover and fences, the dune height can increase approximately 4ft per season. In reality the increase of dune height per season is close to 2ft (Psuty & Ofiara, Coastal Hazard Management, 2002).

2. Dune Slope

The dune slope is affected from the same variables as the dune height. It was measured that in New Jersey coastal dunes were 20 times as high as wide (Gares, Nordstrom, & Psuty, 1982). Other measurements showed that in New Jersey and Long Island dunes were constructed to be 7 to 10 times as wide as high (Psuty & Piccola, Foredune Profile Changes, Fire Island New York, 1991). So it is safe to assume that the ratio of slope could be from 1 to 3.5-5.0 (Psuty & Ofiara, Coastal Hazard Management, 2002)

3. Dune Placement

The position of a dune plays a critical role and is directly related to its ability to withstand storms. The optimal location spot for a dune is sufficiently inland and away from the storm tide position. The further away the dunes are from the sea, the weaker the erosion from the storm will be. Commonly, a dune will survive a 5-year storm if it is located 100ft from the sea line and the beach in front of it has a berm of 5ft (Psuty & Ofiara, Coastal Hazard Management, 2002)

Mechanisms of Stabilization of Sand Dunes

Vegetation is a natural mechanism that steadies the accretion of sand in the dune system. There are certain types of grasses that they can survive the extreme condition of a coastline. Some of them are sea rocket, dune cordgrass, seaside goldenrod and the popula ammophila breviligulata. Apart from the natural traps, sand can also be trapped from fences. Sand fences are costlier and stabilize sand slower than vegetation. Sand fences should be placed 100ft from the mean high tide parallel to the shoreline and most commonly in just a single line. Both vegetation and sand fences work in the same manner. They reduce the speed of the wind with resulted in the sand drop at the lee of the fence or between the vegetation.

Erosion of Coastal Dunes from Storm Surges

Understanding of the processes of coastal dune erosion is very important. Dunes share the erosion with the beach in terms of loss of mass and volume. Dunes as well as beaches are shifted inland under erosion condition. In natural areas wind and waves will change the position of the beach-dune system but the characteristics of it will remain almost the same. Under major storms, the erosion is too severe and the dune system is too difficult to survive. The Federal Emergency Management suggests that dunes should be designed according to 100-year storm (water level occurring once every hundred year). They recommend that the dune area above the 100-year flood level require a sand reservoir area of 540ft^2 (FEMA, 1995).

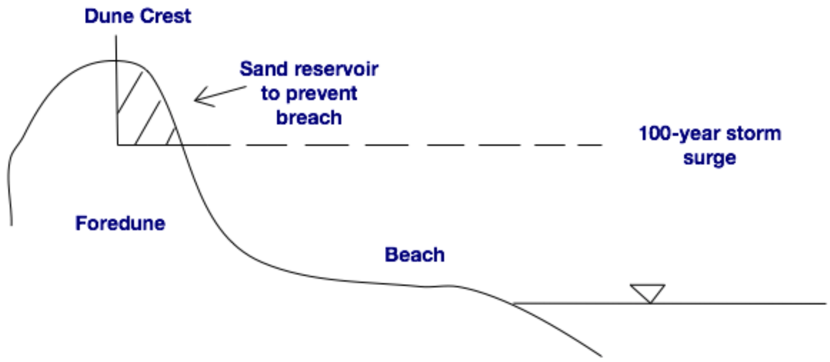

Figure 6: FEMA's Sand Reservoir Area (Modified from (Psuty & Ofiara, Coastal Hazard Management, 2002))

The coastal dunes and especially the foredunes are the first line of defense on a barrier island. The effect of a storm varies not only on the characteristics of the storm, such as the surge and the waves, as well as the elevation of the dunes. Dunes with low elevation are more susceptible than dunes with higher elevation. Sallenger, (2000) noted that the ability of storm surge to overwash a barrier depends on five factors, which are storm surge elevation, storm-wave set-up, wave height, swash run-up and dune height. In fact, some relations were drawn between the storm-induced water levels, R_{high} and R_{low} and the elevation of dune crest and toe, D_{high} and D_{low}, respectively. R_{high} and R_{low} can be found by the following empirical equations:

$$R_{high} = R_{2\%} + \eta_{mean}$$

Where η_{mean} is the mean sea level, which includes astronomical tides and storm surge, and $R_{2\%}$ shows the 2% exceedence of runup (Holman, 1986). $R_{2\%}$ includes both wave setup and swash height and it is given by the following equation:

$$R_{2\%} = H_o(0.83\xi_o + 0.2)$$

Where ξ_o is the Iribarren number, $\xi_o = \beta\ (H_o/L_o)^{½}$, with b to stands for the local beach slope, H_o deep-water wave height and L_o deep-water wave length.

R_{low} represents the "low" runup elevation, from which the biggest part of the beach is subaqueous. The R_{low} is given from the following equation:

$$R_{low} = R_{high} - S_{2\%}$$

Where $S_{2\%}$ represents the exceedence swash amplitude, (Holman, 1986), and it is equal to: $S_{2\%} = H_o(0.85\xi_o + 0.06)$

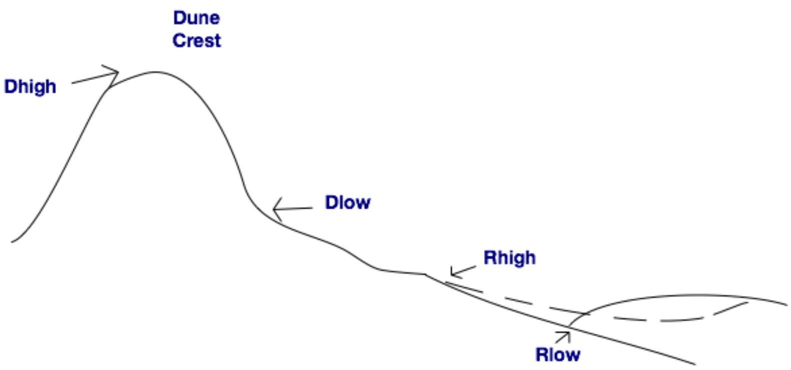

Figure 7: Dune-Beach Profile Showing The Crest (D_{high}) Used to Define The Landward Limit of The Beach System (Modified from (Sallenger, 2000))

Four storm impacts regimes that were defined from Sallenger, (2000) are:

Swash: Total water levels lower than the dune toe ($R_{high} < D_{low}$)

Collision: Total water levels exceed the dune toe ($D_{low} < R_{high} < D_{high}$)

Overwash: Total water levels exceed the dune crest ($R_{high} > D_{high}$)

Inundation: Storm surge and the tide exceed the dune crest ($R_{low} > D_{high}$)

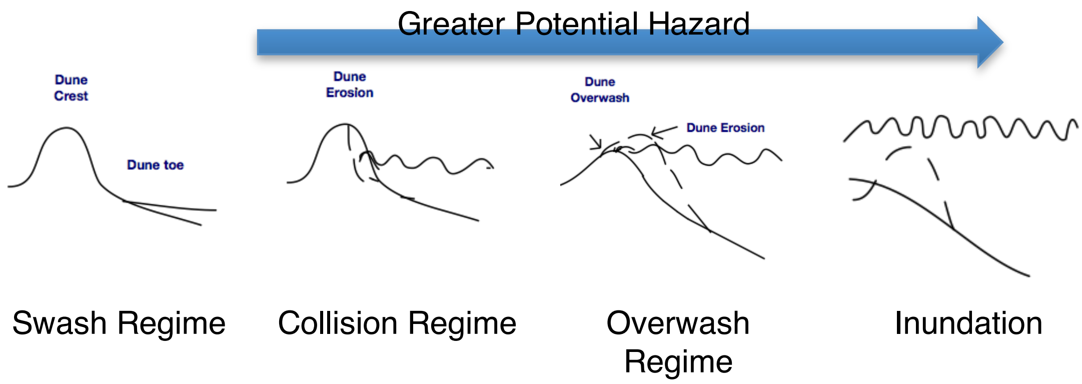

Figure 8: Dune System Regimes Under Storm Surges, (Modified from (Sallenger, 2000))

However, there are some factors that increase dune survival. Some of them are vegetation density, dune continuity, dune system width and barrier island width (Claudino-Sales, Wang, & Horwitz, 1987).

Sometimes a washover deposit helps preserve the mass of the barrier island (Stone, Liiu, Pepper, & Wang, 2004) while Donnely (2006) stated that washover sediment count as a decline in the coastal sediment budget. In fact, by lowering the dune height the risk of having susceptible areas increases.

In New Jersey, there are two major reasons provoking erosion. One is the continue sea level rise and the other is the ongoing development along the shoreline. As the sea level rises and the development gets larger the beaches are getting narrower close to the ocean. It is obvious that along the coastline of New Jersey the development does not provide enough space for dunes so they can cultivate and function as a defensive feature.

Restoration and Maintenance

Dunes are a valuable coastal resource and their dimensions should be maintained and restored. One way to maintain it is to limit the human disturbance by installing pathways or fences. Especially the pathways, it is advised to be elevated in order to avoid becoming locations susceptible to breach. Also, the vegetation, which is a vital component for a dune, should be sustained either by continuous planning or fertilizing. Monitoring programs should be established in order to control periodically the dunes systems and their restoration. A monitoring program should be implemented before storm periods.

In New Jersey almost all the coastal communities that have dunes system, follow ordinance of maintenance and restoration. Many of these ordinances were legislated after the nor'easter of '62. In the past years the ordinances have become better. Mantoloking also have its ordinances for the dune system, which will be described in the next section.

2.2 Coastal Dunes in the Borough of Mantoloking

Mantoloking is well known to have one of the best dune systems in New Jersey. Within the Borough the beach-dune system is the most essential flood hazard safety structure. So, it is vital for the borough to control the shape and location of the dune. Dune Ordinance #407 provides standards and criteria for the preservation and maintenance of dune elevation and shape. Also it implements certain principles for the dune vegetation cover, installation and maintenance of walkways, sand fencing etc. The dunes in the Brought of Mantoloking are private property and therefore its homeowners must comply with the ordinance. In this study the ordinances that are concerned the most are the ones with respect to the height, general shape and location of the dynes. According to the Ordinance #407 it is desirable to have a continuous dune system with respect to the scrap line of ’92. The scrap line of ’92 was formed after the severe storm on 11th and 12th of December in 1992. After the storm of 1992 the dune line was eroded approximately 60 feet. Since then the scrap line of ’92 was mapped at the Borough of Mantoloking to be used as a reference. The standards that were established for the dune system in Mantoloking are (Mantoloking, 1999):

- A seaward edge of the dune should be 25 to 35 feet seaward of the scrap of ’92.
- The slope (width:height) of a dune should be 5:1 or less.
- The minimum dune height should be 18 feet at prevailing dune Crestline.
- A minimum elevation between the Crestline and 25 feet distance westerly of the scrap ’92 should be 16 feet.

Dune ordinances have been strengthened, even more by the presence of a dune consultant. The Borough has added a new provision to its ordinance in which all walkways to the beach must be elevated over the dunes. This provision is important as overwash is directly linked to walkthroughs and street openings.

3. Background on Superstorm Sandy

In the western Caribbean Sea a tropical wave that left the west coast of Africa on October 11th formed Sandy. On October 22th and in a time interval of six hours it was developed to Tropical Storm Sandy. Toward Great Antilles it was transformed to Hurricane Sandy. On October 25th Hurricane Sandy got his highest potency and it was upgraded to category 3 while it was over Cuba. Hurricane Sandy weakened to a tropical storm once passing through Bahamas and then gradually turned toward northeast. Its speed increased and regained its strength on October 27th, which transformed it to a category 1 Hurricane. Later on October 29th, while it has passed hundreds of miles southeast of North Caroline, it weakened again to a post-tropical cyclone and made its landfall on the Coastline of New Jersey near Brigantine at about 2330 UTC, (Blake, Kimberlain, Cangialosi, Berg, & Beven II, 2013). Figure 9 shows the path of the storm.

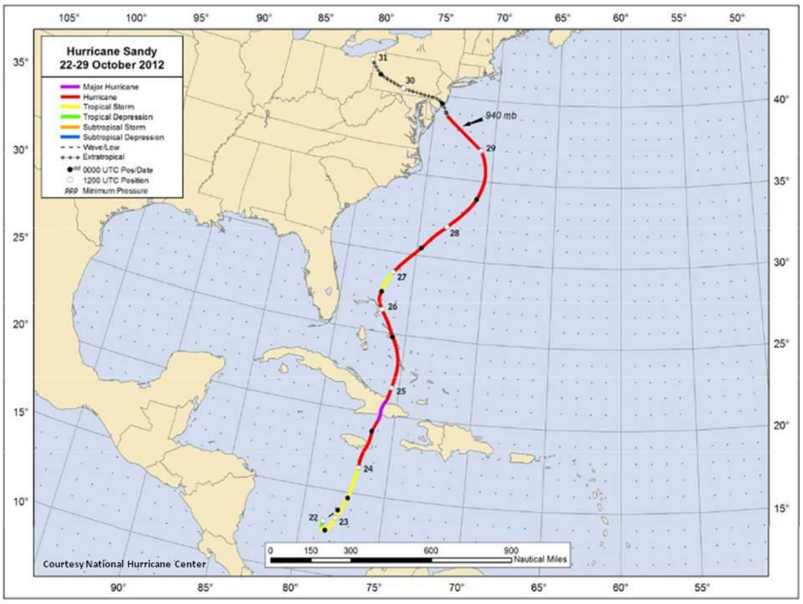

Figure 9: Track positions for Sandy, October 22-29, 2012. Source: NHC TCR

Sandy apart from its wind and low pressure causes the water to rise from the coast of Florida northward to Main. The highest water levels and powerful damaging waves were observed along the coastline of New Jersey, New York and Connecticut.

3.1 Water Levels

3.1.1 Storm Surges

According to National Hurricane Center a storm surge is defined as:

"*An abnormal rise in sea level accompanying a Hurricane or other intense storm, and whose height is the difference between the observed level of the sea surface and the level that would have occurred in the absence of the cyclone*."

It is the change above the predicted astronomical tide and because is the change among water levels it does not have a reference level. The main cause of a storm surge is the high winds from a Hurricane or a storm that pushes the water surface of an ocean. In general, where maximum winds are blowing near shore due to a Hurricane storm surges are provoked. Other secondary reasons are the bathymetry and the low pressure at the center of the weather system, (NOAA, 2013).

Almost all locations along the East and Gulf Coast are susceptible to storm surge. During Sandy along the coastline of United States the storm surge was formed due to low pressure and the northeasterly winds.

In New Jersey the storm surge with the highest value was measured by the tide gauge at Sandy Hook at 8.57ft, above normal tide level. This was the last measurement before the gage collapsed. It is possible that higher storm surges occurred after the gauge collapsed. (Blake, Kimberlain, Cangialosi, Berg, & Beven II, 2013). Tide gauge at Rockaway Inlet near Floyd Bennet Field in New York measured a peak storm surge at 11.75ft above NGVD 1929.

3.1.2 Astronomical Tides

Astronomical tides are the rise and the fall of the sea level as a result of the gravitational forces of the earth, moon and sun. The gravitational forces of the earth, they act as internal so they hold the water to earth surface while the gravitational forces of the moon and the sun act as external and they force the water to deform from its equilibrium shape.

Astronomical high tides coinciding with the landfall of Sandy contributed to even higher water levels. The tides observed on October 28th-29th were some of the highest of the year 2012. Sandy Hook tidal gage has mean tidal range of 4.7 feet and mean diurnal range of 5.22 feet (NOAA tide station 8531680) and it was observed to have at tide height of 10.42 feet above the NAVD88 datum. (Blake, Kimberlain, Cangialosi, Berg, & Beven II, 2013)

3.1.3 Inundations

The total water level that happens on dry ground as a result of the storm tide is inundation. Inundation is expressed in terms of height above ground level. At the shoreline, normally dry land is approximately described as areas higher than the Mean Higher High Water (MHHW) or normal high tide line. One of the most catastrophic inundations was recorded along the Jersey Shore. Entire blocks of houses in Monmouth and Ocean Counties were washed away.

In the following Table 1, inundations were measured through high watermarks.

Monmouth and Middlesex Counties	4-9feet
Essex and Bergen Counties	2-4feet
Union and Hudson Counties	3-7feet
Atlantic, Burlington and Cape May Counties	2-4feet
Ocean County	3-5feet

Table 1: Inundation levels in Some Counties of NJ

The highest watermark was measured at Sandy Hook at the value of 8.9ft in the U.S. Coast Guard Station on Sandy Hook. This high-water mark coincides with the data taken from the nearby NOS tide gauge just before it fails. (Blake, Kimberlain, Cangialosi, Berg, & Beven II, 2013)

3.1.4 Water Levels Along the Atlantic Coast-NYHOPS

It was noticed that the maximum water levels were away from the center of the eye of the Tropical Cyclone Sandy. The wave run-up on top of the storm surge and the high tide provoke record setting water levels along the coastline of New York, New Jersey and western Connecticut.

The New York Harbor Observing and Prediction System (NYHOPS), (Stevens Institute of Technology, 2006), enables the user to have access in real-time assessment of ocean and weather conditions in New York Harbor and New Jersey Coast Region. In this thesis, special focus was given on region of Atlantic Coast of New Jersey. This area was chosen because it contains the coastline of the Borough of Mantoloking. This program predicts the water level and wave field every hour along the coastline. The water level that is calculated contains the storm surge level and the tide level while the wave field only includes the wave height. By visualizing the measurements, starting from the 28th of October 2012 and ending at 30th of the same month it was noticed that the highest total water level = tides + storm surges + waves, was at the 29th at 19:00 to 20:00 EST, (Figures 10 and 11 show the water level and wave field respectively). Water elevation reached as high as 22ft from MSL during the Superstorm Sandy. Because all of the terrain elevations presented here were measured with respect to NAVD88 datum, the water elevation had to change with respect to this datum. Information derived from the National Oceanic and Atmospheric Administration's (NOAA), tidal gages indicated that the conversion from MSL to NAVD 88 was a small change of 0.21ft. So the water elevation regarding NAVD 88 was a little bit higher than 22ft.

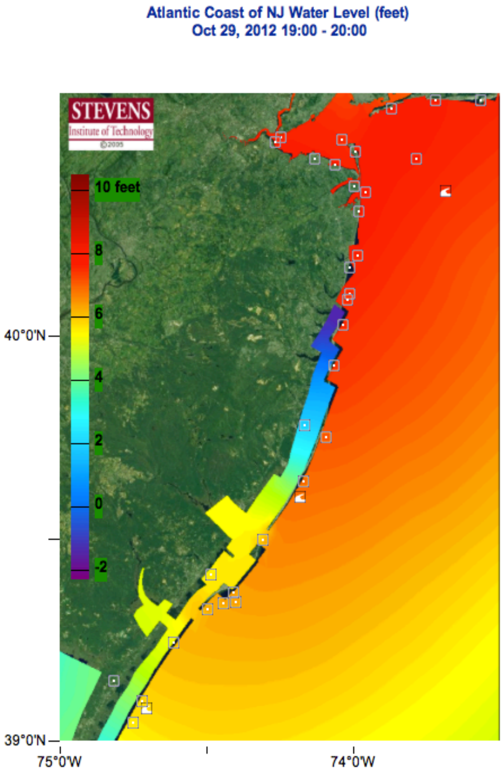

Figure 10: Water Level Atlantic Coast, 09/29/13, Source: NYHOPS

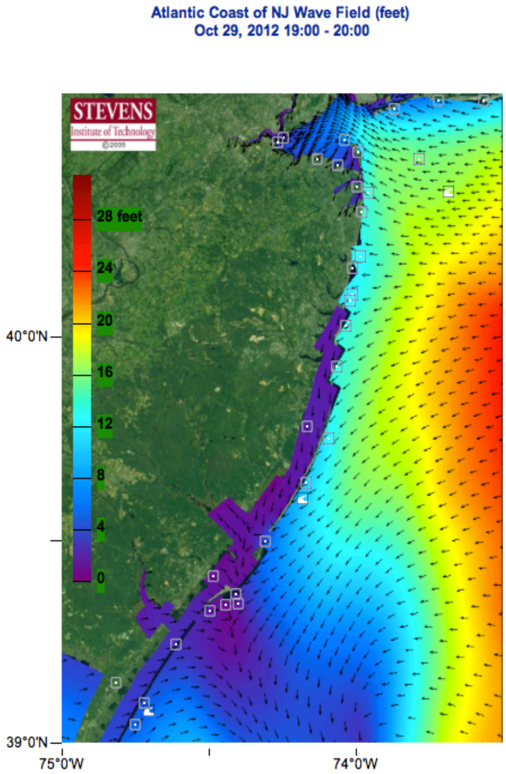

Figure 11: Wave Field Atlantic Coast, 09/29/13, Source: NYHOPS

4. Background on LiDAR Data & Quick Terrain Modeler

Light detection and ranging (LiDAR) is a useful mapping technique used in order to obtain topographic information for coastal dunes and areas above the low water mark. The use of LiDAR has become very popular among engineers, geomorphologists and coastal management personnel, [(van der Wal, 1996) (Irish & White, 1998); (Sallenger, et al., 1999); (Andrews , Gares , & Colby , 2002); (Saye, van der Wal, Pye, & Blott, 2005); (Robertson , Zhang , & Whitman , 2007)]. The creation and display of LiDAR has been increasingly accepted as a new technology that shows high-resolution digital elevation data. LiDAR allows the mapping of bare earth, vegetation and structures. A transmitted laser beam scanner fixed on an aircraft emits light pulses, which are reflected by the terrain of the earth. The elevation values are calculated from the time delay between the transmission of light and reception of it. A typical laser scanner can reach up to 100,000kHz pulses of light per second. The Global Positioning System (GPS) and the inertial navigational measurement unit, (IMU), which record constantly the three-dimensional position and the altitude vectors of the aircraft, respectively, allow an accurate registration of the LiDAR data. Thus, the creation of an elevation dataset with precise horizontal position (x and y with resolution of up to 1-2m) and vertical accuracy (z with resolution of 15-20cm) has become possible. It is a relatively quick method and provides spatially dense and accurate topographic data, [(Cracknell, 1998); (Mason , Gurney, & Kennett, 2000)]. An airborne laser altimeter, The Airborne Topographic Mapper (ATM), was created from National Aeronautics and Space Administration (NASA) with scope to map the ice sheet in Greenland, (Krabill, Thomas, & Frederick, 1995). Later on, NOAA to apply on coastal mapping created ATMII. In the ATMII an aircraft flies over the shoreline and collects 3000-5000 points of elevation per second with a horizontal accuracy of 0.8m and vertical at 15cm when flying at 700meters, (Meredith, Eslinger, & Aurin, 1999). A set of protocols for using LiDAR data, in order to map the coastline, was set by NASA, US Geological Survey (USGS) and NOAA. This set of protocols was formed after The Airborne LiDAR Assessment of Coastal Erosion (ALACE) research project, (Center, 1997).

From the LiDAR data, digital elevation models (DEM) are created. All the DEM's are geo-referenced to the same coordinates using the North American Datum of 1983/HARN adjustment (NAVD83/HARN) for horizontal datum and the North American Vertical Datum of 1988 (NAVD88) as vertical datum (USGS, 2012).

For this research LASer (LAS) files were downloaded from the Center of LiDAR Information, Coordination and Knowledge, (CLICK). USGS coordinates this virtual center in order to advance the access in digital land elevation data. CLICK provides the user with the data viewer. Data viewer is an interface where point cloud data can be downloaded in LAS format files or in ASCII X,Y,Z text file. LAS format files are binary file format and they were developed to make easier to manipulate three-dimensional LiDAR point cloud data. They are more popular than ASCII files because they are smaller in size and faster in process.

The constant change along the coastline has made the LiDAR data an excellent tool to monitor this change. Nowadays, the terrestrial and bathymetric LiDAR system has brought accuracy, speed and precision to the assignment.

As far as the Mantoloking dune susceptibility assessment is concerned the free trial software, produced by Applied Imagery, Quick Terrain Modeler was used in order to identify weaknesses in the dune system and highlights areas that may be vulnerable to storm damage. QT modeler, created by the Johns Hopkins University's Applied Physics Lab, while is not a comprehensive LiDAR production system like MARS or Terrasolid it excels for end users of LiDAR data. QT Modeler can process visualize and analyze massive LiDAR sets. In this thesis QT Modeler was used in order to help process multiple LAS format LiDAR data in less time than if different geospatial software was used. QT modeler apart from importing “raw” LAS data it can also import existing models like QTT surface models.

QTT surface models are commonly used to visualize terrain by removing any trees or houses. By importing a LAS file in a QTT form, QT Modeler constructs a surface model by setting a regular grid and placing a height value on all vertices. The scope of this process is to build one solid surface. QTT form makes the terrain visualization more realistic and allows easier manipulation.

Moreover, QT Modeler allows the change of the altitude coloration and display characteristics like classification, number of returns and intensity. Moreover, it has the ability to save and export data. 3-D models whether point cloud (.qtc) or surface (.qtt) can be exported to several formats. The most popular formats are LAS for point clouds and GeoTIFF DEM for DEM's and other surface models. QT Modeler also allows the exportation of of QTT and QTC file formats or UTM models into KML. Exporting outline into KML enables the user to establish a catalog of data on Google Earth. In this research special focus was given on exporting measurement lines and markers to Google Earth.

The Quick terrain Modeler provides many useful tools to allow the user to better analyze a model. One of the most beneficial is the tool of the measurement line. This tool can perform measurements along a straight line or a complex one. By using the examine height profile in the mensuration window, the elevation profile of the model across the mensuration line will be generated. This tool was used extensively in this research. Also the tool that constructs multiple cross sections is practical because it can analyze and compare multiple terrain profiles. Finally, another tool that was used in this work is the volume calculation. This tool enables the user to perform accurate calculations of volumes of objects or terrain areas in a model. There are few steps that should be followed prior to the calculation of the volume. First a subsection area should be chosen by using the select polygon tool and after to what this area will be compared to. The choices are:

- ❑ Compare to a reference plane. Here the height of the reference plane must be chosen

- ❑ Compare to another model.

After the comparison has been made a measure has to be chosen. Some of the choices are volume 1 above volume 2, volume 2 above volume 1, signed delta volume and unsigned delta volume. In this work the signed delta volume was used. This measurement calculates the net change in volume. (Applied Imagery LLC, 2012)

5. Methodology

5.1 Study Area

The focus of this study is an approximately 10800ft stretch of Mantoloking, New Jersey that was impacted by Superstorm Sandy, (2012). The limits of the study area are from North at Carrigan Place to south at Curtis Point Drive. Particularly, this work is focusing on three locations that were breached by the storm. The first area of interest (AOI) is where a breach of 300 feet of width occurred at Herbert Street where a bridge connected the Ocean County with the mainland. An inlet was generated and took several days to get closed by the Army Corps of Engineers. The second AOI is a little bit North at the 1117 Ocean County and the third AOI is at Lyman Street where again storm surges demolish the dune formations and cut through the barrier island. The width of the breach at this third AOI point is less than the one at Herbert Street and approximately of a width of 150ft. There have been more breaches reported but as far as this work is concerned the focus is given to the ones that remained opened right after Superstorm Sandy passed Mantoloking. While the interest was focused on how to explain the insufficiency of the dune system at those AOI, the whole coastline of Mantoloking was segmented in order to identify if there were any other locations that could be breached but they did not. The following Figures 12 shows the specific three AOI that where formed after Superstorm Sandy made landfall.

Figure 12: Breached AOI in Mantoloking, NJ. Credit: Aerial Photograph courtesy of the NOAA Remote Sensing Division.

5.2 Data Process – Measurements

Six LAS format files were downloaded from the database CLICK in order to form the 3-D, DEM of Borough of Mantoloking in QT Modeler. The six LAS files contain the LiDAR data obtained from USGS, the so-called “tiles”, that show the DEM of the Borough. In this work, the LAS data sets were imported as QTT (gridded surface) format with adjusting the gridded sampling to 3 feet. It was also set the LAS classification, by checking the class 2 and 9, which corresponds to showing only the terrain and the water. With the LAS specification set, a QTT surface was created. By applying the classification it was easier to create DEM that will eliminate any point cloud that corresponds to structure or vegetation. Also it was chosen to display height coloration in the DEM, in order to visualize easier any changes in the height of the ground. The height coloration pallet that was used was from blue to red. This means that dark blue color corresponds to lower altitude while dark red color to higher altitude. The value representing the dark red color is 25.2ft and higher while the value representing the dark blue is 0.4ft and lower. The unit of measurement used in this point cloud is feet and the datum for vertical data was NAVD88. Figure 13 shows the digital elevation model of the Borough of Mantoloking that was imported from the LAS files in the form of QTT. In this figure it should be noticed that the legend showing the height coloration appears in the down left corner while in the upper right there are the coordination system. Also the black area matches to no data.

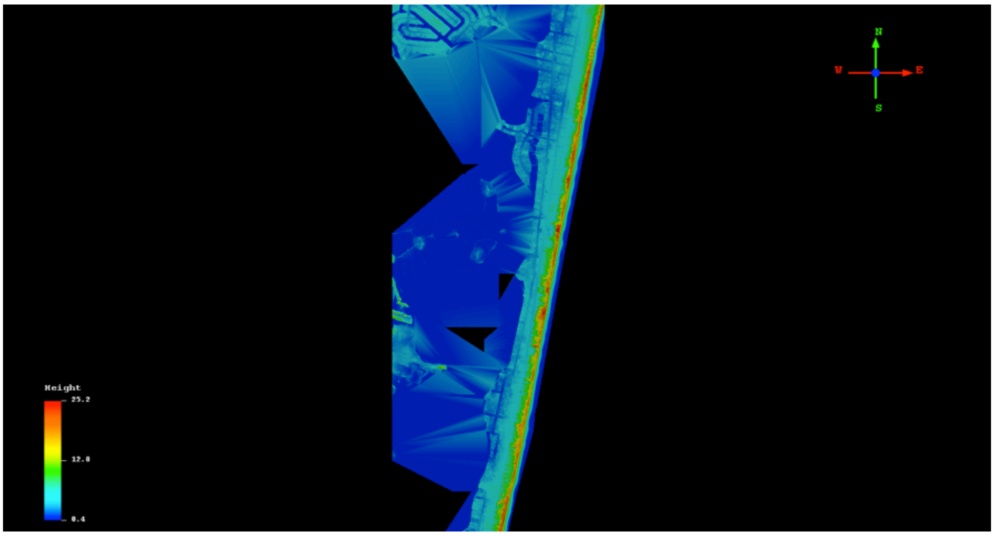

Figure 13: QTT surfaces Digital Elevation Model OF Borough Mantoloking, NJ

On this 3-D solid surface, 216 evenly spaced at 50ft-apart lines were drawn in order to perform a cross section analysis of the coastline along of the Borough of Mantoloking. First step in this process was to create a simple measure line with a start point and end point. After trial and error it was observed that it was more efficient to draw a line starting from some point inside the Barnegat Bay and ending at some point into the Atlantic Ocean. With this selection no important terrain points were excluded. One more thing that was considered was which line will consist the main line so multiple cross sections are to be constructed parallel to it and at what constant distance interval. Different measure lines were drawn, some from the northern boundary, some other from the southern boundary and some even at Herbert Street where the 1st large breach occurred. It was noticed that the first measurement affects the outcome with respect to the constant distance. Some constant distances that were experimented: 600ft, 200ft, 100ft, 50ft and 20ft. So by trial and error it was concluded that with a starting line from the north boundary of the Borough and an evenly spaced distance at 50ft the cross section analysis was giving quite fair results. Also, the constant distance of 20ft gives even better results by omitting fewer points, but the number of the measurement lines makes it unacceptable for manipulation. In this thesis, elevation profiles of some cross sections with smaller distance between them were created in order to better examine the specific AOI. The results are included in the 6th Chapter. These cross sections can be used to provide a better understanding of the elevations at certain AOI along the shoreline. Figure 12 shows with red color, which looks dense because of the high resolution and multiple cross sections. In this study, the cross sections were constructed from the north limit of the study area of the Borough to further south. Also the 216 cross sections were exported into Google Earth so as to visualize where exactly each cross section corresponds to the actual map of the Borough of Mantoloking. Figure 13 shows the cross section exported to Google Earth. It should be mentioned that the 10800ft stretch of Mantoloking coastline includes a length outside from the boarders of the municipality so as to obtain a better over view.

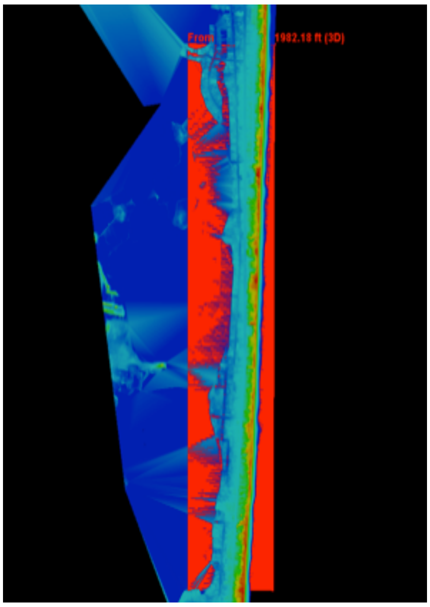

Figure 14: 216 Cross sections in QTT Surface

Figure 15: Exported Cross sections to Google Earth

In this research the cross section analysis is scoping to generate the elevation profile of the crest line of the dune system of Mantoloking. This profile is shown in the Chapter 6 along with the identification of the most vulnerable places.

The QT Modeler allows examining the height profile of every measurement line. Therefore, for each of the 216 cross sections a height profile was created. For the height profile in this particular work as it was mentioned before, it only shows the change in elevation of the terrain and the water surface with respect to NAVD88 datum. For each of the altitude profiles the highest point was identified. It was noticed that the dune maximum heights are ranged from 16ft to 26ft. Figure 16 shows the height profile of the 1st measurement line that was drawn at the northern end.

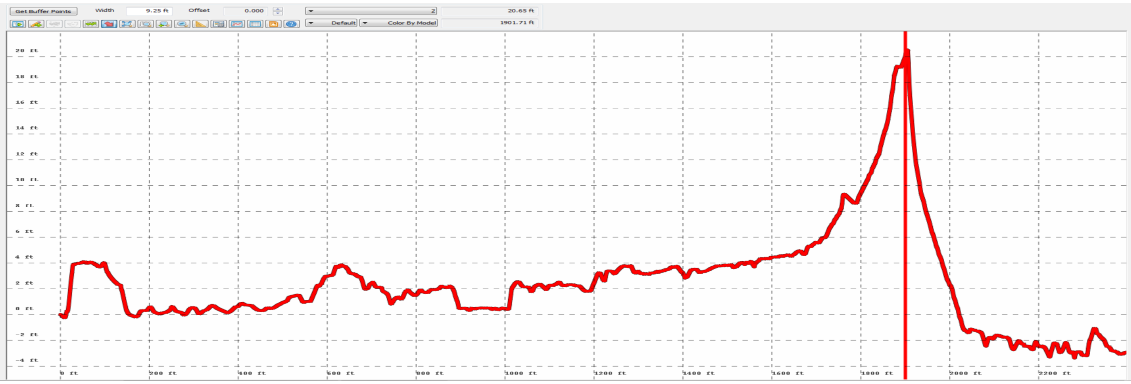

Figure 16: Cross Section Height Profile of 1st Measurement Line

At the left side of the above height profile is the start point and at the right side the end point. In this particular figure, one can notice that the profile starts with an elevation of 0 feet, which corresponds to water elevation in Barnegat Bay with respect to NAVD88, and continues with a sharp increase of elevation at 4 feet because of the presence of land. On the right side the end point drops into the Atlantic Ocean. On this side it is observed that the elevation gradually decreases and reaches – 3ft. From this side is difficult to predict where exactly the ocean surface is, because it depends on whether the LiDAR data were obtained on high or low tide. Also the vertical red line shows where is the highest point of elevation and its measure. All the height profiles are included in the Appendix A.

The second criterion that was used in order to identify which of the lowest places were the most critical was the criteria of dune volume. By creating multiple cross sections, this time with distance of 600 ft. (constant), from north to south, each volume between each opposing cross sections was calculated. In dune volumes the constant distance between the cross sections and the position of the first measurement line play an important role. So it was a necessity to figure out a pattern that would have given truthful results without deducting to huge errors. First attempt was to create multiple cross sections for every 300ft. This distance was chosen with respect to the width of the biggest breach noticed at Herbert Street. Also at this attempt the first measurement lines were drawn with respect to the limits of the breach. This choice was made with respect to the consideration that if the dune volume of 300ft width at Herbert St. failed, it could be considered as comparison base for the rest volumes. In this state of mind different distances of 100ft, 600ft and 1000ft were exploited. After calculating the volumes and constructing the chart of volume over the coastline it was observed that a constant distance of 600ft, the doubled distance of 300ft, it was giving the same results but it made it more comprehensible by omitting small variances. Whereas, the constant distance of 100ft had too many points to manipulate and the constant distance of 1000ft was excluding important information. The first measurement lines were drawn from the center of breach at Herbert Street. Figures 17 and 18 show the cross sections every 600ft in the QT Modeler interface and their exportation to Google Earth, respectively.

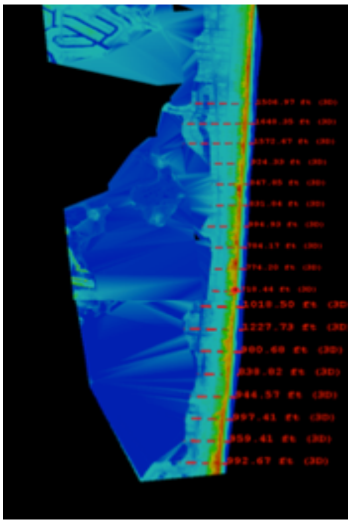

Figure 17: Cross Sections every 600ft, QT Modeler

Figure 18: Cross Sections every 600ft, exported in Google Earth

QT Modeler supports the user to perform accurate and quick volume calculations by using the volume calculation tool. However, before the volume is calculated a specific area of the model must be defined. By using the select polygon tool a specific area between adjacent two cross sections is chosen. In this thesis, the areas were selected with respect to height coloration and particularly with respect to 6 feet height, which corresponds to the beginning of the green coloration. Hence, areas that started with green color from the east side and they were ended with green color at the west side were chosen. This selection was made so as to focus on the areas that their altitudes were taller than 6ft and as a consequence to the formation of the dunes. Figures 19 and 20 depict with white color a selected area in order to calculate its volume.

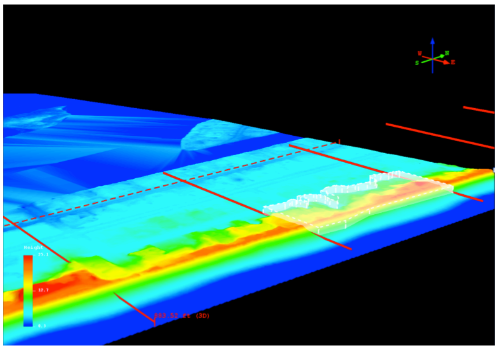

Figure 19: Selected Area for Volume Calculation, View from Atlantic Ocean

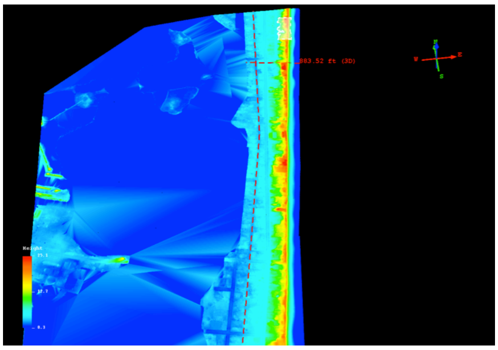

Figure 20: Selected Area for Volume Calculation, Plan View

QT Modeler volume analysis tool quickly calculates volumes as compared to another model or reference plane. Here volumes were calculated compared to a reference plane. The reference plane that was used, was the 0 feet elevation with respect to NAVD88. Figure 21 shows volume calculation for a selected area. Once the comparison has been defined as above, the choice on how to measure it, has to be made. In this research the comparison was defined as Signed Delta Volume (SDV). SDV calculates the net change of volume in the defined area. This means, that the calculated volume it was the multiplication of the area and the altitudes of the whole selected area, while a zero volume was subtracted. The zero volume resembles the volume calculated by the whole area and zero elevation. Nonetheless, this is not the final volume used to draw conclusions in this study. Since each specific area is selected accordingly to height coloration the volume under the approximate 6ft elevation has to be subtracted. To calculate the volume of 6ft and under, the area information was used. By taking the area from the area information (Figure 22) of each drawn polygon and multiplying it by 6ft and then subtracted it to the already whole calculated volume from the volume tool, the volume above 6ft elevation is calculated.

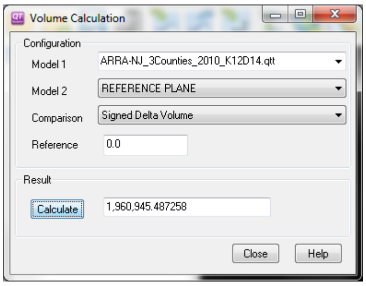

Figure 21: Calculation of the volume of Selected Area

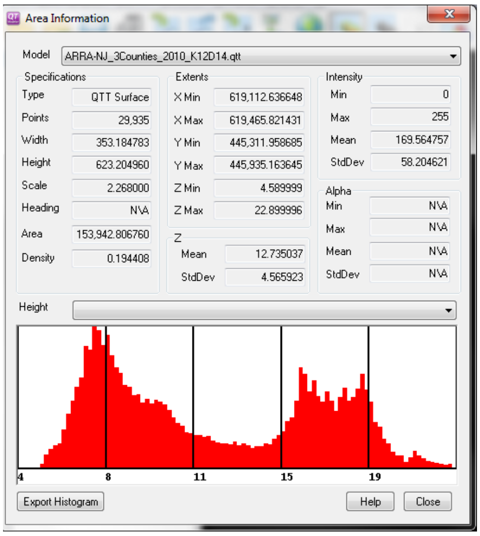

Figure 22: Area information of Selected Area

6. Results and Discussion

6.1 Breach Locations vs. Pre-Storm Dune Heights and Volumes

This research is focusing on doing a dune assessment in order to identify and try to explain why the dune system, one of most well preserved, in the Borough of Mantoloking was demolished in certain locations.

The manipulation of the year-2010 LiDAR elevation data from QT Modeler quantified the susceptibility variables. As it is mentioned in the previous Chapter 5 this dune vulnerability assessment is based on two criteria: the altitude and the volume of the dunes.

The elevation profiles of the cross sections were generated and the highest points were located. All the cross-sectional profiles are shown in Appendix A. Based upon the highest points for each of the 216 cross sections the profile of variation of dune heights along the coastline, (the dune crestline) was constructed. Figure 23 depicts this variation. Then the places with lowest elevations were spotted. Three places were observed to have the lowest ones. The first one was the 47th cross section at Lyman Street with an elevation of 17.34ft. The next one was the 128th near Herbert Street with an elevation of 17.24ft and the last one was noticed between Carpenter Lane and Albertson Street, 180th cross section with an altitude of 17.37ft. Figures 24, 26 and 28 show the corresponding cross sections. Additionally, Figures 25, 27 and 29 show the cross-sections exported on Google Earth analogous. Also in these figures the highest altitudes correspond to the markers.

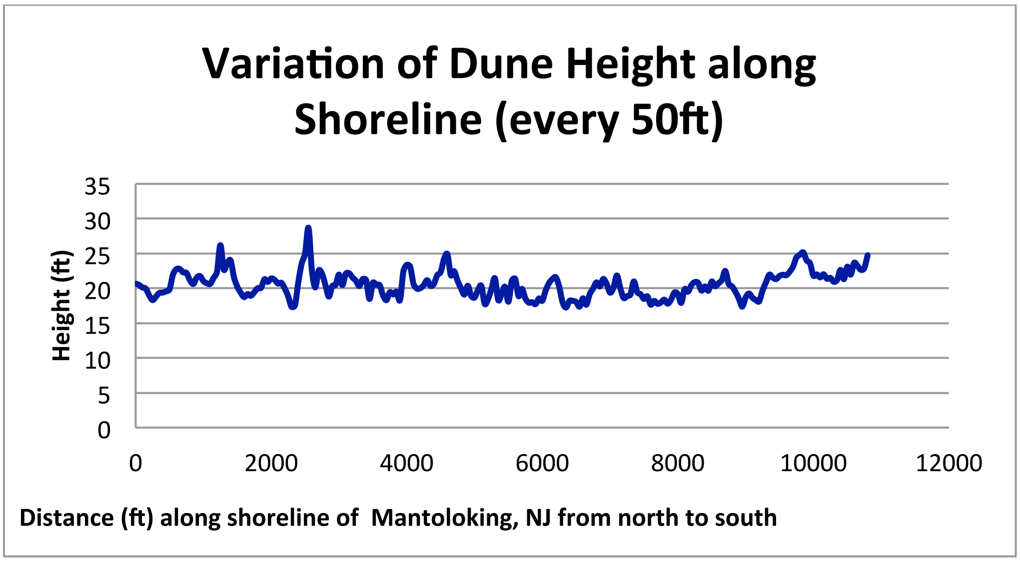

Figure 23: Chart of Variation of Dune Heights along Shoreline of Mantoloking, NJ

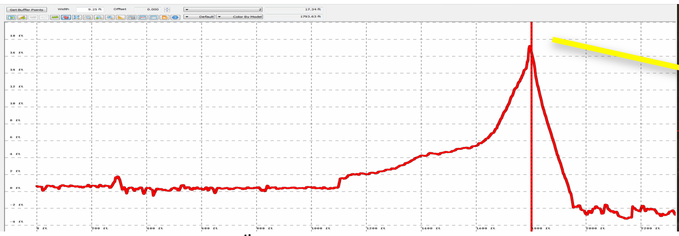

Figure 24: 47th Cross-section at Lyman St.

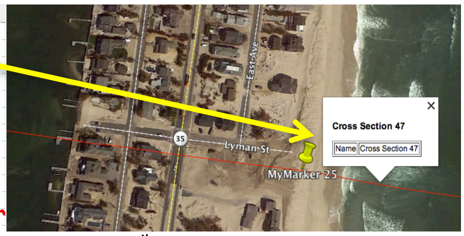

Figure 25: 47th Cross-section at Lyman St. exportation on Google Earth

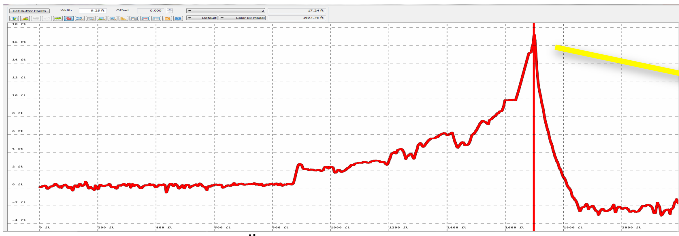

Figure 26: 128th Cross-section at Herbert St.

Figure 27: 128th Cross-section at Herbert St. exportation on Google Earth

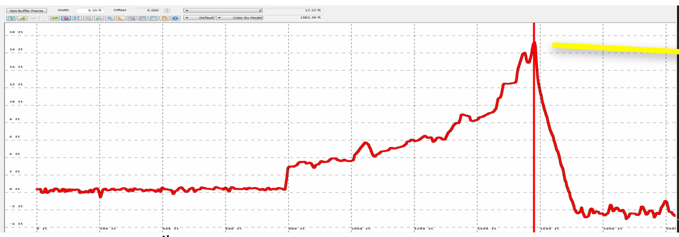

Figure 28: 180th Cross-section between Carpenter Ln. and Albertson St.

Figure 29: 180th Cross-Section Between Carpenter Ln and Albertson St, exportation on Google Earth

In the above three cross-sections one should observe that cross-section concerning the breach at 1117 Ocean Avenue was not included. The breach at Ocean Avenue falls between the cross section 116th and 117th sections with heights of 18.55ft and 17.95ft respectively (Appendix A). Between the Carpenter Lane and Albertson Street it was stated to have one of the lowest cross sections. This new area triggered the interest of this work to further investigate, in order to compere this 4th AOI to the three breach locations.

Further investigation with respect to cross-sections was conducted for the breached areas and the new low height between Carpenter Lane and Albertson Street that was found. Creating multiple cross-sections and focusing on the AOI, some new low elevations were found.

The results from the cross sections were:

At Lyman Street was found a low height of 17.19ft. Figures 30, 31 show the cross section on the QTT surface and the elevation profile respectively.

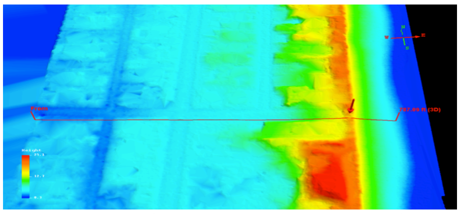

Figure 30: Lowest Cross-section at Lyman St. on QTT Surface

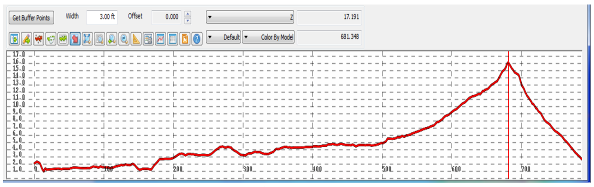

Figure 31: Lowest Cross-section at Lyman St

At 1117 Ocean Street a low height of 17.66ft was found. Figures 32, 33 show the cross section on the QTT surface and

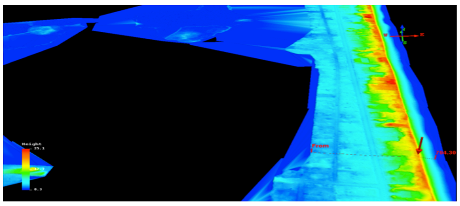

Figure 32: Lowest Cross-Section at 1117 Ocean St. on QTT Surface

the elevation profile, respectively.

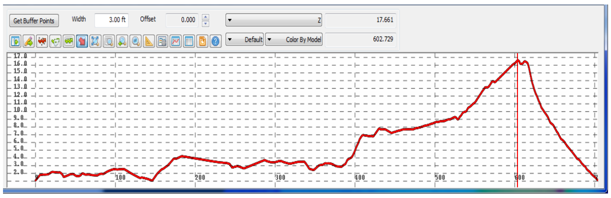
Figure 33: Lowest Cross-section at 1117 Ocean St

At Herbert Street a low height of 16.58ft was noticed. Figures 34, 35 show the cross section on the QTT surface and the elevation profile respectively.

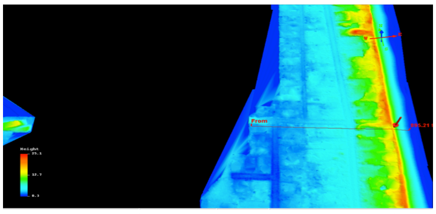
Figure 34: Lowest Cross-section at Herbert St. on QTT Surface

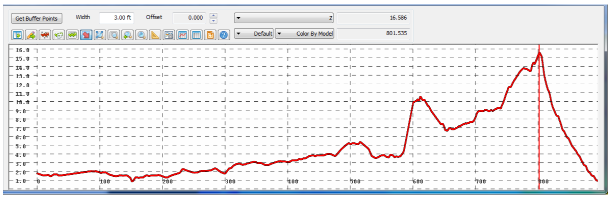
Figure 35: Lowest Cross-section at Herbert St

Finally at the new location between the Carpenter Lane and the Albertson Street the height of 16.66ft was found. Figures 36, 37 show the cross section on the QTT surface and the elevation profile respectively.

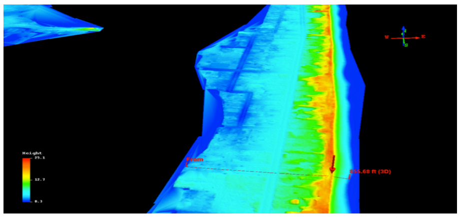
Figure 36: Lowest Cross-section at Between Carpenter Ln. and Albertson St., on QTT Surface

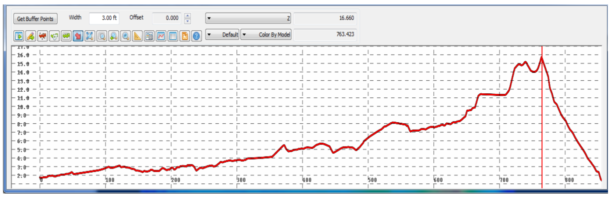
Figure 37: Lowest Cross-section Between Carpenter Ln. and Albertson St.

From the above the profile of the crest line can be used to assess the beach dune system. To further assess the dune system the criterion of the volume was examined. By segmenting the beach-dune system parallel to the shoreline from the north limits of the municipality to the further south, 18 zonal analysis areas that are each 600-foot-long were formed. For each of those zones the dune volume was calculated by using the analysis mentioned in the previous Chapter 5. All the zones and their calculated volumes are shown in Appendix B. The output of the variation of the dune volumes is summarized in the following Table 2 and in Figure 38.

Distance on the shoreline	Area between two cross line	Volume of under 6ft	Hole Area Volume	Final volume
600	153942.8067	923656.8402	1960945.48	1037288.64
1200	158858.413	953150.478	2006970.253	1053819.775
1800	140706.1654	844236.9924	1809809.455	965572.463
2400	134714.5123	808287.074	1758929.813	950642.7394
3000	133807.0562	802842.3371	1900500.675	1097658.338
3600	190261.0605	1141566.363	2332270.252	1190703.889
4200	177398.8759	1064393.256	2292679.398	1228286.143
4800	152308.4123	913850.4738	2205257.4	1291406.926
5400	159560.1312	957360.787	2079352.206	1121991.419
6000	123144.3152	738865.8914	1598199.056	859333.1643
6600	134690.6625	808143.9749	1637512.161	829368.1858
7200	156963.1883	941779.13	1862276.57	920497.4402
7800	168359.0275	1010154.165	2202930.139	1192775.974
8400	174782.9898	1048697.939	2256233.065	1207535.126
9000	180726.3024	1084357.814	2040717.179	956359.3651
9600	182933.602	1097601.612	2317904.096	1220302.485
10200	175988.294	1055929.764	2385193.024	1329263.261
10800	187854.9995	1127129.997	2756294.138	1629164.141

Table 2: Volume Calculations Along Shoreline of Mantoloking, NJ

According to the Table 2 it is noticeable that the lowest dune volumes of the dune system, pre-storm, were at the area of Herbert Street. Especially the 600ft distance along the shoreline, in front of the new Bridge of the Borough of

Mantoloking has the lowest value of 829,368.19ft^3. Additionally, the adjacent areas from north and south of this area also have the second and third lowest. Particularly the one from north at the 6000ft distance from the first is of 859,333.16ft^3. The breach observed at 1117 Ocean Avenue was smaller in width from the breach at Herbert Street and it falls in the area of volume 859,333.16ft^3. The volume of the dune area at which the breach of Lyman Street occurred is 950,642.74ft^3. However the volume that includes the new low height between Carpenter Lane and Albertson Street is 956,359.36ft^3.

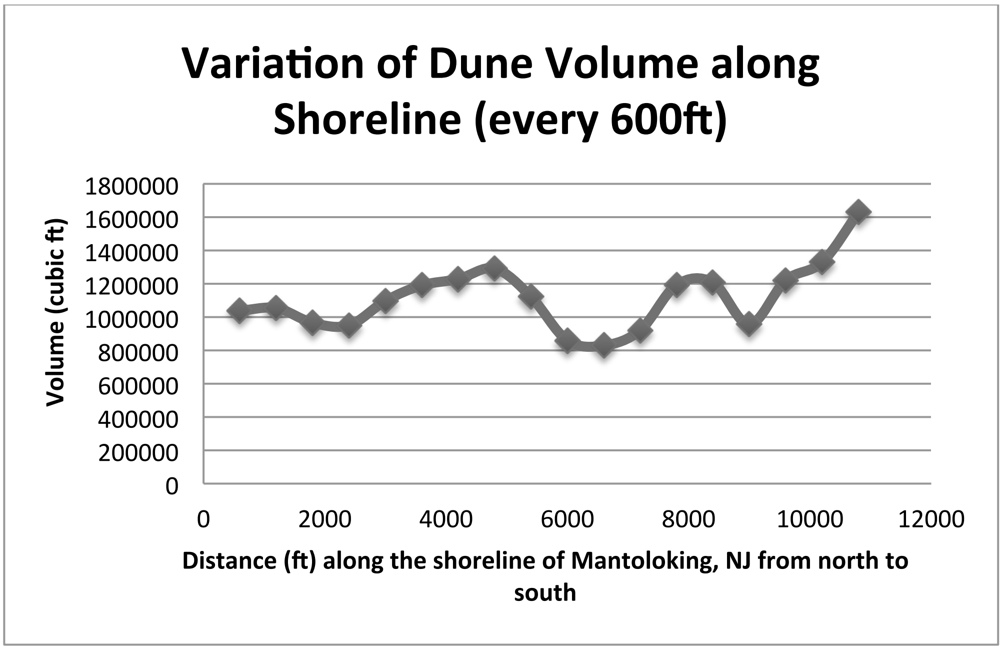

Figure 38: Variation of Dune Volume along Mantoloking Shoreline

From the dune volume variation profile one can observe the vulnerable locations. In the dune volume variation profile, Figure 38, the susceptible places are shown as the concave areas. It is observed that where the three breaches occurred from north to south (Lyman Street, 1117 Ocean Avenue and Herbert Street) concave areas with more than one low points appear.

Whereas at the southern location between the Carpenter Lane and the Albertson Street only one point of volume corresponds to a low.

The following Figures 39, 40, 41 and 42 show the four susceptible locations along the shoreline of Mantoloking, NJ in the QQT surface.

Dune volume at the 1st vulnerable place (includes breach at Lyman Street) was calculated as 950,642.74 ft^3.

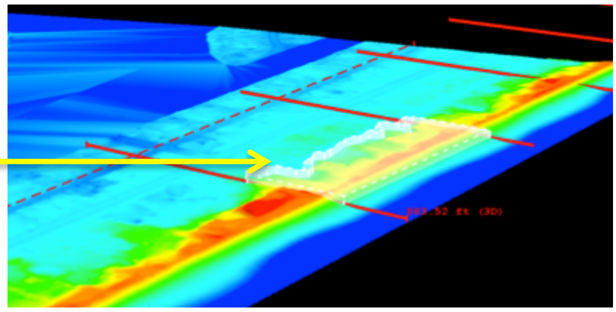

Figure 39: Dune Volume – Lyman St.

Dune volume at the 2nd vulnerabe location (includes breach at 1117 Ocean Avenue) was calculated as 859,333.16ft^3.

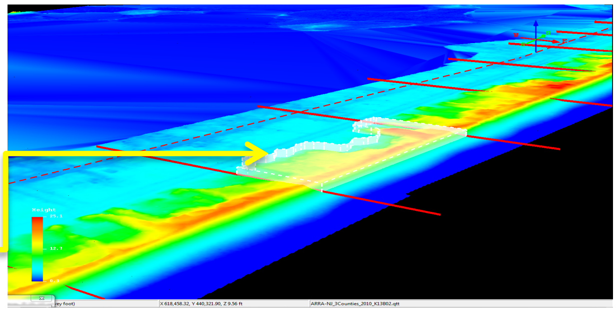

Figure 40: Dune Volume-1117 Ocean Av.

Dune volume at the 3rd vulnerable place (includes Herbert Street) was calculated as 829,400 ft^3.

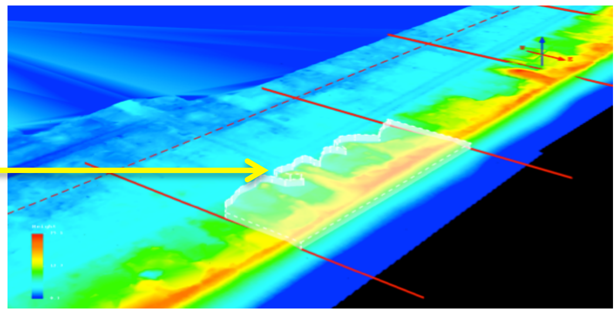

Figure 41: Dune Volume – Herbert St.

Dune volume at the 4th vulnerable place (includes low height between Carpenter Lane and Albertson Street) was calculated as 956,400 ft^3.

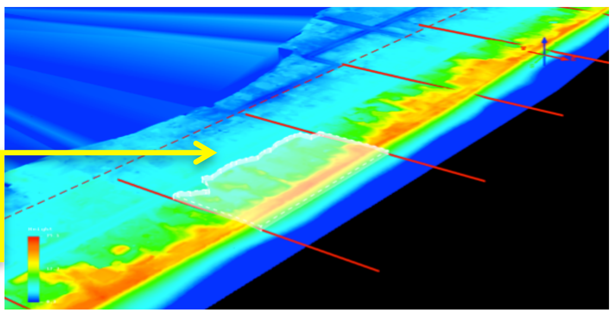

Figure 42: Dune Volume – Between Carpenter Ln and Alberston St.

In order to add credibility to this analysis a visit to the Borough of Mantoloking, NJ was scheduled a couple of months after the pass of Superstorm Sandy. The scope of the visit was to witness real time conditions at the three locations that were breached and to investigate the fourth AOI between Carpenter Lane and Albertson Street that was not.

Entering the Borough of Mantoloking from north, the enormous impact of Superstorm Sandy was obvious even several months after the event. Hundreds of properties were destroyed or totally washed away from their foundations. Sand and debris was even washed away into the Barnegat Bay. Huge open spaces were observed at the AOI were breaches occurred during Sandy. At Herbert Street a 50 foot of steel sheet piling was constructed. The sand dune system was restored and the breaches were filled. At the 4^{th} AOI, between Carpenter Lane and Albertson Street concrete foundation was observed at many of the houses. Figure 43 is a picture showing the concrete foundation of the house that corresponds to the lowest cross section.

Figure 43: House With Concrete Foundation at The 4^{th} AOI.

6.2 Water Levels vs. Dune Heights

At this point of the research a preliminary contrast of the dune system and the water levels occurred during Sandy can be made. As mentioned in Subsection 3.1.4, the total water level modeled by NYHOPS reached a height of approximately 22ft over NAVD88 during Superstorm Sandy. The dune heights at the observed breach locations were quantified above to be less than 18 ft. Therefore; the water should have gone over these dune locations during Superstorm Sandy.

6.3 Related Dune-Beach Morphological Studies

The Richard Stockton College of New Jersey Coastal Research Center, (CRC) has been assessing and monitoring the beach-dune system of this Borough. CRC has been conducting the beach survey at five particular sites on quarterly base over past many years. CRC enhances its assessment with the official dune walk where a visual review is given. The most recent report assessing the beach-dune system of Mantoloking prior to the Superstorm Sandy is December 2011. Some of the results from the assessment are: the dune heights at the 5 monitored locations ranged from 19ft to 23ft, berms at elevations of 5ft to 7ft, while the volume is expressed in terms of a net change. The cumulative volume including all those 5 sites was used in calculating the net change. A volume of 65,437yds^3 was lost between August 30 to December 15, 2011 during which Hurricane Irene occurred in late August and a Nor'easter occurred in late October (CRC, The Richard Stockton College of New Jersey Coastal Research Center, 2012)

CRC also did a survey after the landfall of Tropical Storm Sandy and issued a report assessing the changes of the dune system at the New Jersey Beach Profile Network (NJBPN) sites. In the area of Mantoloking only one site was investigated at the location 153, which corresponds to 1117 Ocean Avenue. Comparing the two profiles, one from September 2012 and one right after the landfall, a net change of volume of sand was calculated to be -109.595yd^3/ft.

CRC also made a vulnerability assessment for a 100-year storm. This susceptibility assessment was based on the 2000 LiDAR data topography and included several variables that affect the performance of a dune system: dune height, width beach elevation and width, vegetation, bathymetry etc. By using the numerical erosion model SBEACH (Storm induced BEAch Change), (Rosati, Wide, Kraus, & Larson, 1993), CRC stimulated the 2-dimensional beach and dune erosion under varying storms. Their analysis concluded that for a 100-year storm many locations of the dune system would be breached, overwashed or reduced to the level of the sea. (CRC, The Richard Stockton College of New Jersey Coastal Research Center, 2004).

The U.S. Geological Survey after Superstorm Sandy made a susceptibility assessment of the coastline of New Jersey. By calculating the difference between the total water levels and the dune system elevations the probabilities of the three regimes of collision, overwash and inundation were calculated. It was assessed that during a storm like Sandy a 98% of the coastline will experience collision, 55% overwash and 22% inundation. (USGS, 2013)

USGS also conducted a LiDAR visual survey over the area at Herbert Street (the most severe breach location included in this study) immediately after the landfall of Post Tropical Sandy. The change of dune height pre and post storms was shown in coloration of the terrain (USGS, 2013).

This study in contrast with the above CRC and USGS studies is segmenting the whole shoreline of Mantoloking using the latest 2010 LiDAR data, pre-storm, and focuses on the two morphological characteristics of height and volume. It focuses on and calculates the exact numerical heights and volumes that consist of the lowest among the Borough, while it constructs the crest line height profile and the volume variations along the whole shoreline of Mantoloking. Whereas, CRC or USGS has performed either field topographic surveys or just preliminary contrast between pre and post Sandy topographic LiDAR data.

6.4 Other Dune-Breach Factors

Variable Characteristics of the Beach

At this point it should be discussed the variable characteristics of the beach and how they could have affected this work. Apart from the dune and its characteristics focus was given to the beach properties. Dune forms are positioned to occupy the upper portion of the beach profile. Therefore; some critical relationships can be drawn from the beach profile. As far as the beach morphology is concerned, a special focus was given to the width of the beach. The beach width affects wave reach and thus wave impact on the dune during a storm surge. Identification of the smallest width is crucial. The dune system is more susceptible to erosion if the beach width is smaller. In this research the width of the beach was almost constant and approximately less than 150ft so it could not affect our results and thus it was eliminated as a factor.

Seaward Bathymetry

The bathymetry profile affects in the same manner as the beach width the reach of storm surge over the shoreline. Consideration on bathymetric properties must be given on how it can affect the water level and velocity at the coast. The most important property is the seaward facing slope. A slope of 1:100 is proven to be an effective block to storm surges. (Weaver, 2008)

Also, if the sea floor in front of the dune-beach system is channelized, a larger amount of seawater will be directed towards the corresponding location, making the system more vulnerable.

From the bathymetric data of New Jersey coastline neither slope of 1:100 nor channelized sea floor is observed. Therefore those breached couldn't be affected from the bathymetry in contrast to the rest of the shoreline of the Borough.

Possible Influence of an Old Inlet in the Area of Mantoloking

According to the Manasquan Inlet to Barnegat Inlet feasibility study performed by the US Army Corps of Engineers and The New Jersey Department of Environmental Protection on old inlet between Bay Head and Mantoloking, opposite of Metedeconk River used to exist. The Metedeconk River inlet was closed 1755. Although the old Metedeconk Inlet appears to be near the dune breach locations in Mantoloking, it is unlikely be a major factor influencing the breach locations since the old inlet was closed more than a quarter century ago and no apparent valley/channel in the seaward bathymetry was observed nearby. (US Army Corps of Engineers & NJDEP, 2002)

Wind Field vs. Uniform Sand Dune System

Winds generated by storm can also affect the formation of the dune system. Apart from accelerating currents and generating water velocities that enhance the water runup, winds can also affect the formation of the dune directly. In this thesis a particular interest was given in whether a wind field could have an influence on the breach locations. It is known from the physics that the higher the elevation the higher the velocity of the wind. So it would be expected that more sediment erosion/scour to occur on the dune crest where the elevation is higher. This would be contrary to the observed breach locations where the pre-storm dune crest elevations were lower.

7. Conclusions

From this study a set of conclusions can be drawn:

- By generating the cross-sections along the shoreline of Mantoloking using the LiDAR data, four locations were considered the most vulnerable based on their low dune heights and volumes. The area around the New Bridge at Mantoloking (Herbert Street) was the most susceptible to breach with respect to dune height and volume variation. In this area, the minimum dune height was 16.5ft that was the lowest along the entire Mantoloking shoreline and the dune volume was 829,400 ft^3 that was the lowest along the entire Mantoloking shoreline. The most severe breach was observed in this area. The 600ft. area north of Herbert Street area had the dune height and volume among the lowest with the minimum height of 17.66ft and the volume of 859,333 ft^3, and a breach was also observed. The area at Lyman Street also had the dune height and volume among the lowest with the minimum height of 17.34ft and the volume of 950,642 ft^3, and a breach was observed too.

- The last area with the dune height and volume among the lowest was between Carpenter Lane and Albertson Road with the minimum height of 16.6ft and the volume of 956,400 ft^3, but no breach was observed. During the field observations, it was noticed that at this location the houses had concrete foundation instead of wooden foundation.

- The dune system was observed not to be uniform along the shoreline and hence points of weakness existed. The damaged dune could be rebuilt more uniformly. A better maintenance program could also be implemented to prevent the weak links.

- This research has demonstrated a methodology for assessing the dune system’s variable responses to future storms.

8. Future Work

Future research effort should focus on some other aspect concerning the dune-beach system. Two of them are:

- ❖ Rebuilding standards

  Superstorm Sandy has triggered an intense research aiming to set new standards that would limit the risk of future disaster. A $1,050,000 has been initiated to fund the Manasquan Inlet to Barnegat Inlet project plan. The study area of this plan is a stretch of 14 miles from Point Pleasant to Island Beach State Park, and this study area includes the Borough of Mantoloking. Those funds consists the preliminary steps needed to move toward initial construction, which include the completion of Limited Reevaluation Report, develop, approve and execute the Project Partnership Agreement, award the construction contract etc. US Army Corps of Engineers have planned to build a dune system of a height up to 22 feet and wider beaches. Further investigation whether these rebuilding standards would implement a good solution should be consider.

- ❖ LiDAR data post storm

  If LiDAR data right after the Superstorm Sandy's landfall become public, further examination should be considered in order to calculate the net changes in volumes and heights of the dune system. During this study and until now no such LiDAR data have been found.

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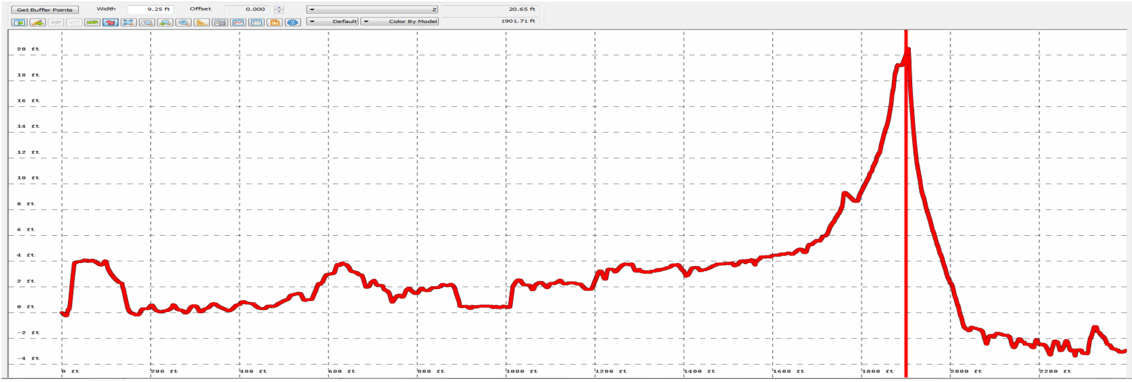
Appendix A – Elevation Profiles Of Cross Sections Along Shoreline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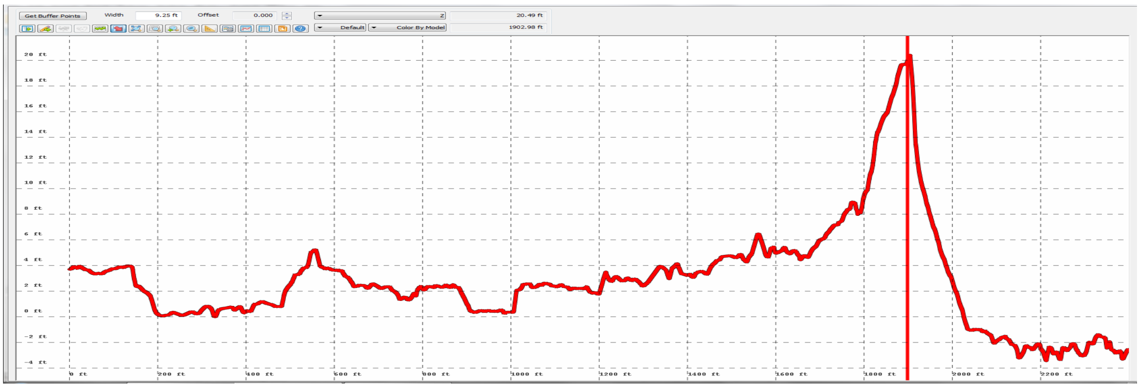
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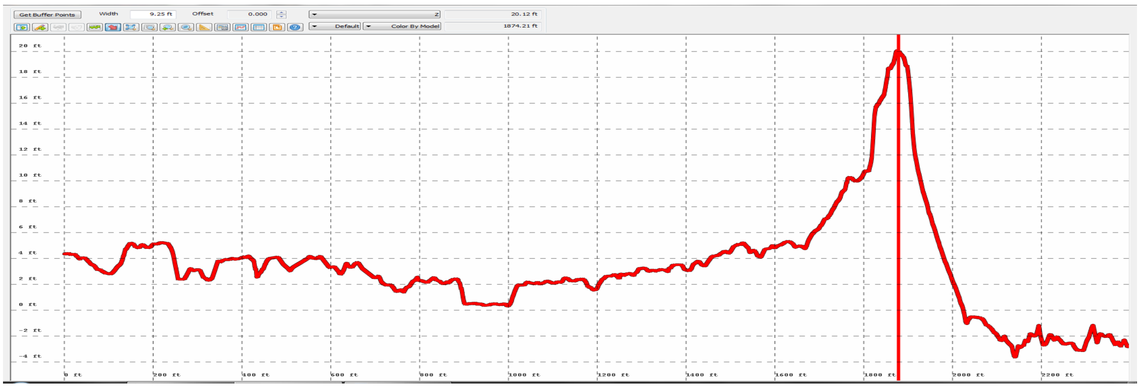
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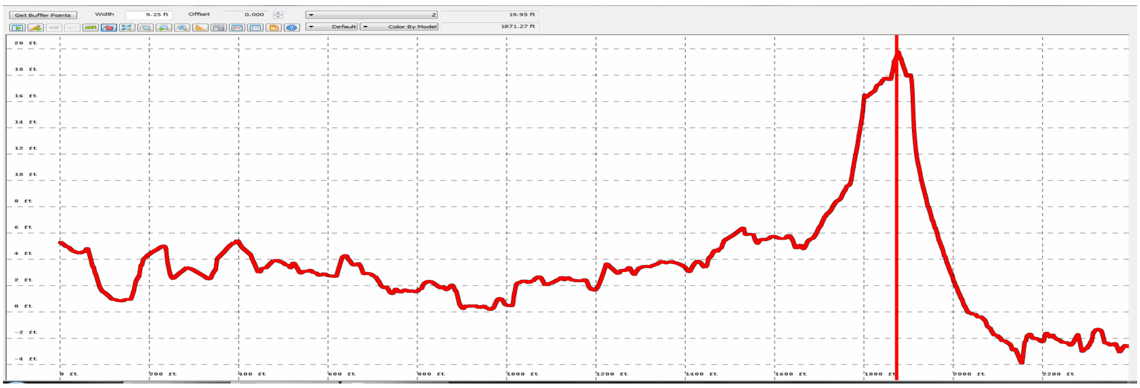
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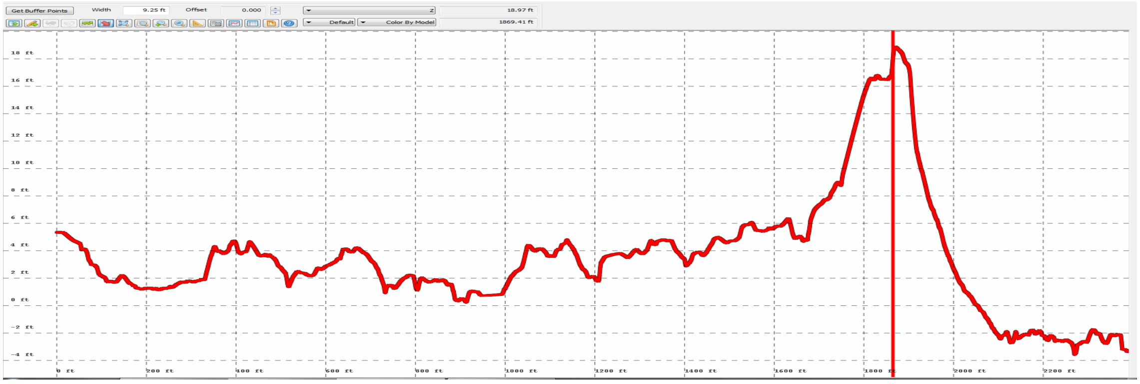

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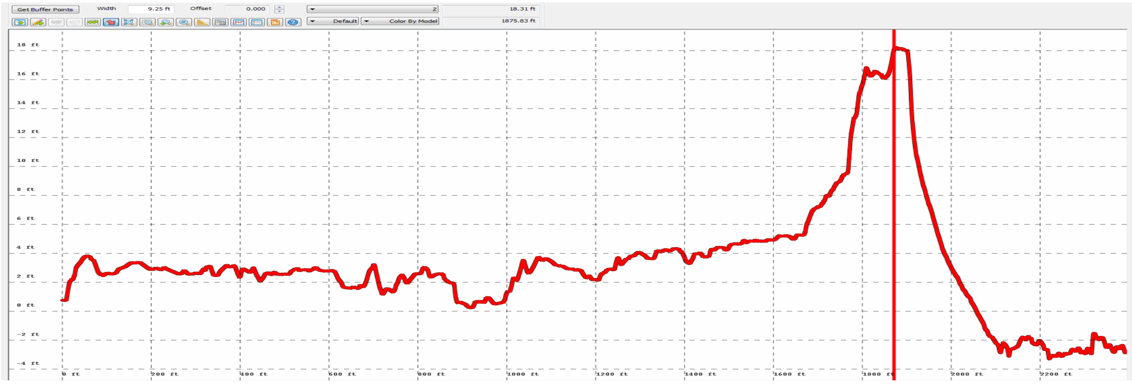

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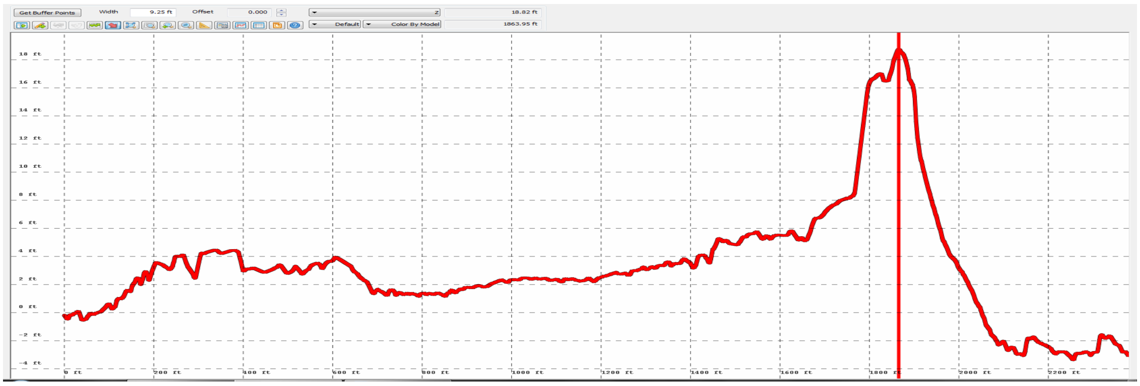

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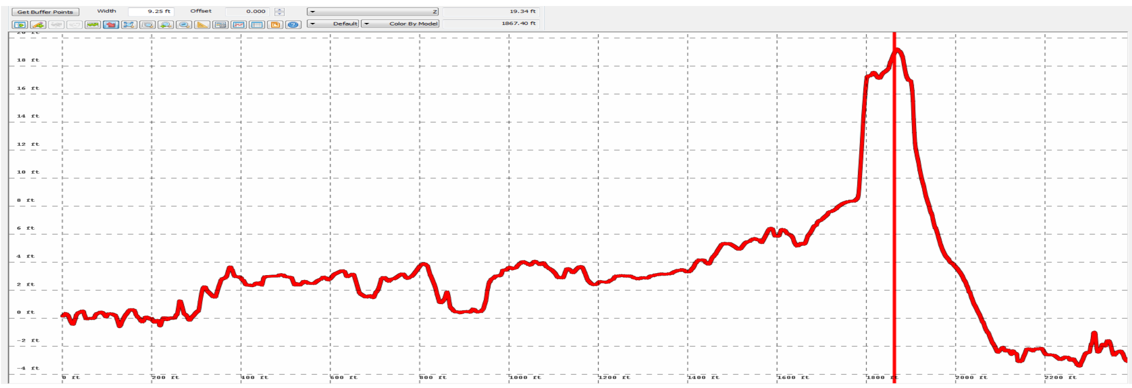

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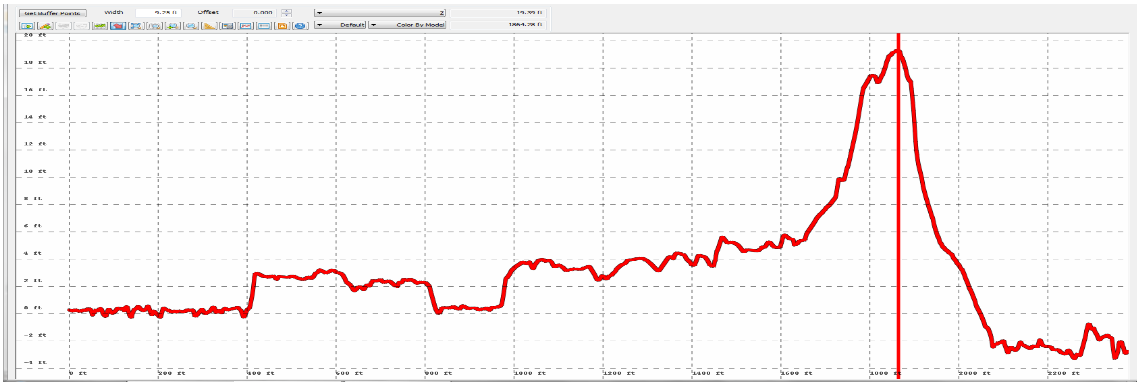

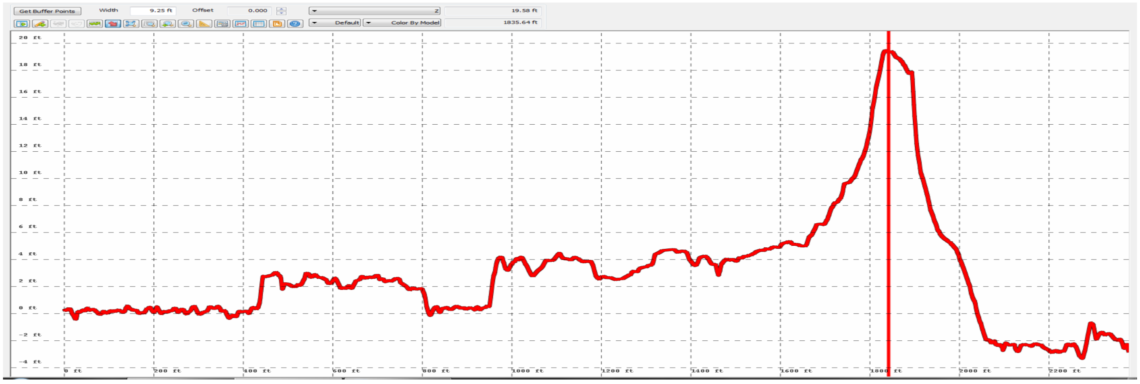

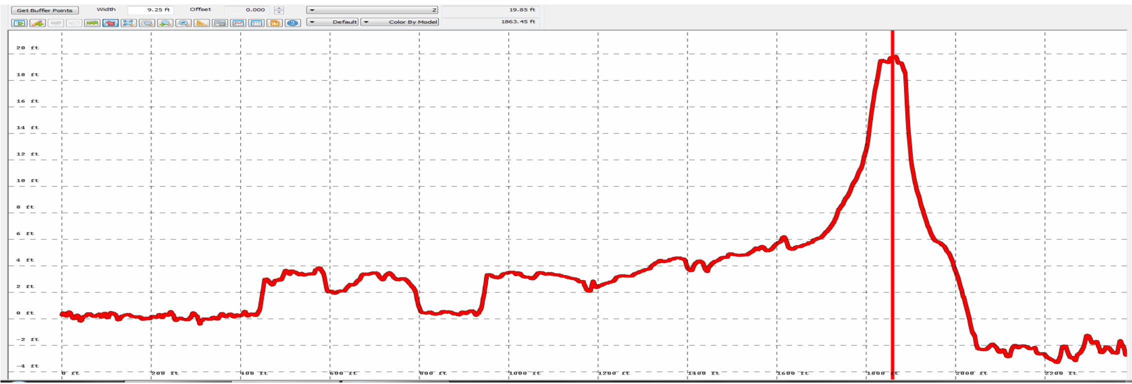

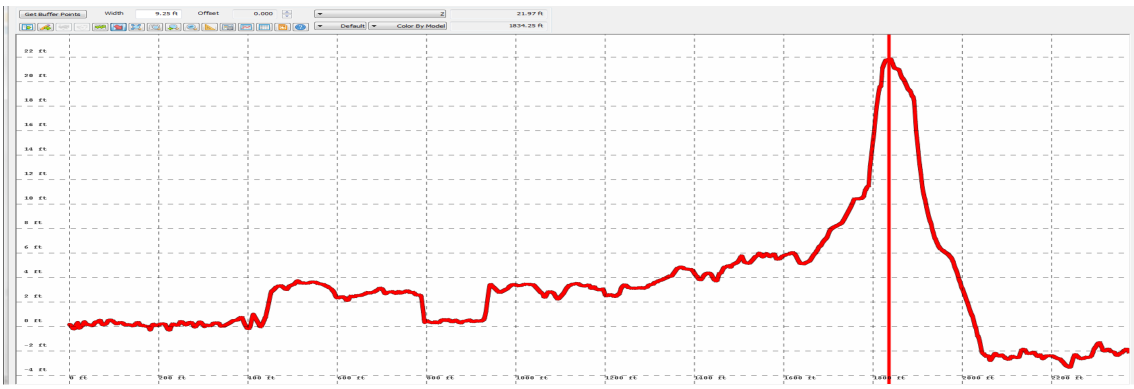

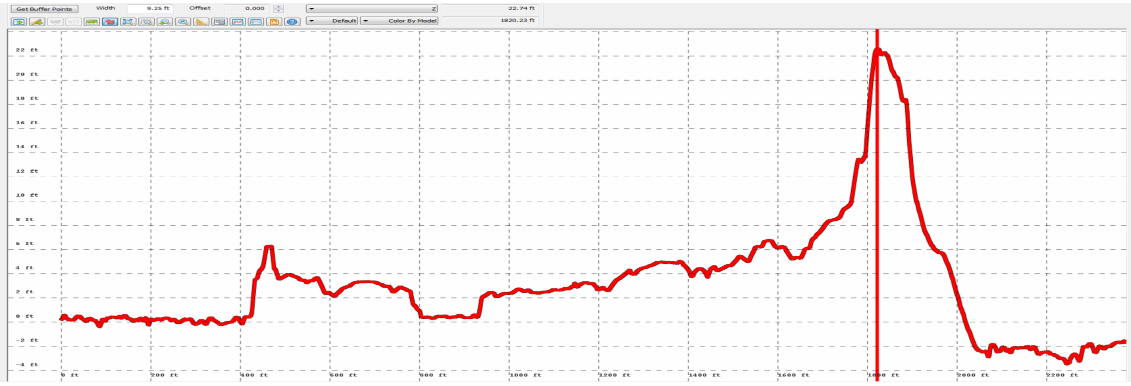

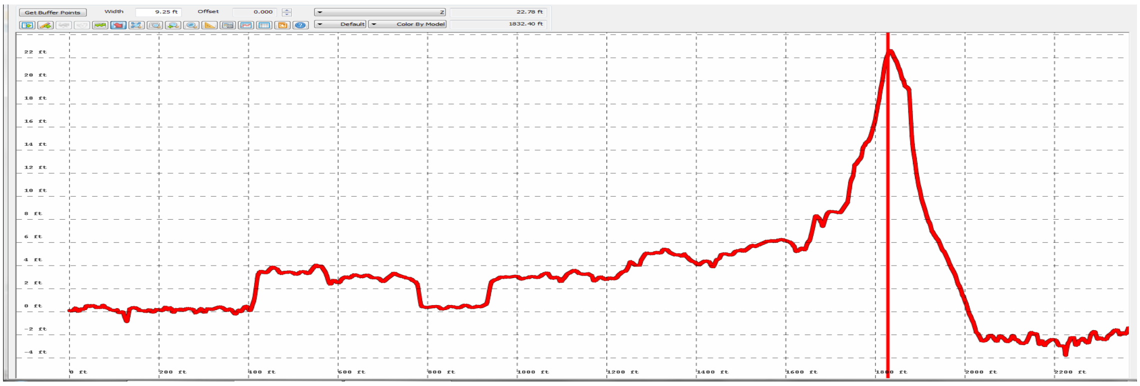

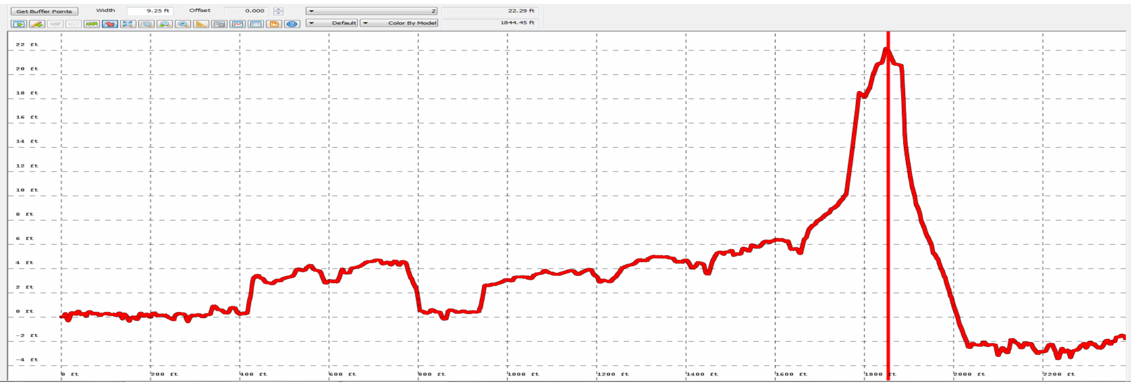

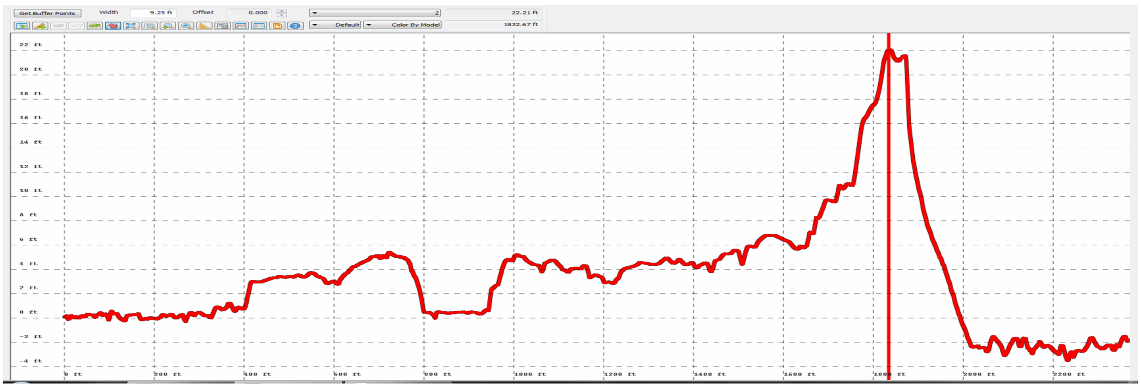

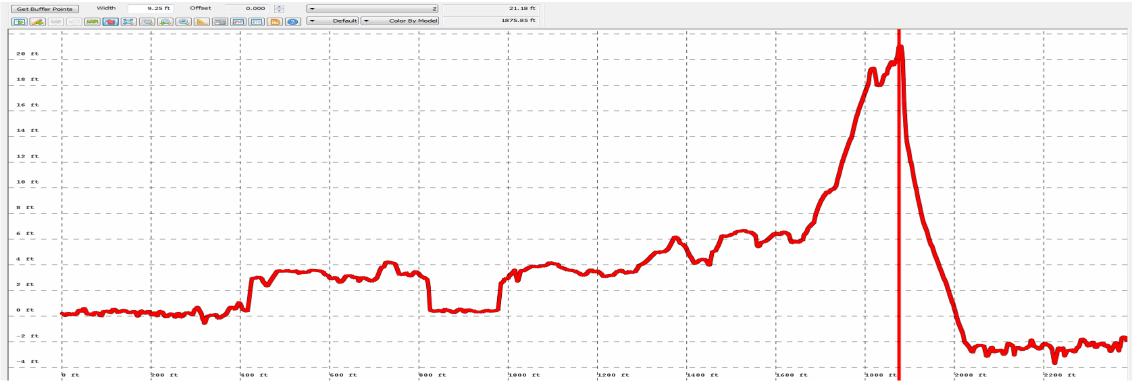
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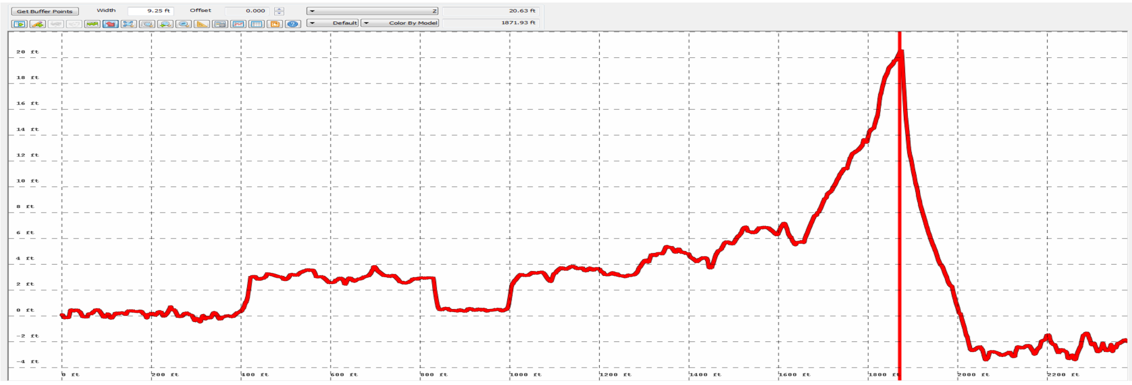
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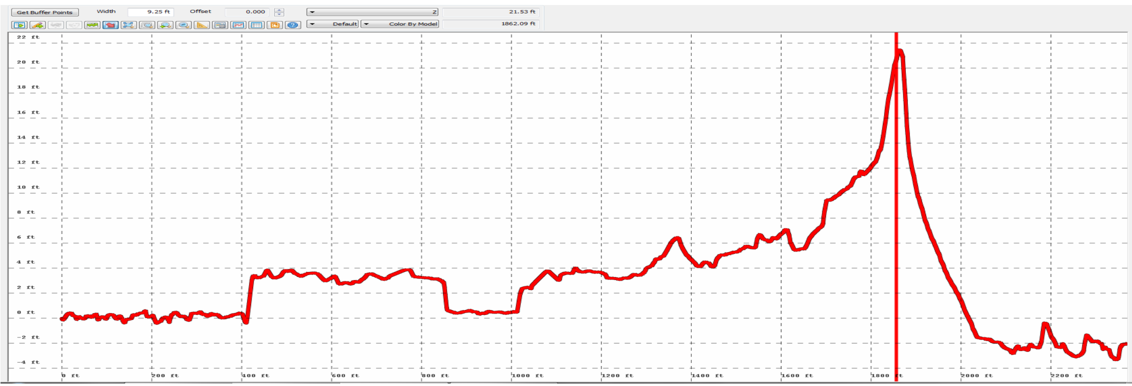
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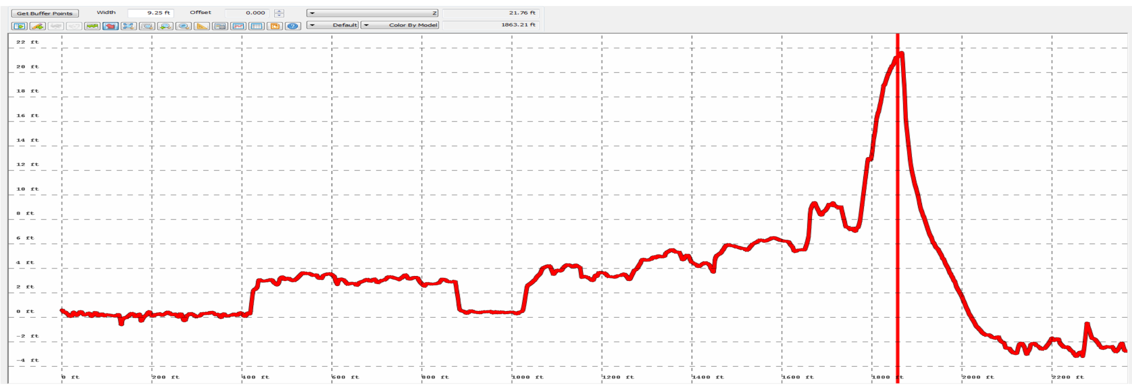
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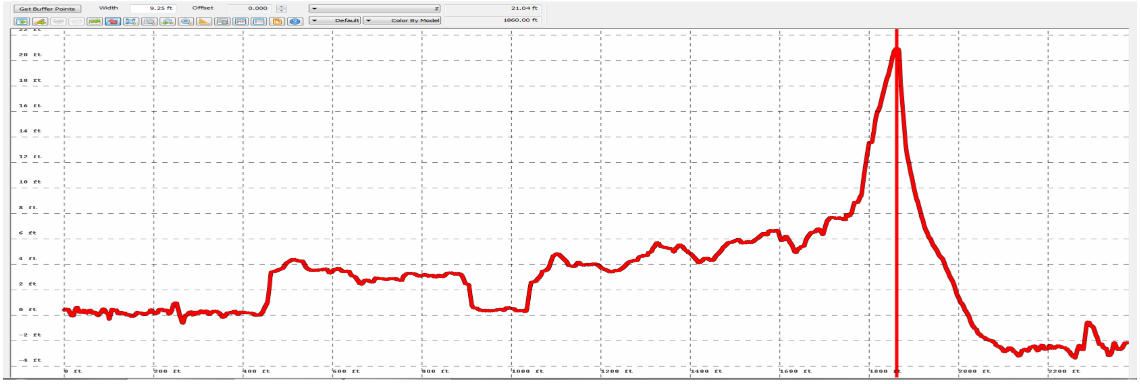
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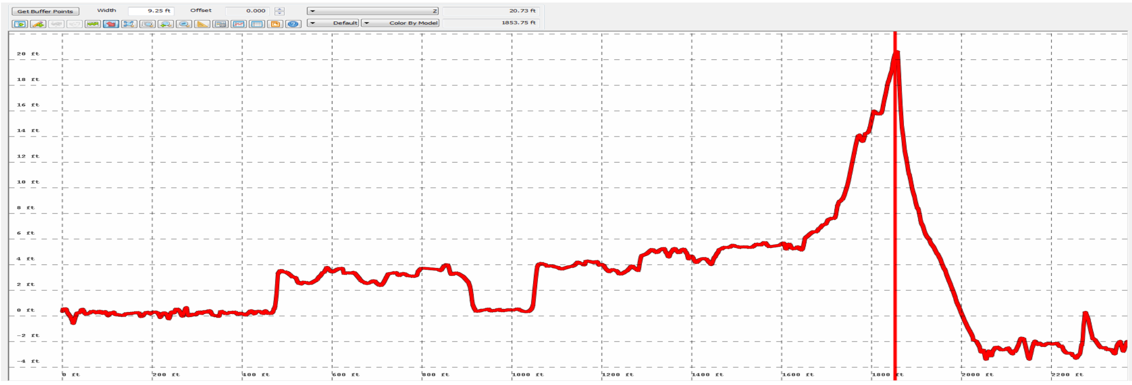
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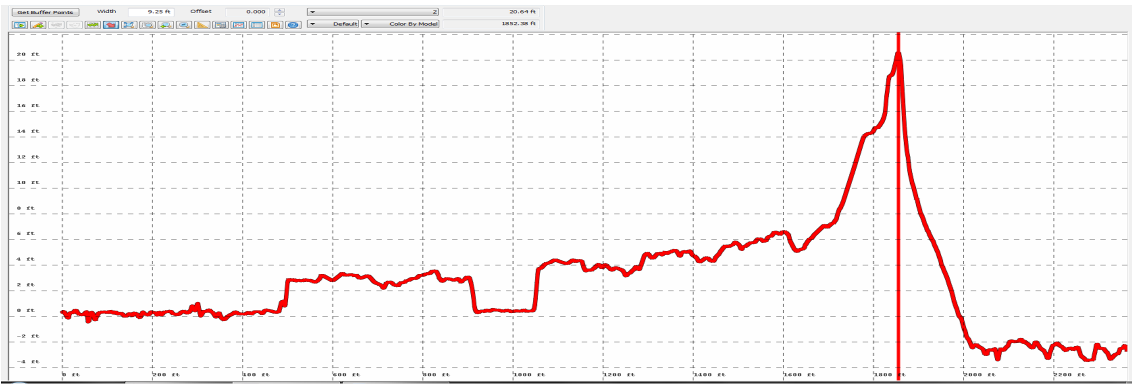
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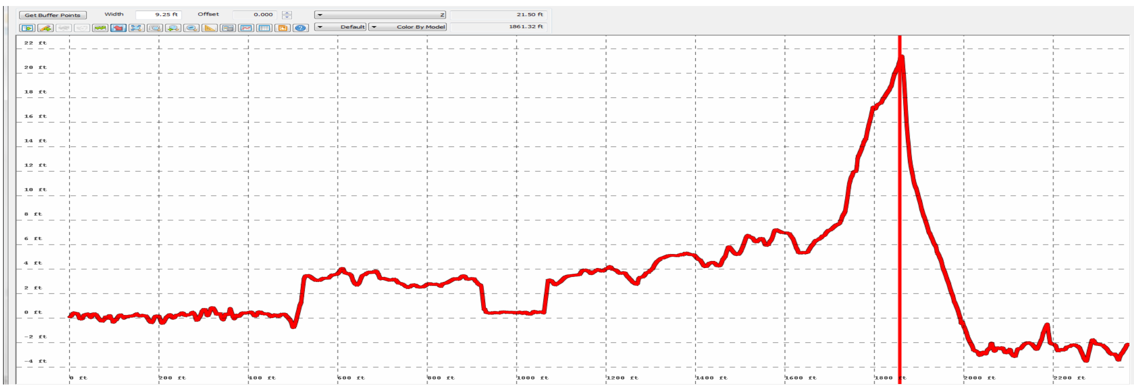
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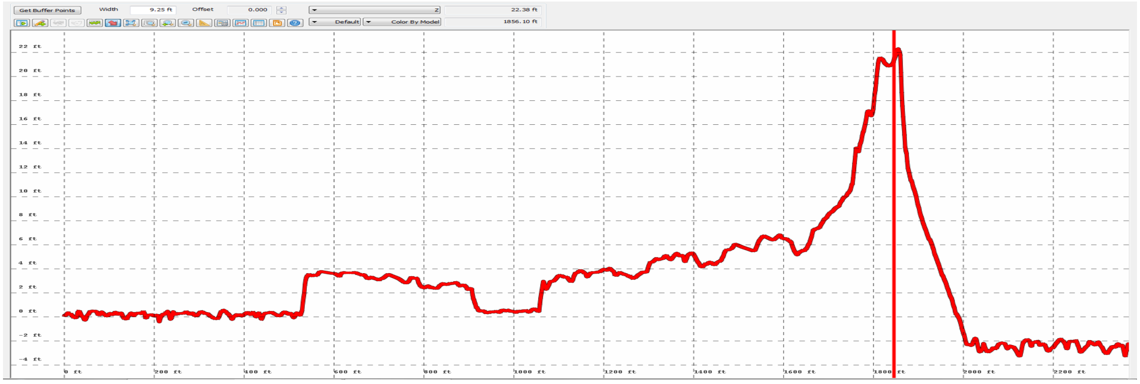

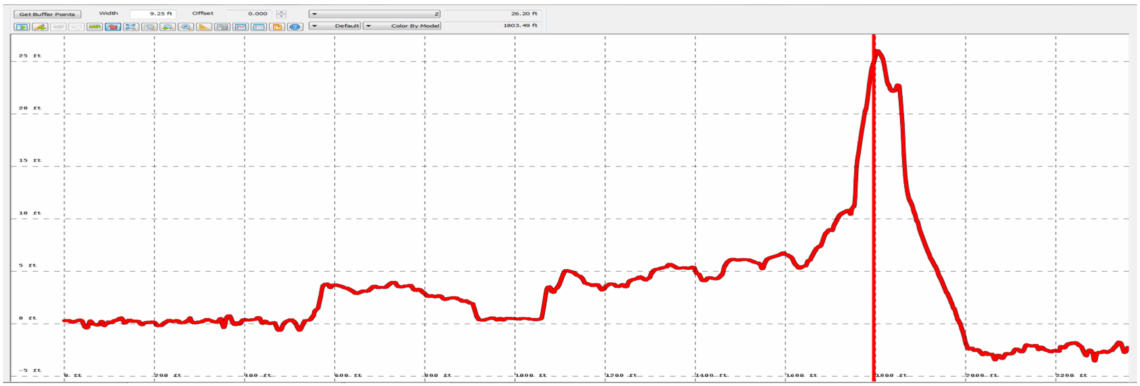

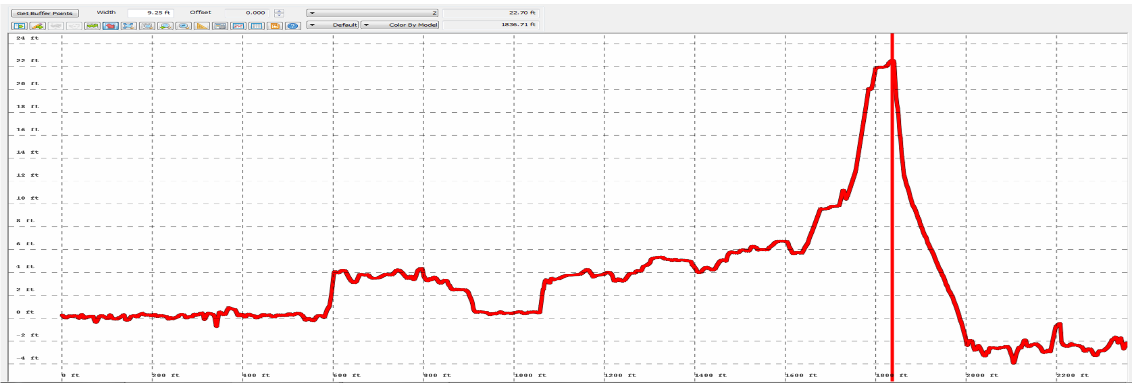

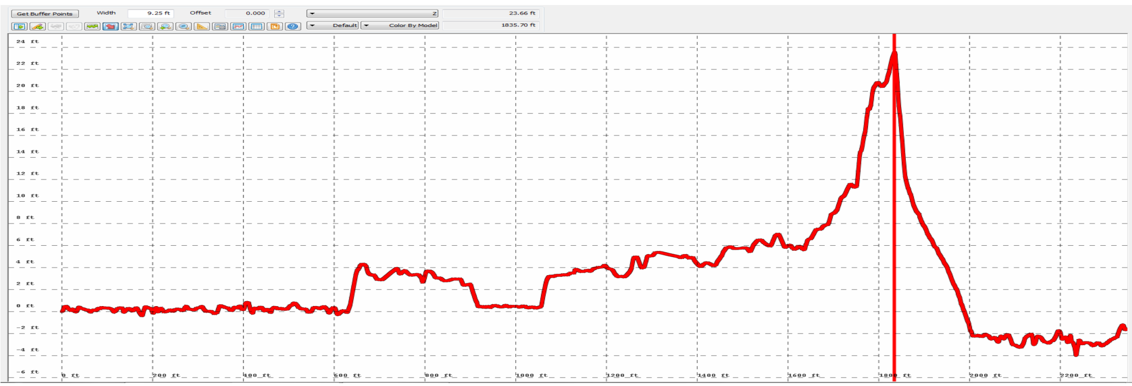

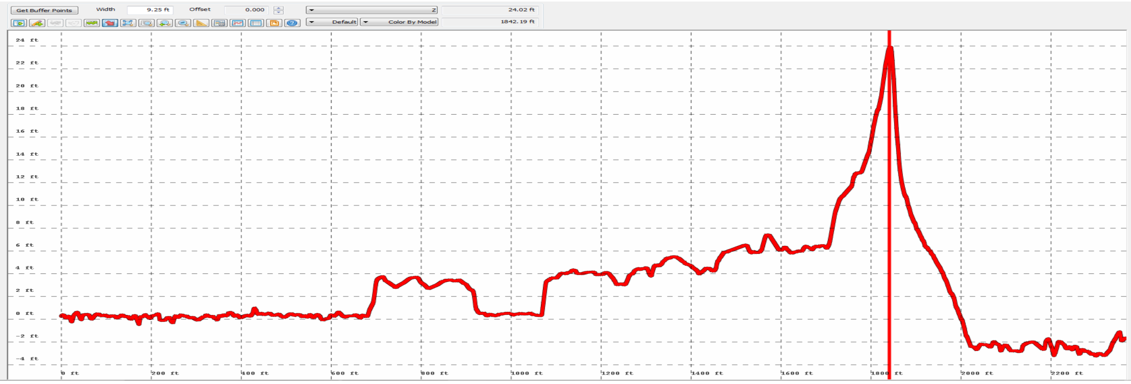

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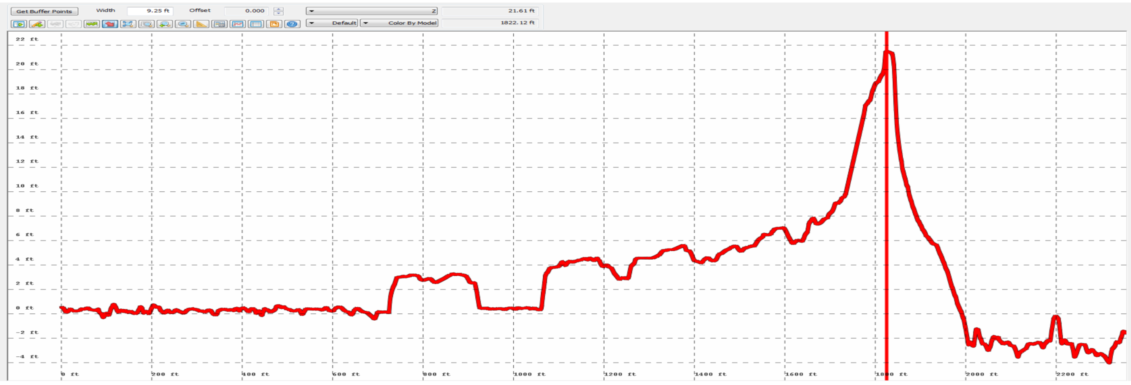

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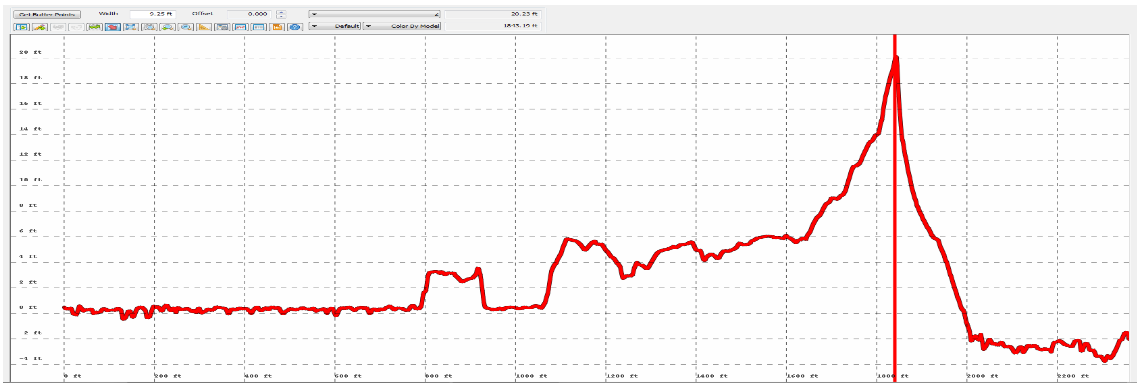

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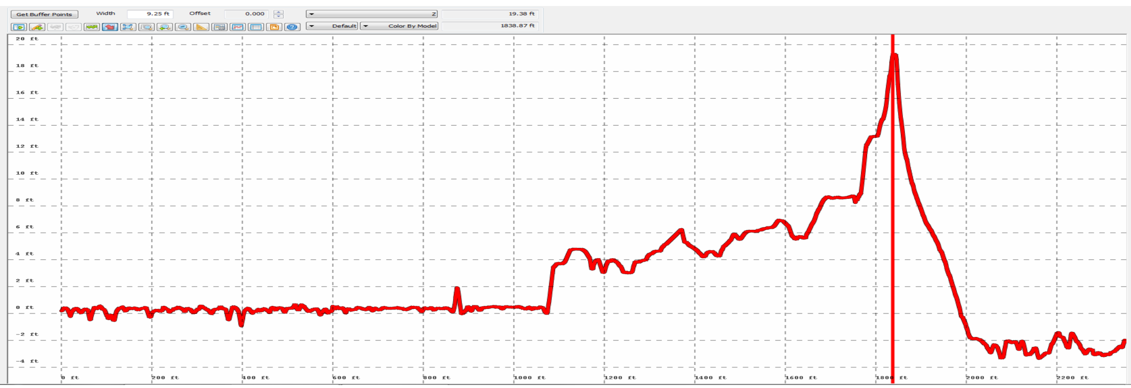

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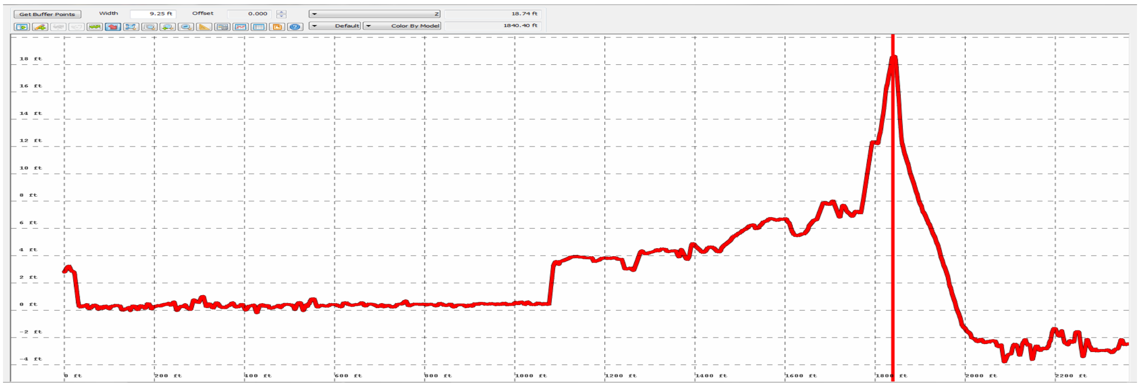
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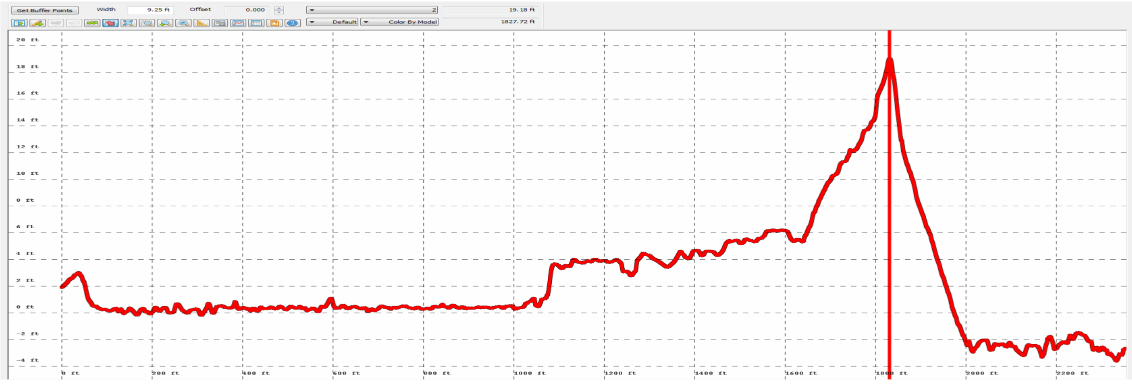
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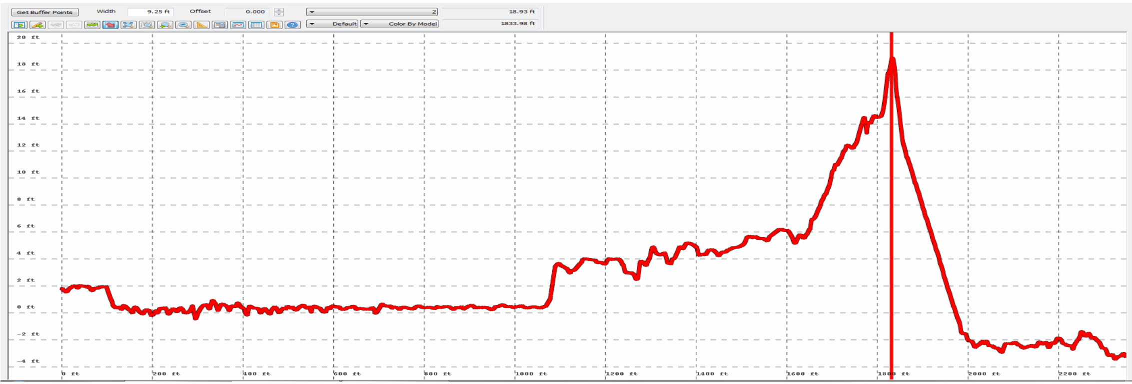
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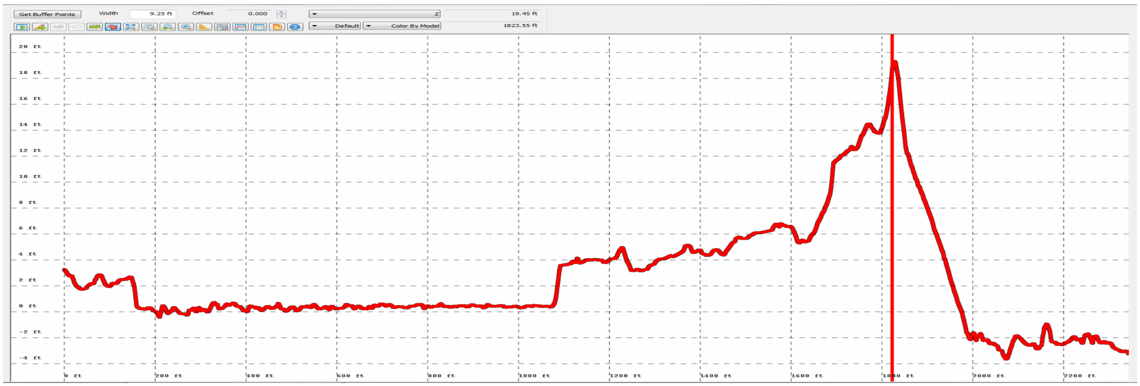
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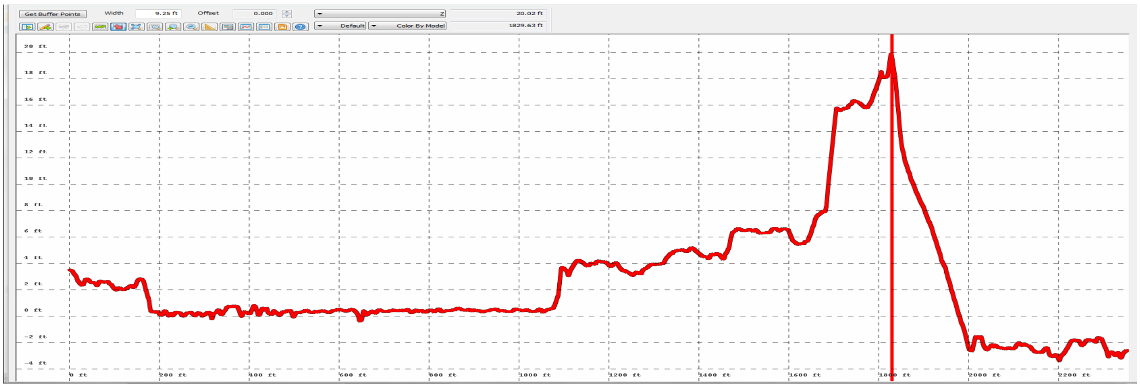

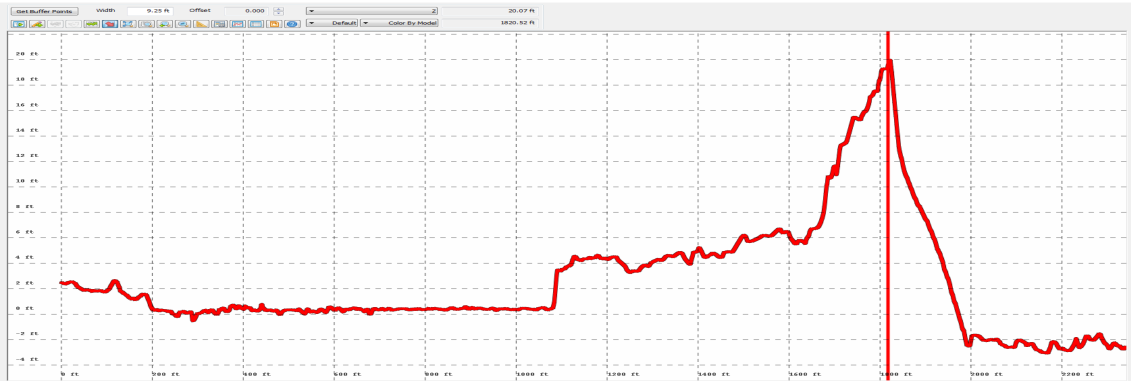

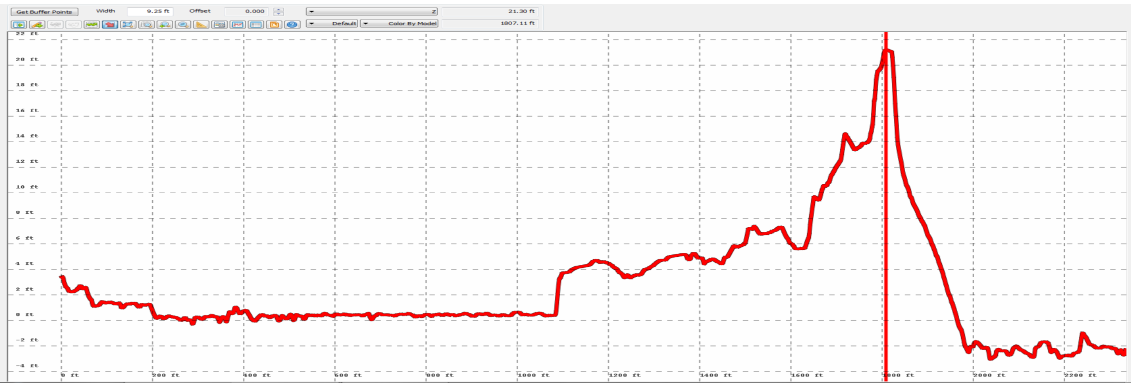

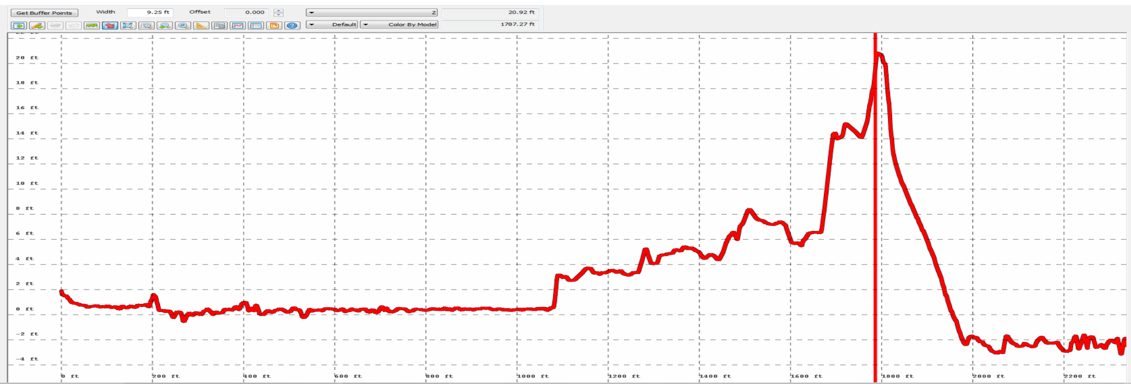

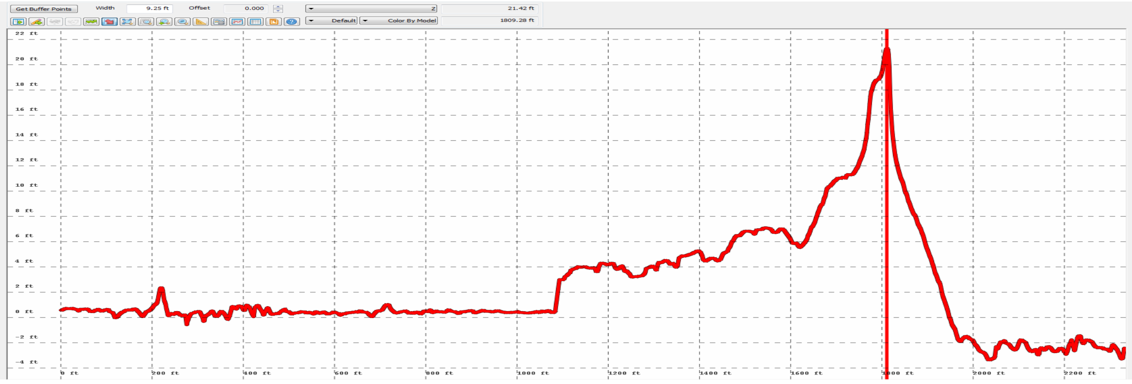
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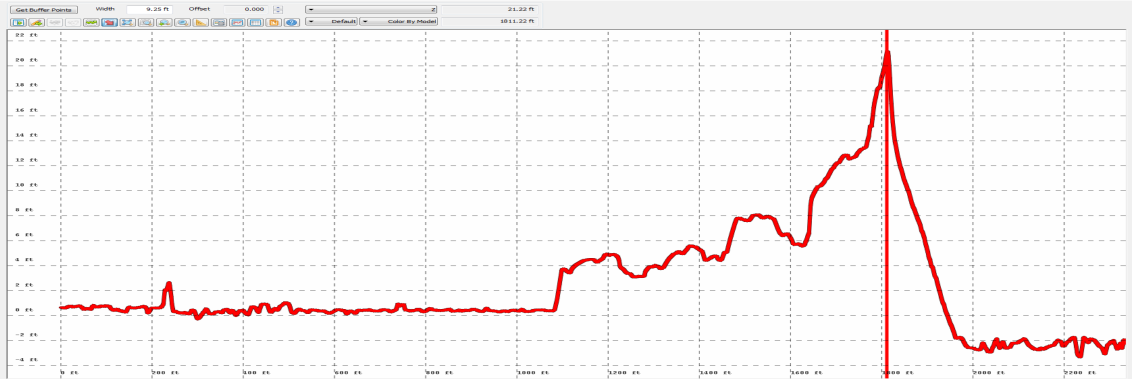
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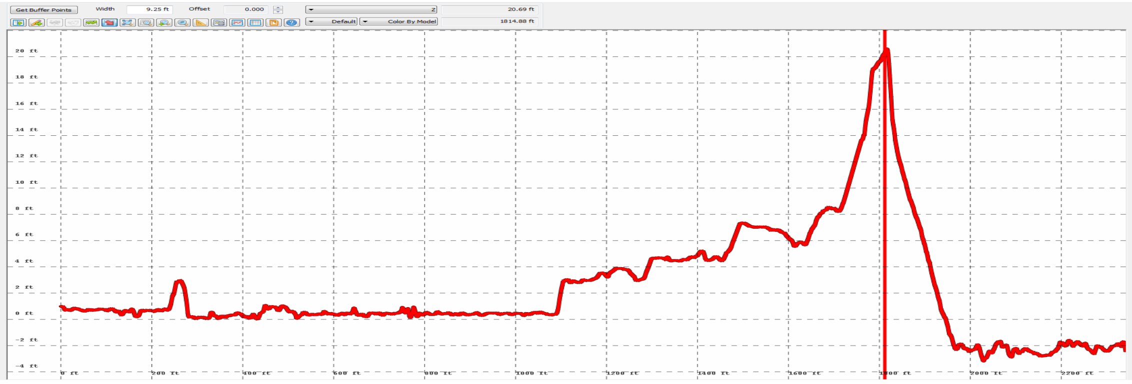
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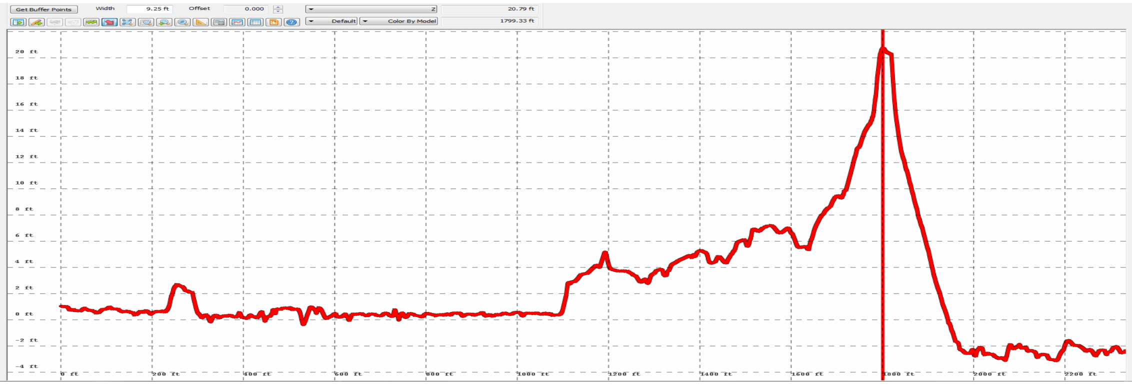
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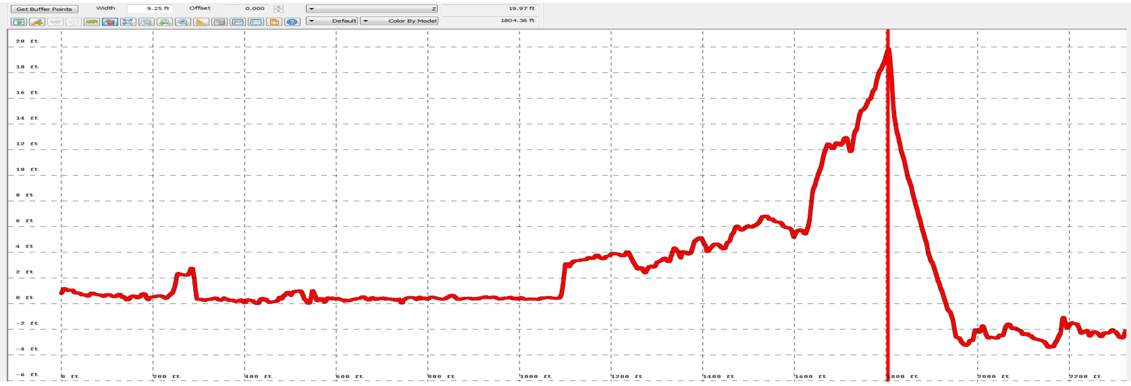
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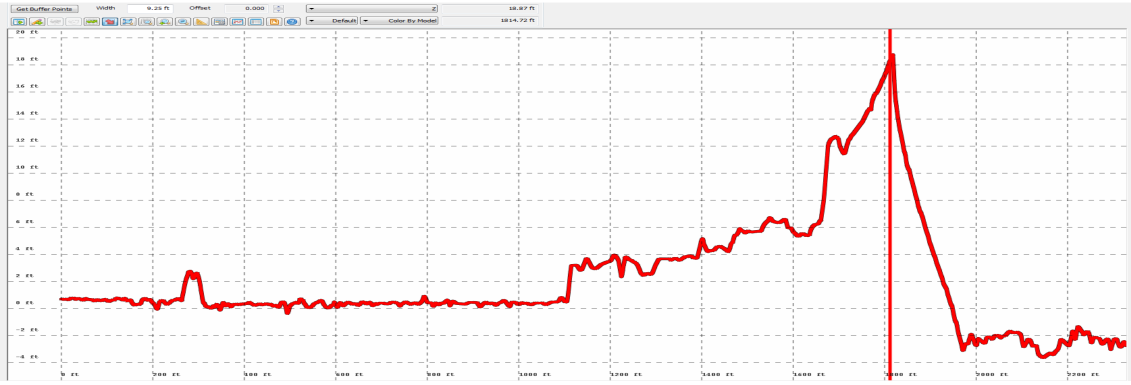
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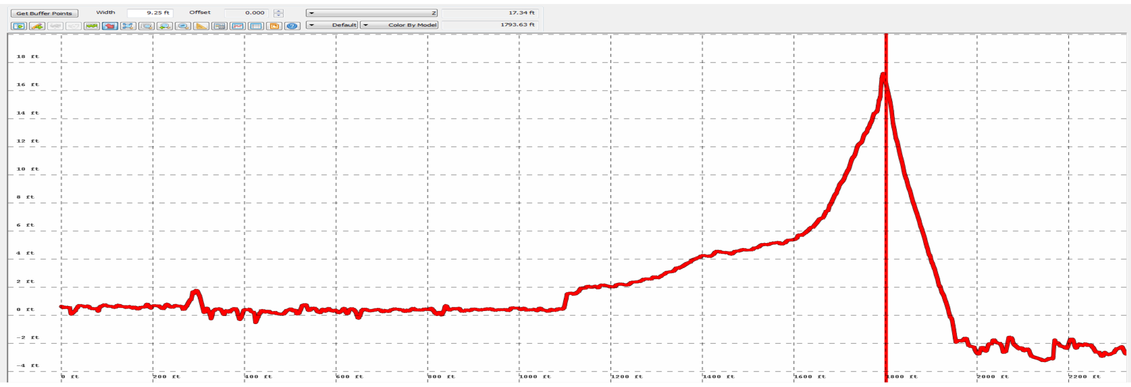
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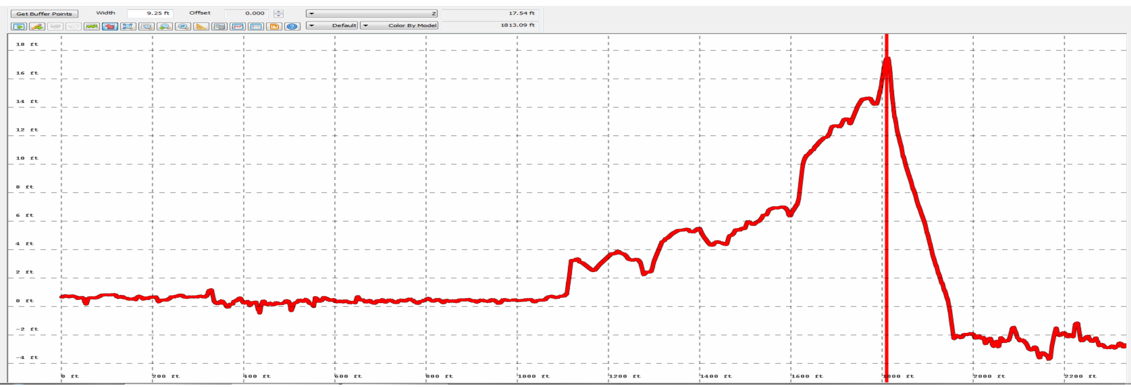
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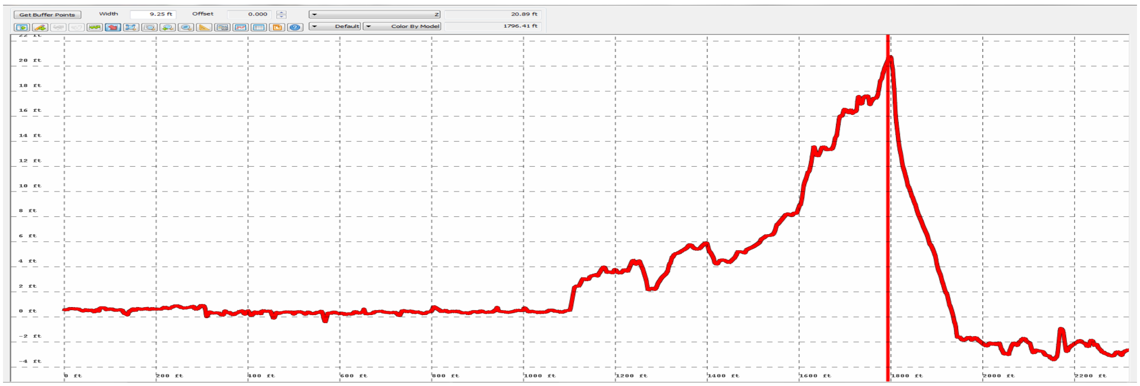

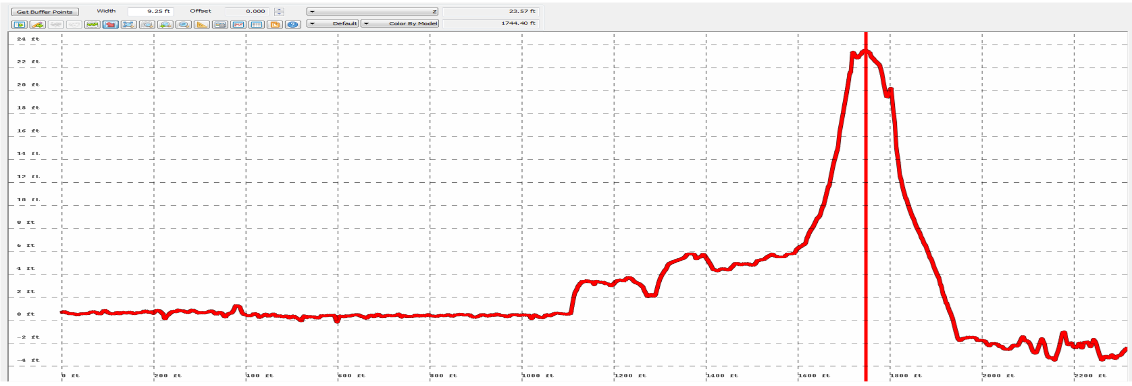

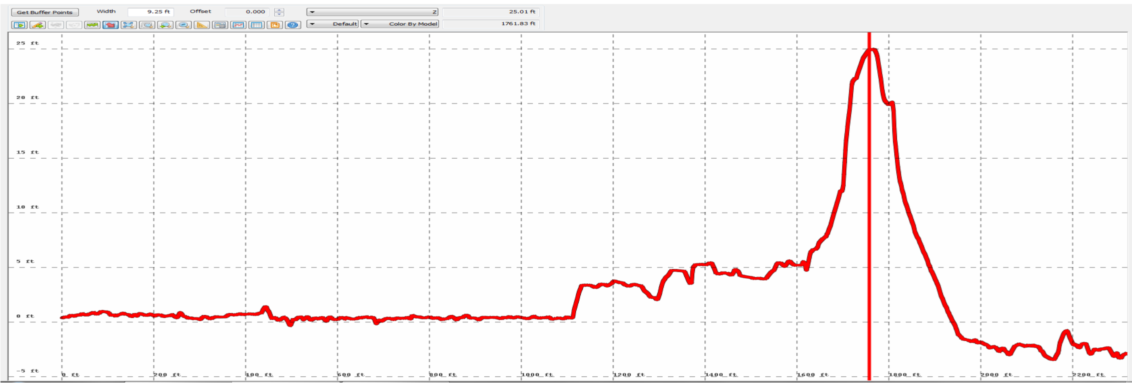

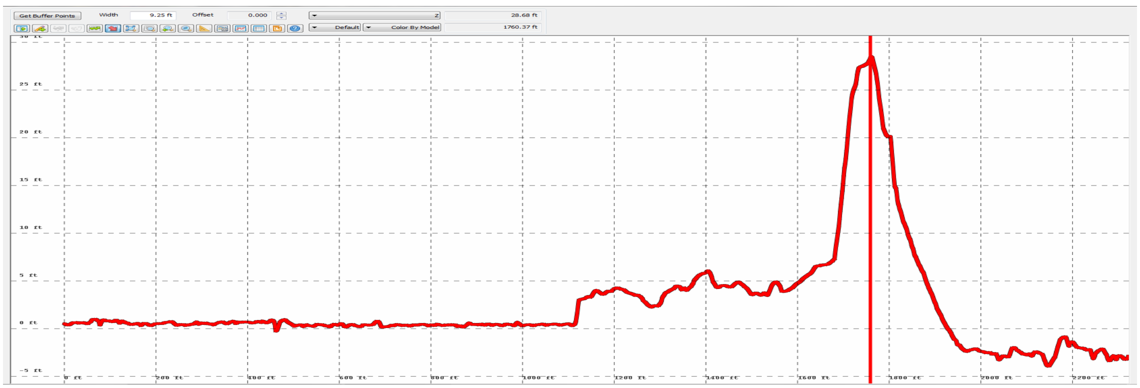

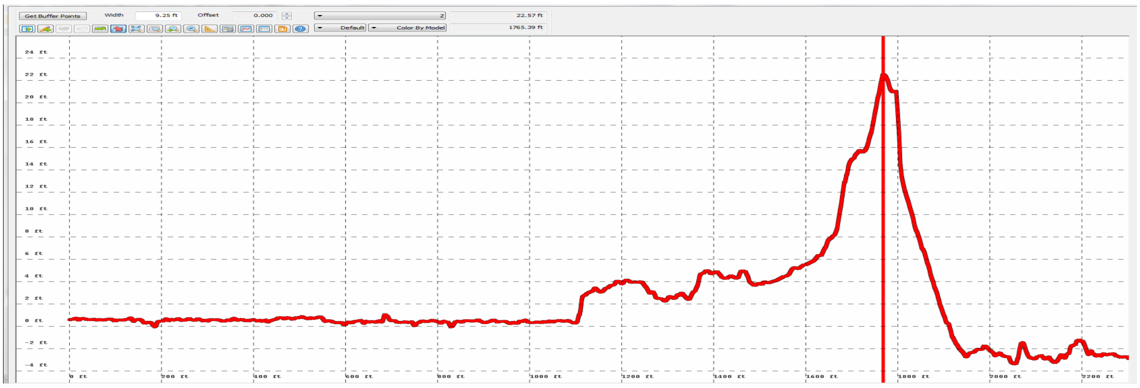
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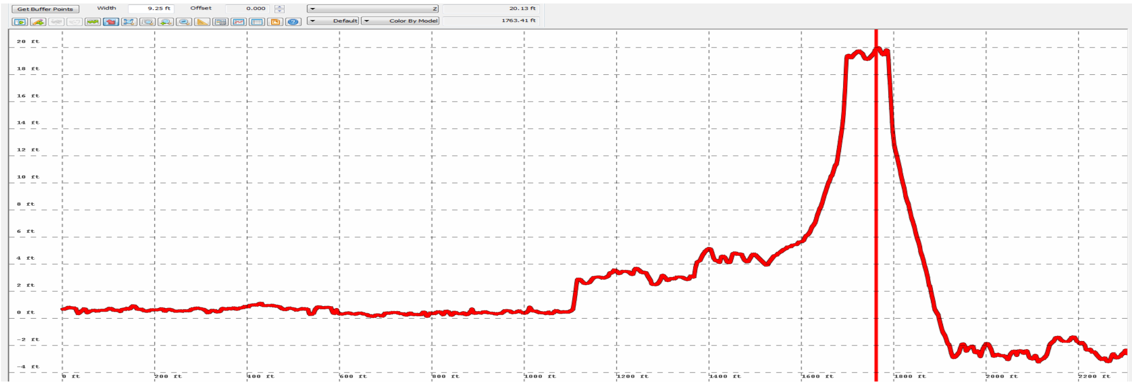
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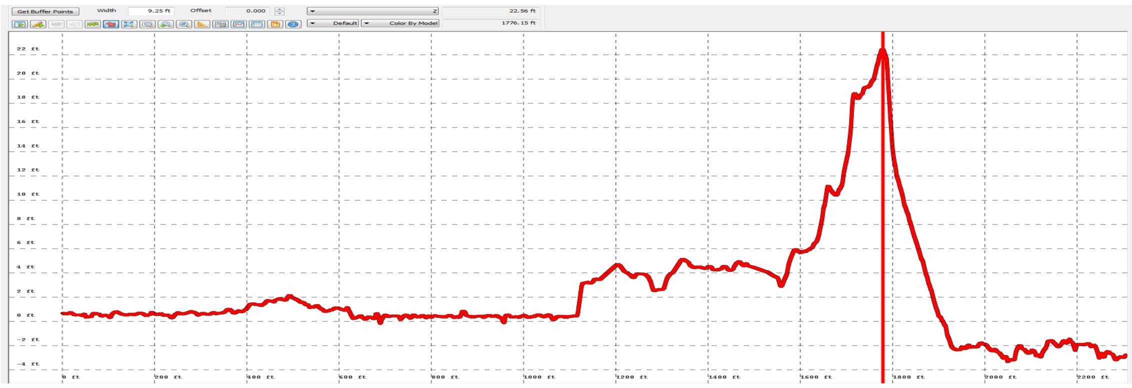
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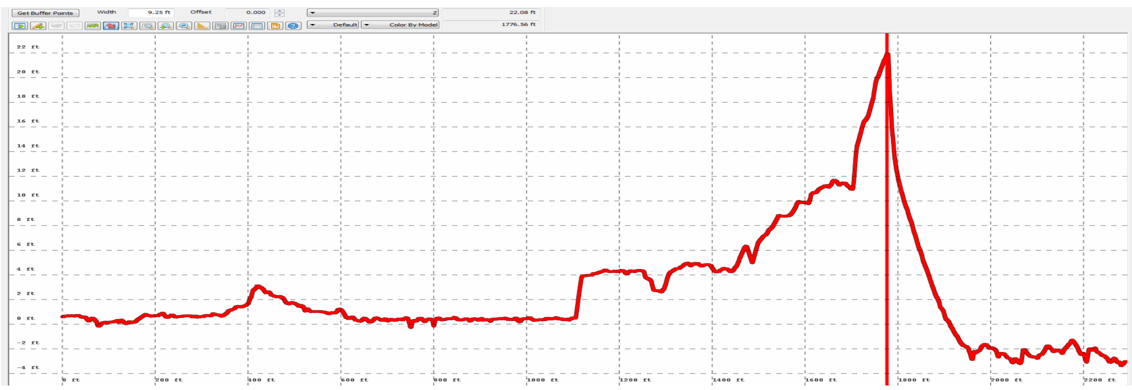
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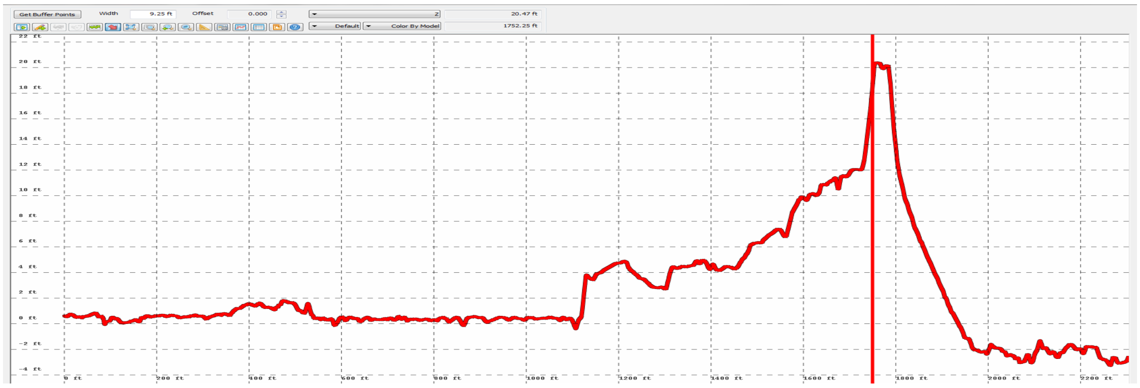

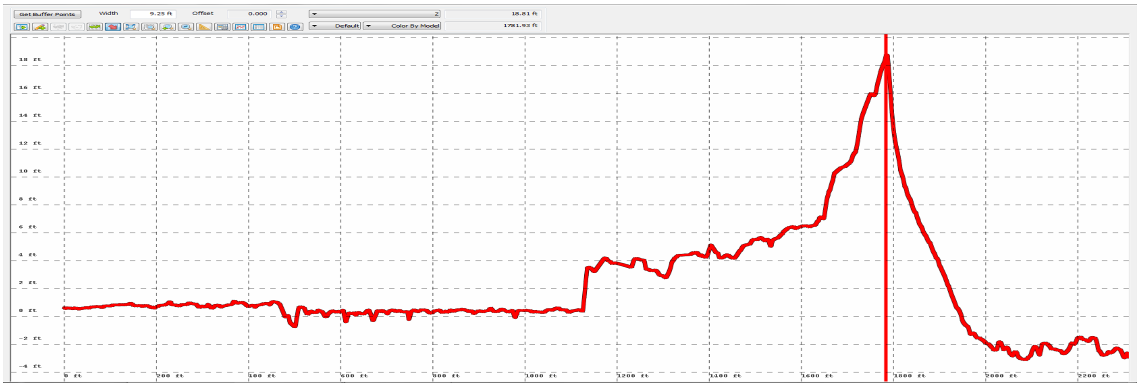

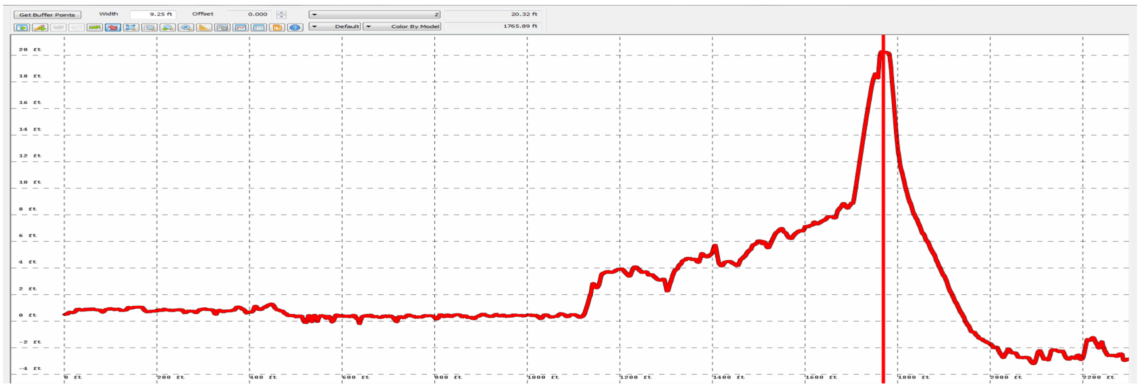

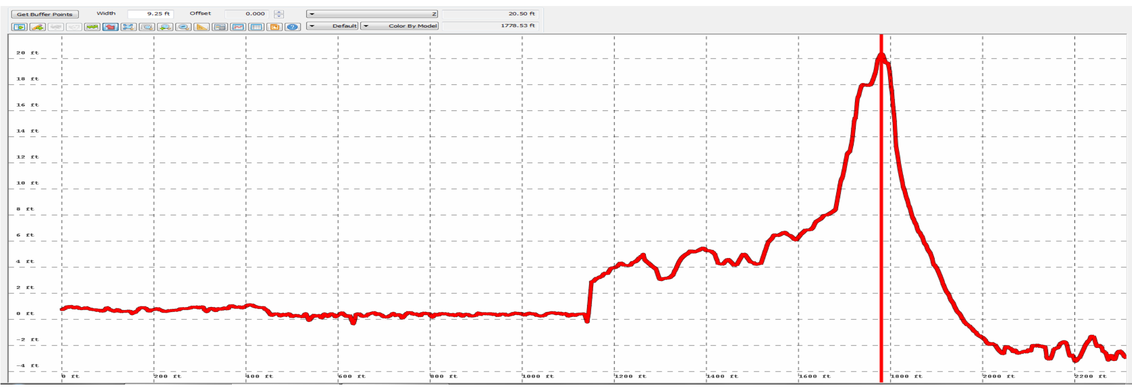

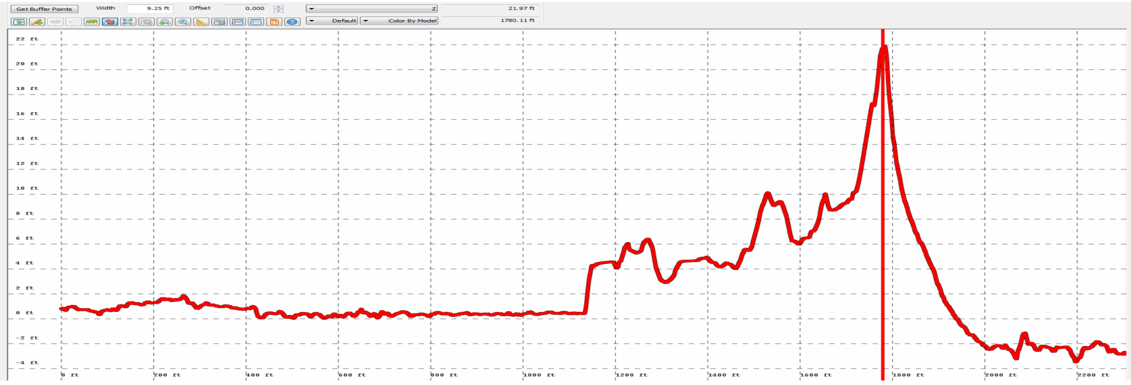

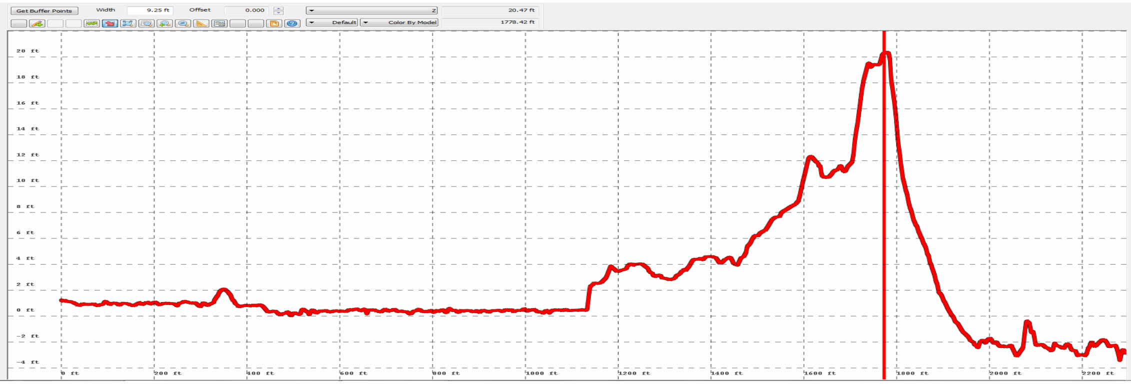

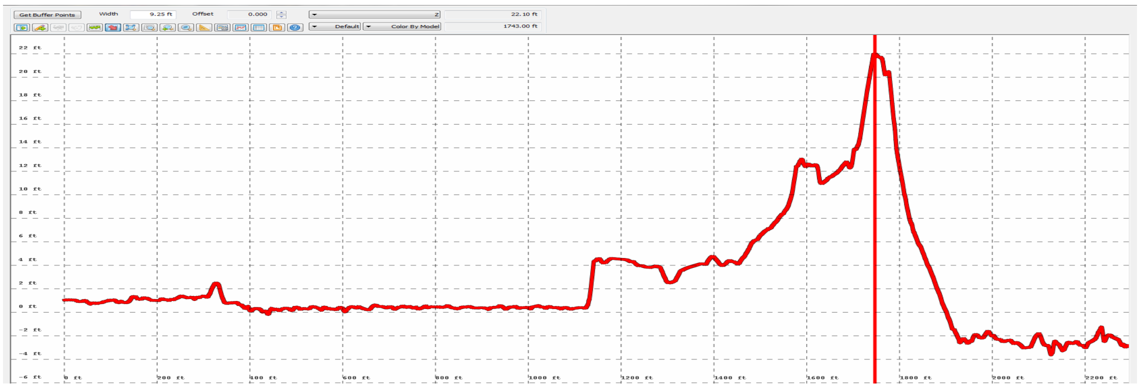

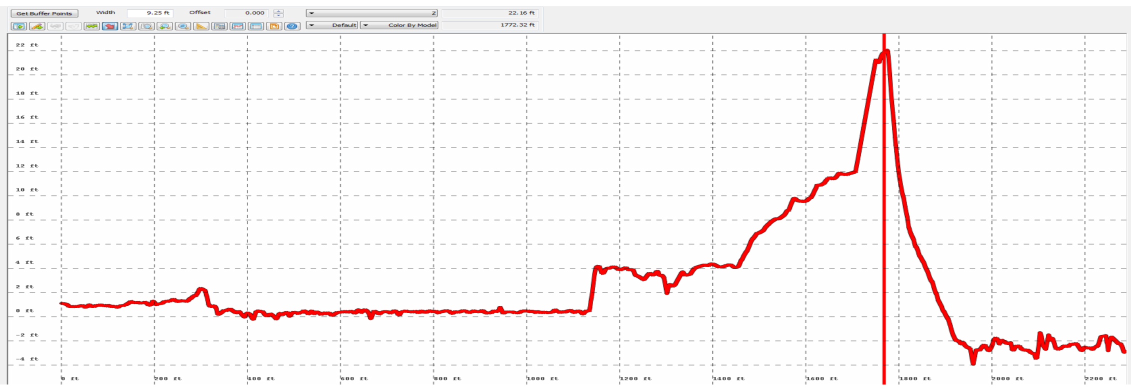

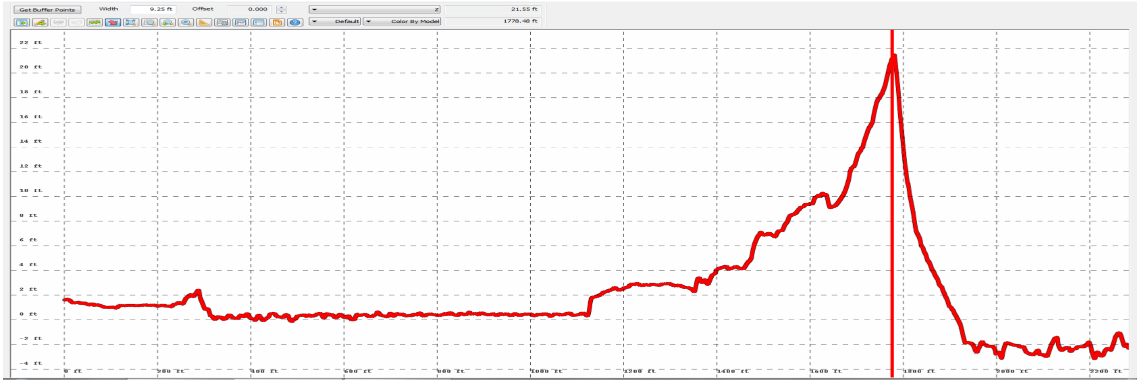

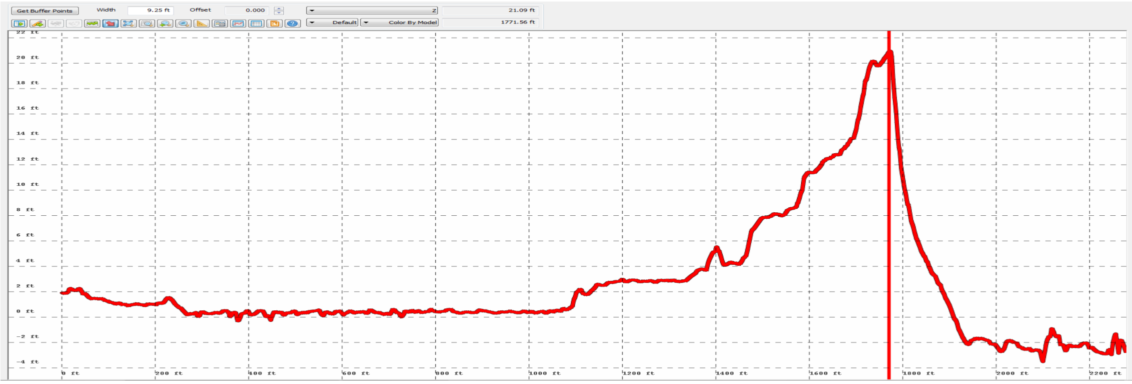

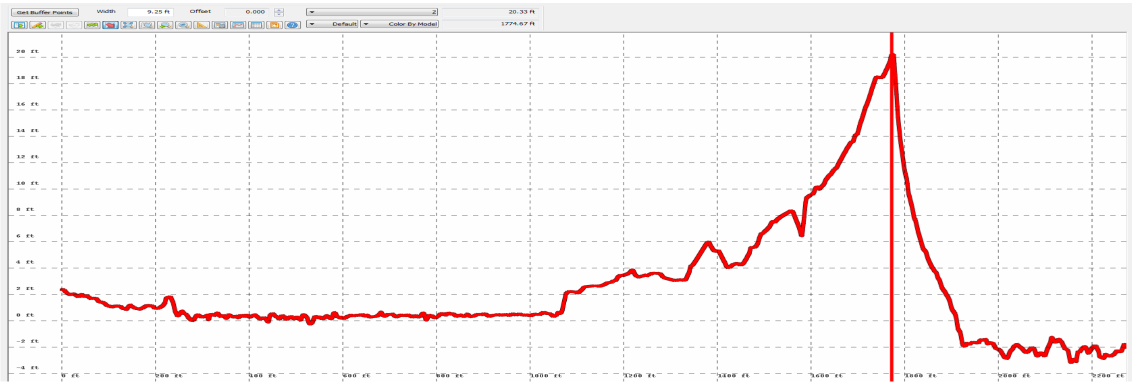

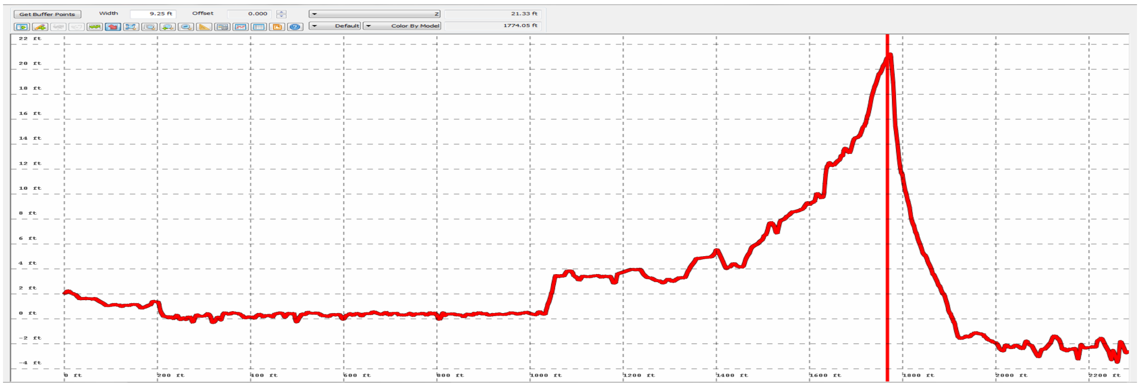

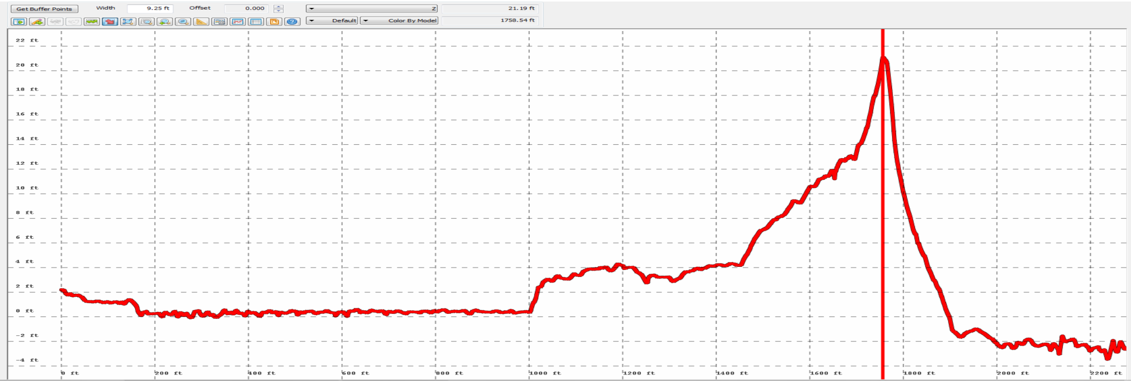
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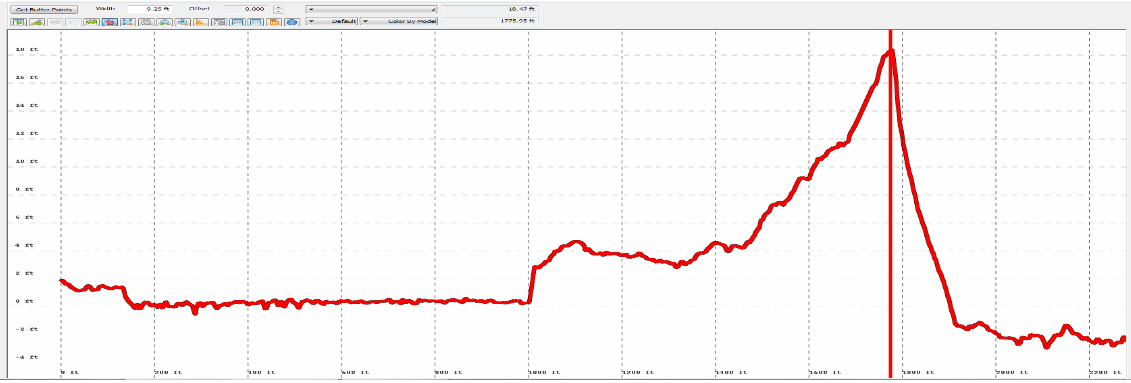
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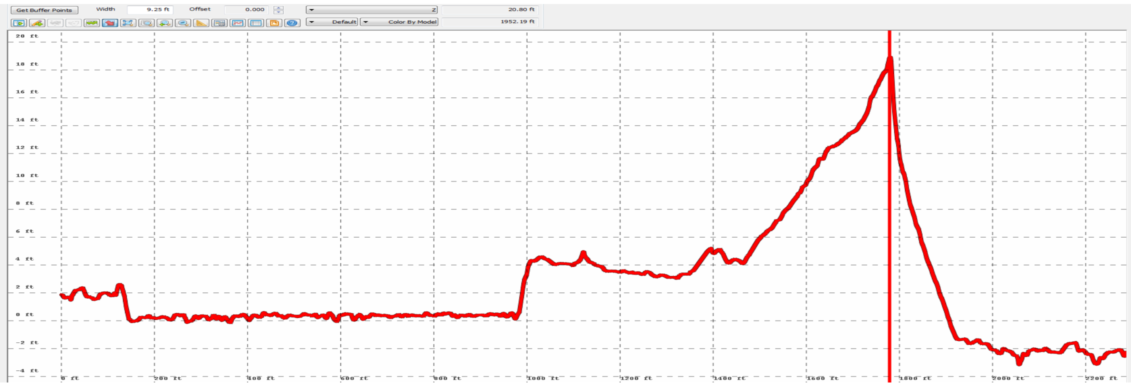
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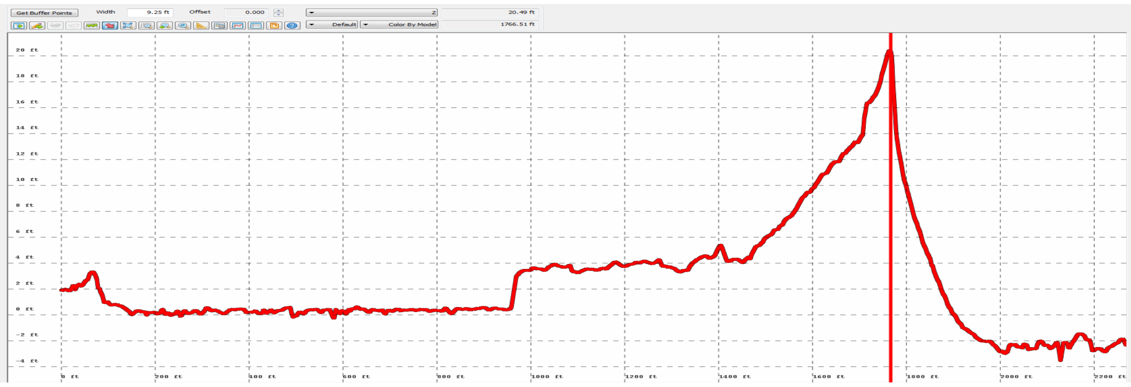
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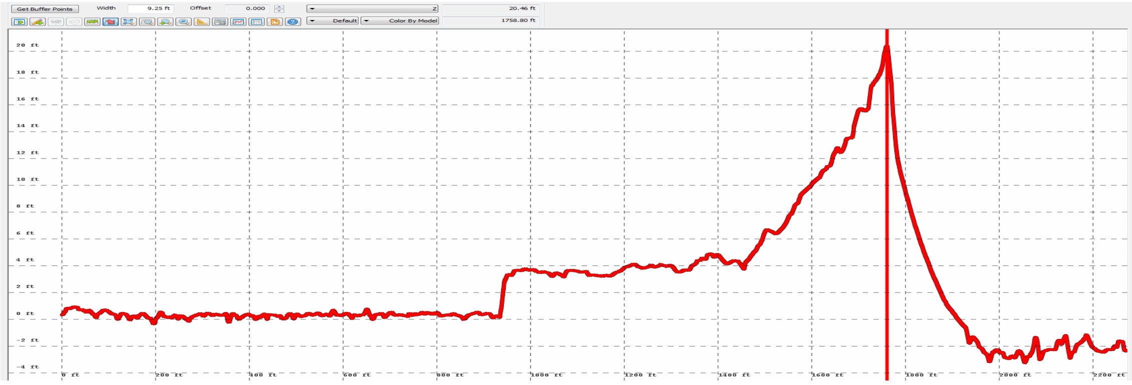
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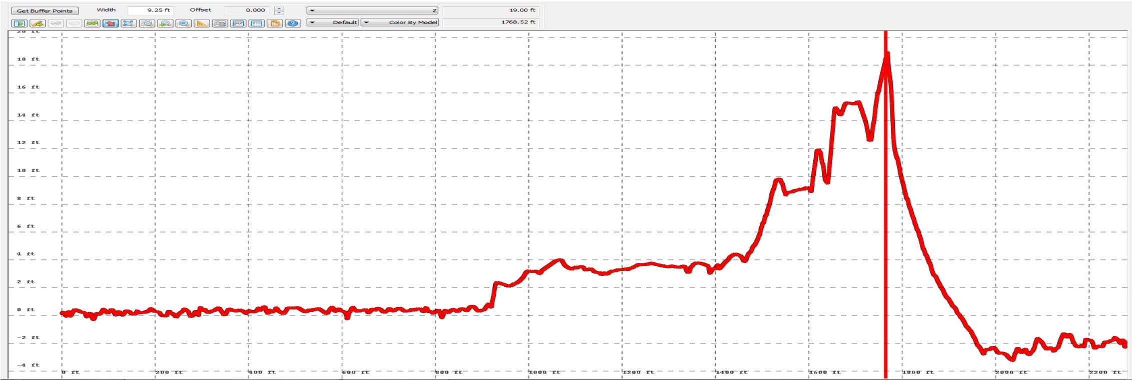
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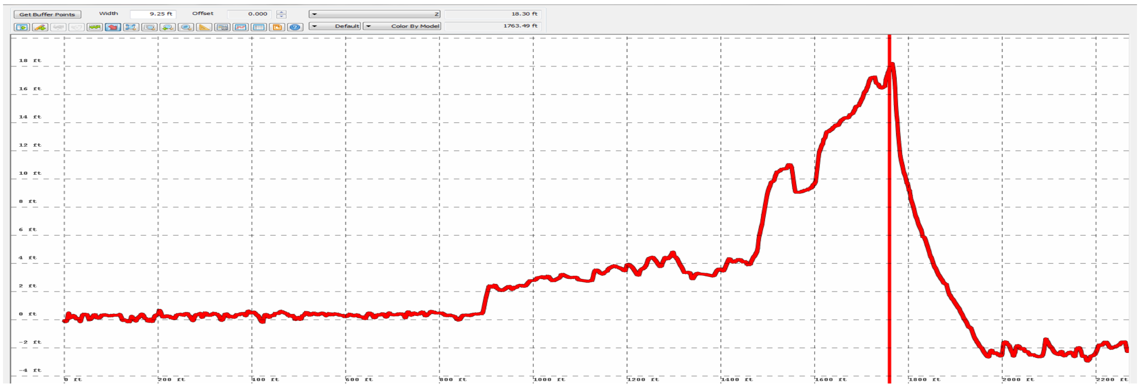
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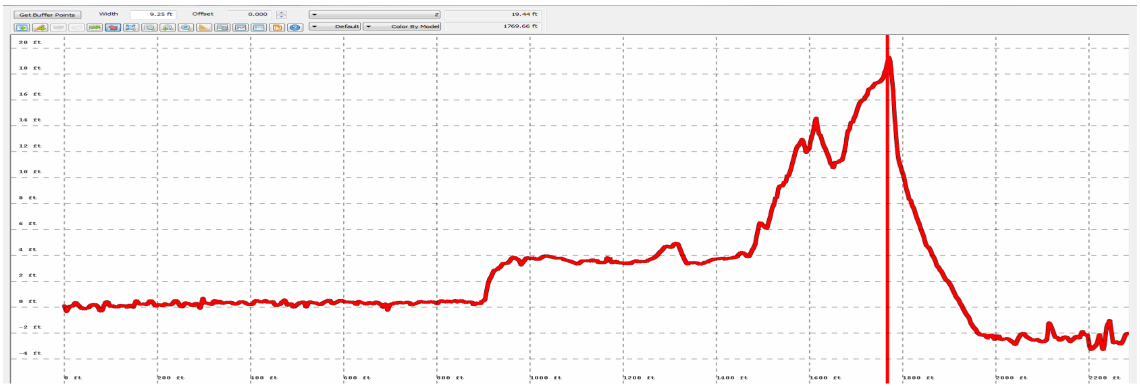
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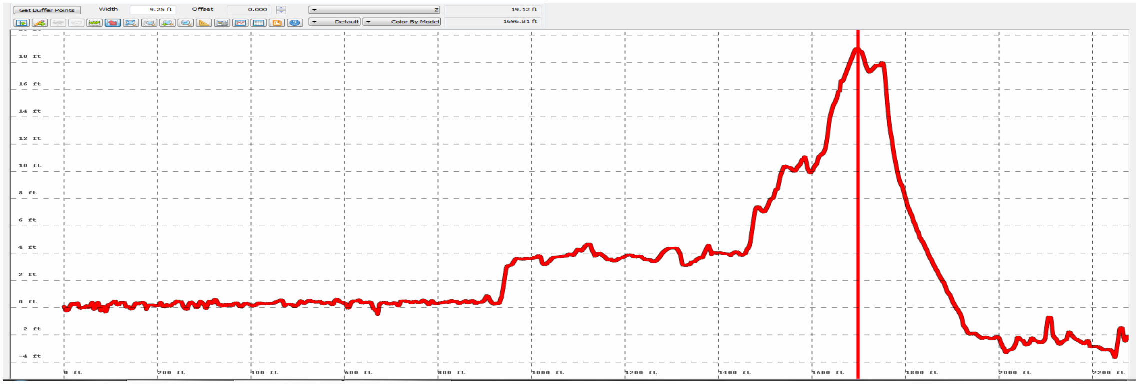
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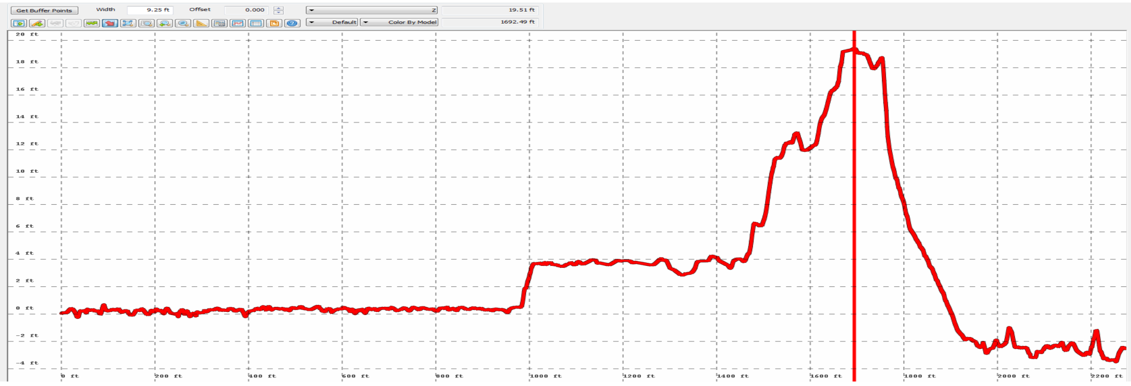
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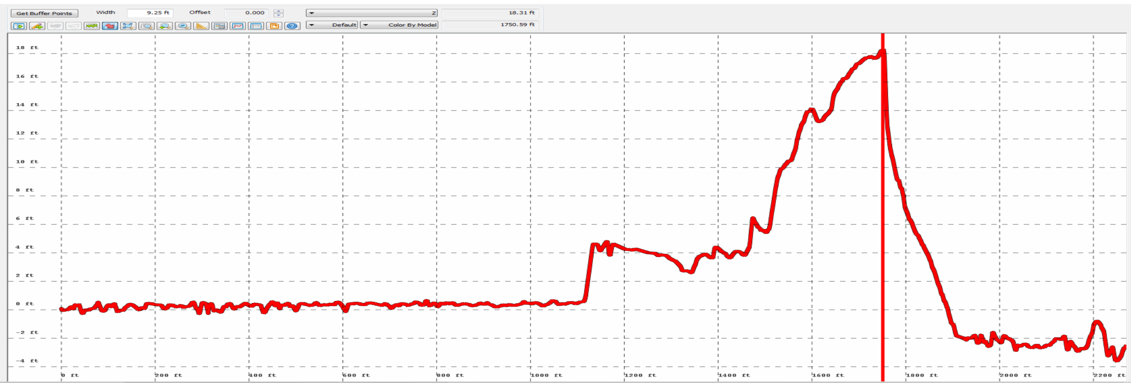
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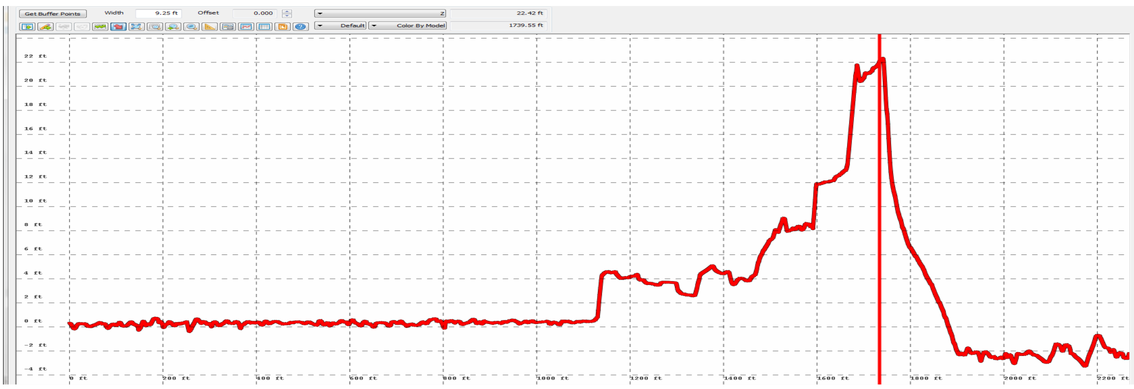
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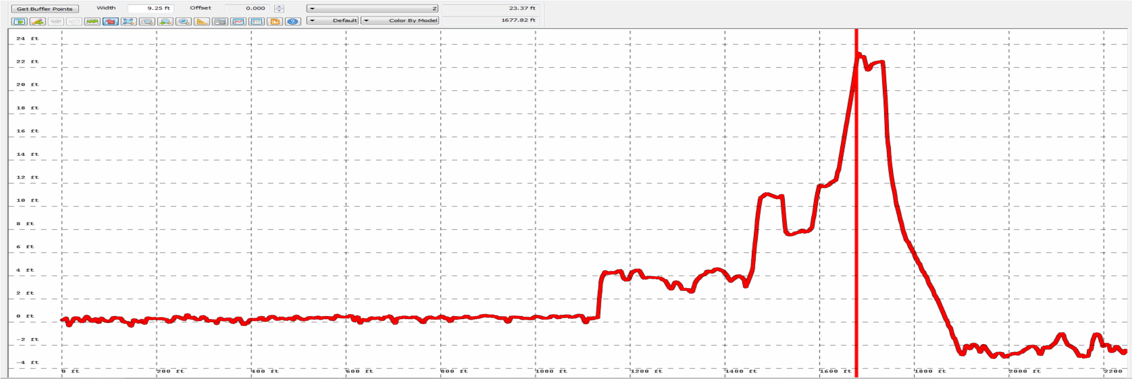

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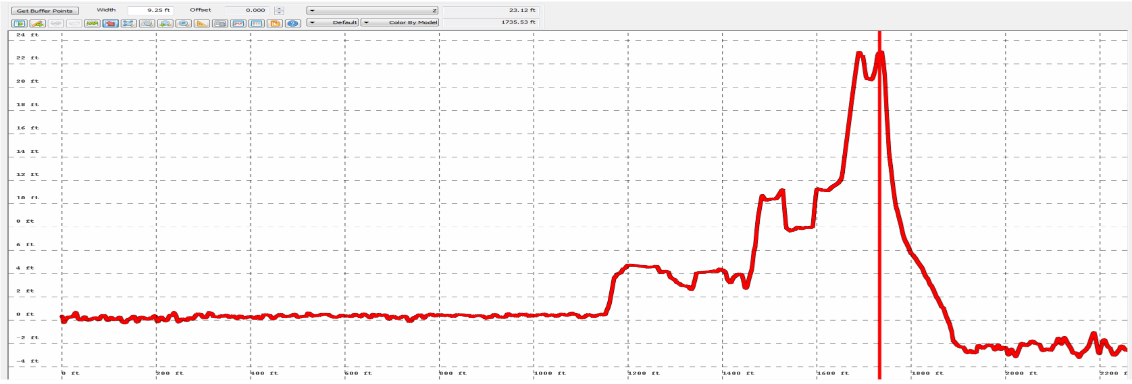

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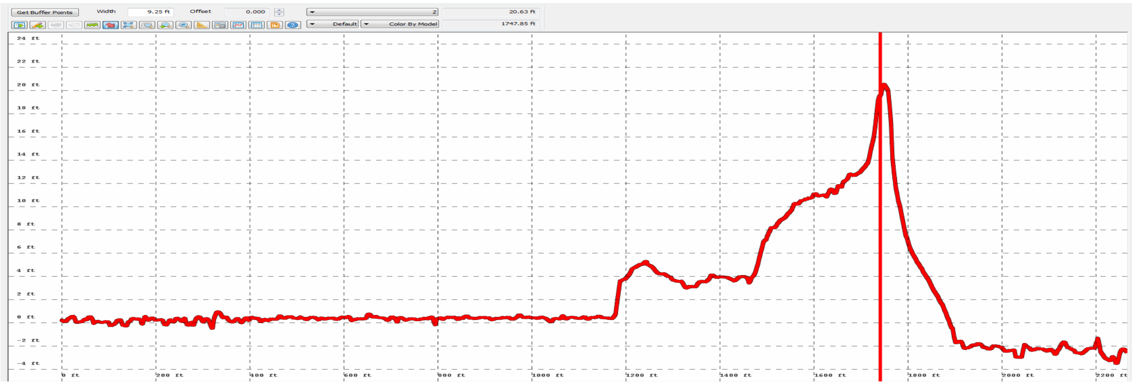

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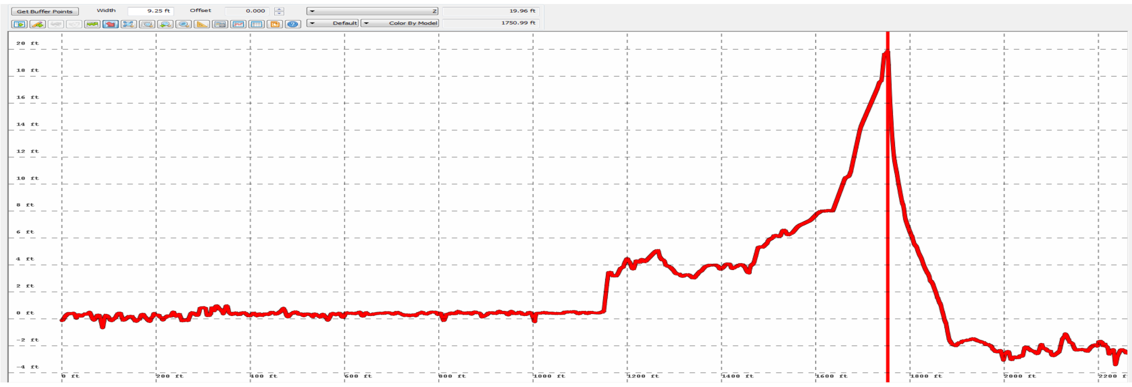

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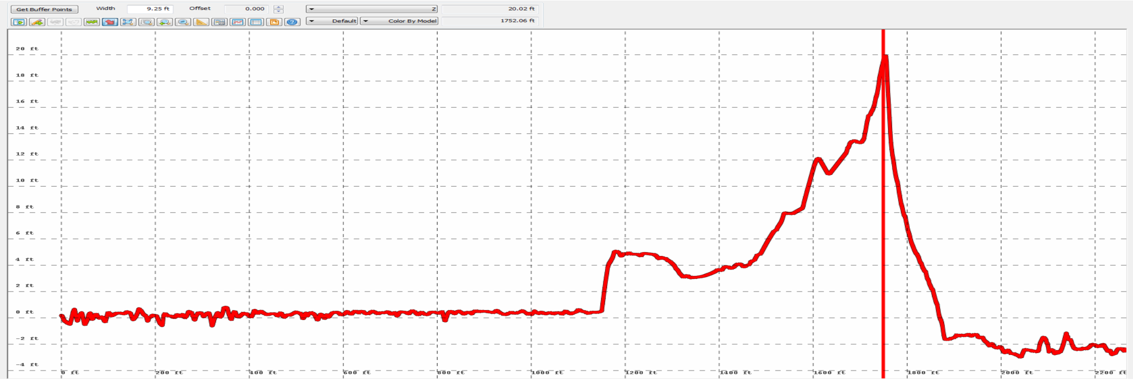
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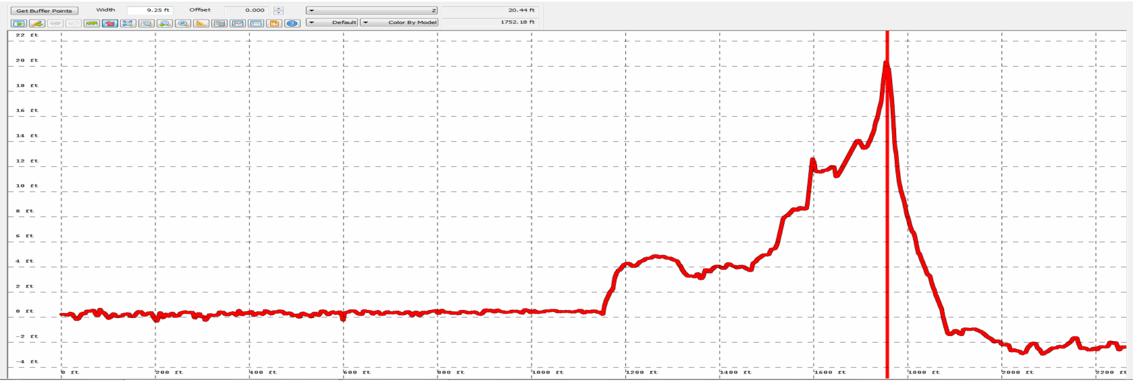
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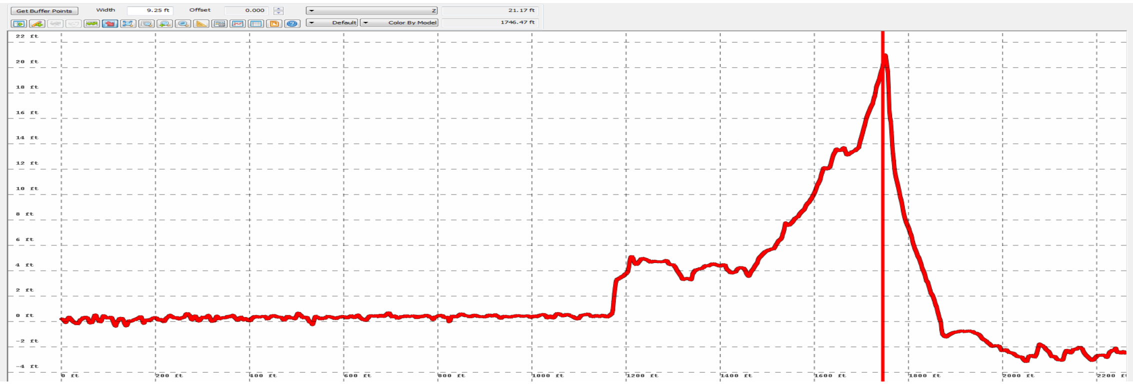
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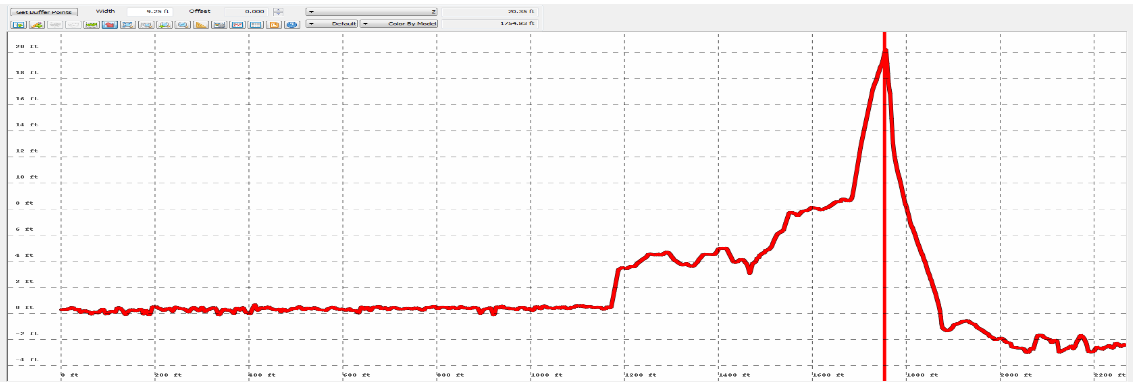
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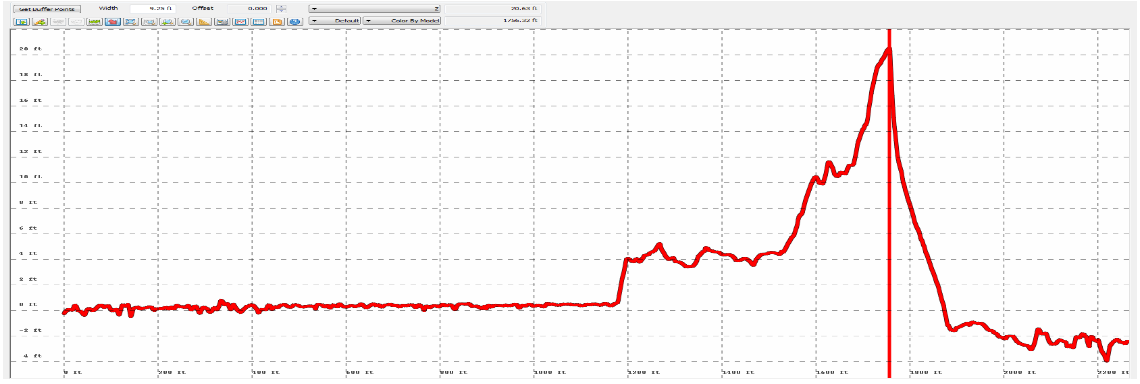

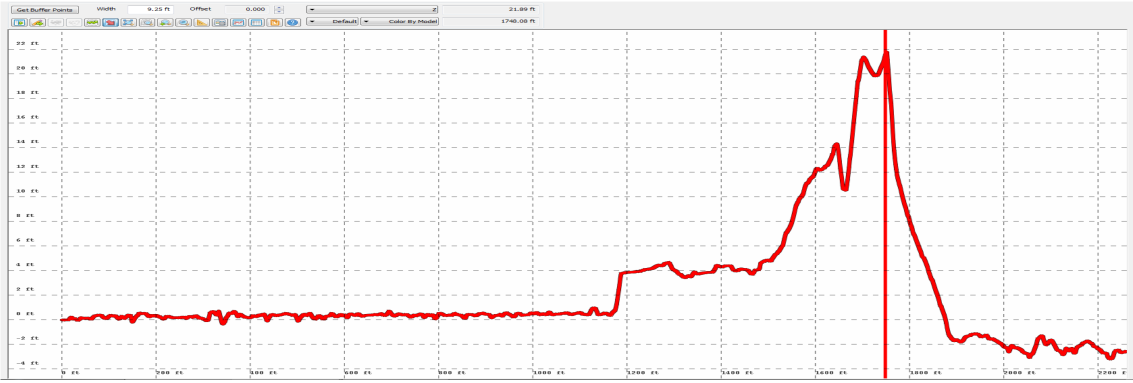

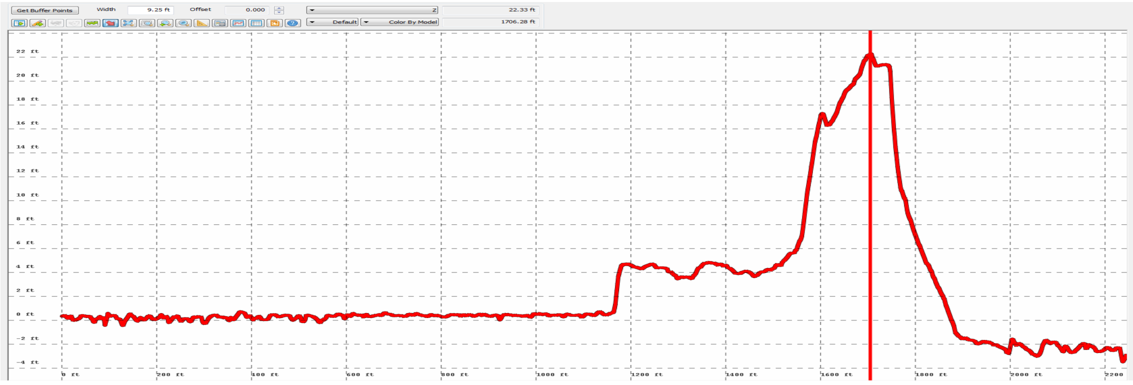

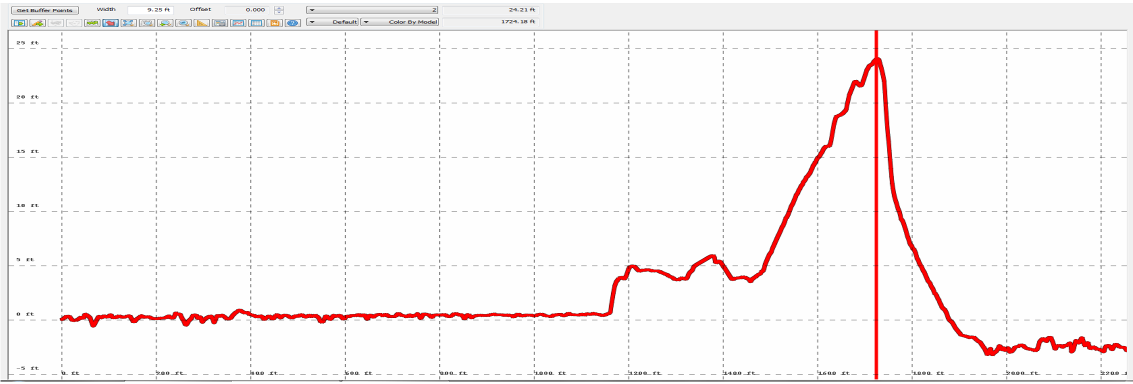

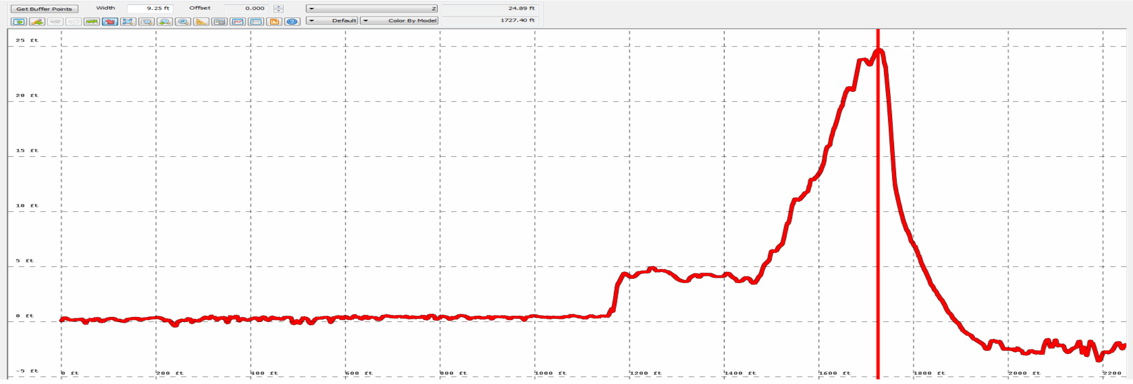
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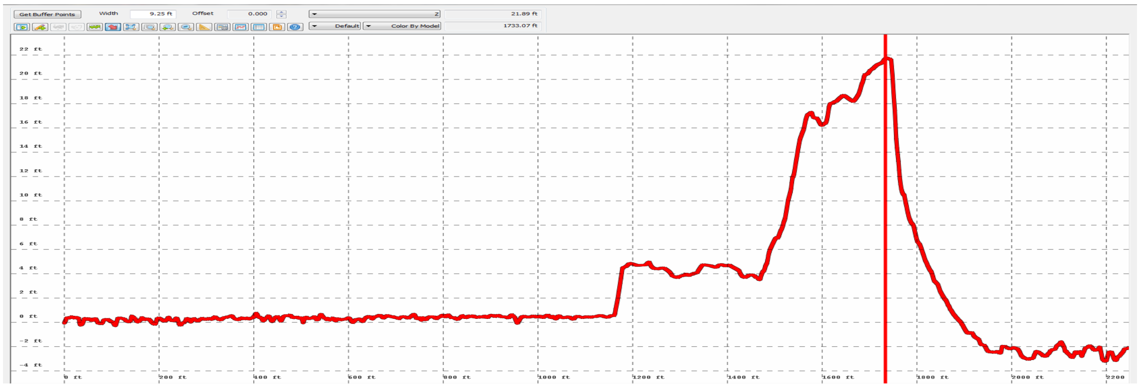
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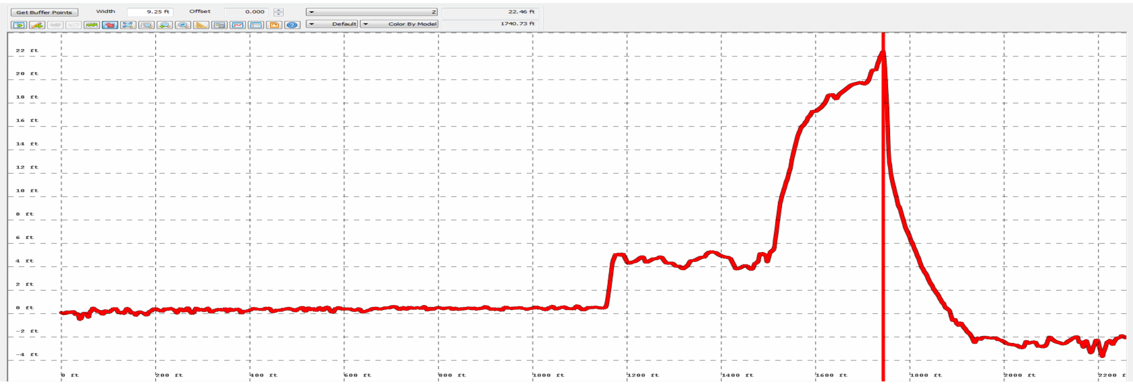
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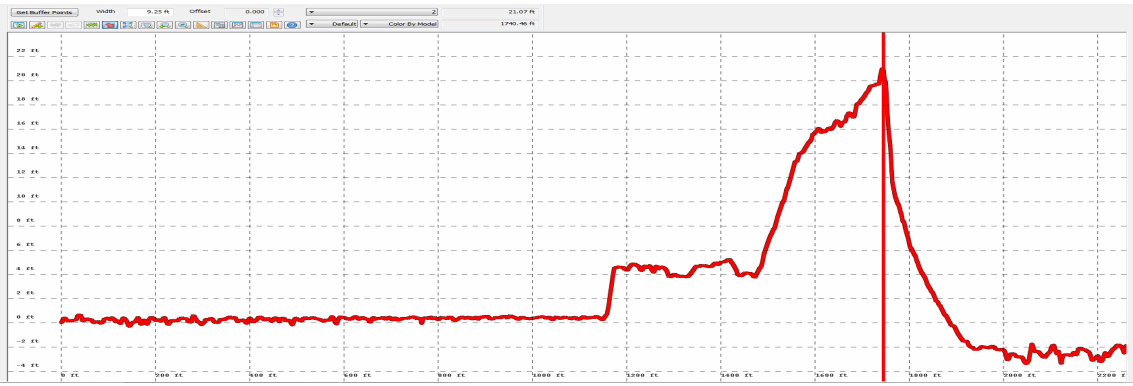
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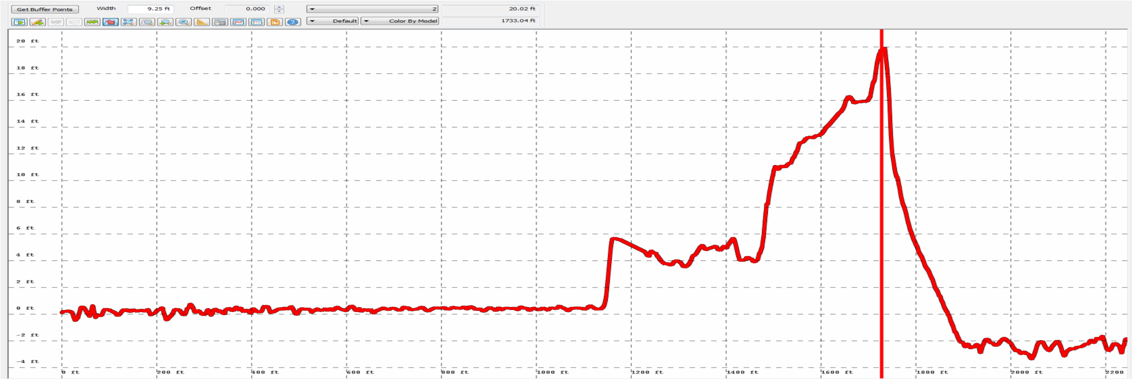

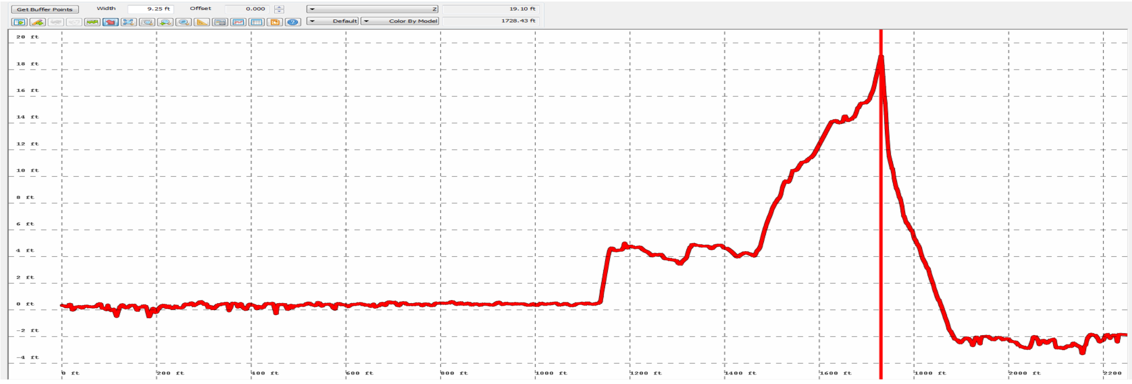

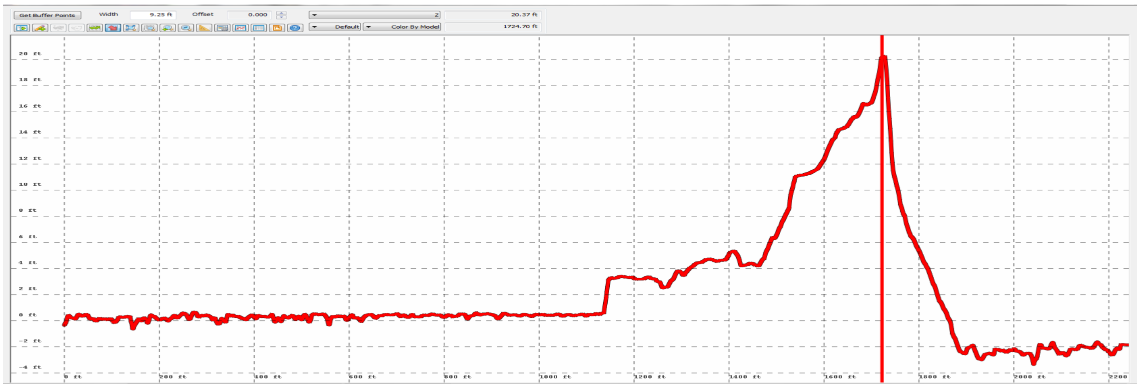

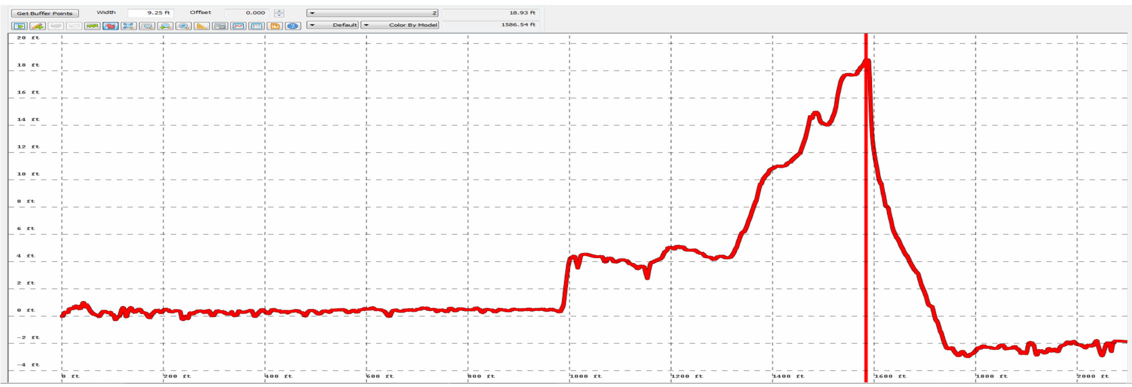

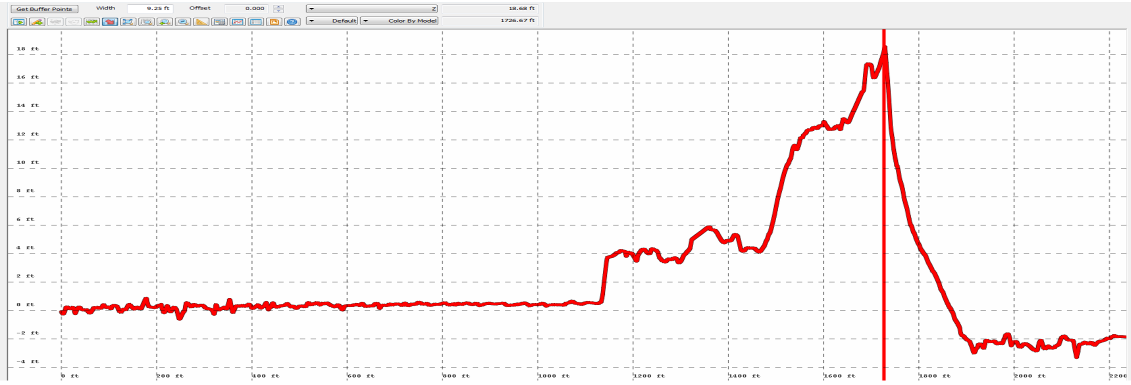
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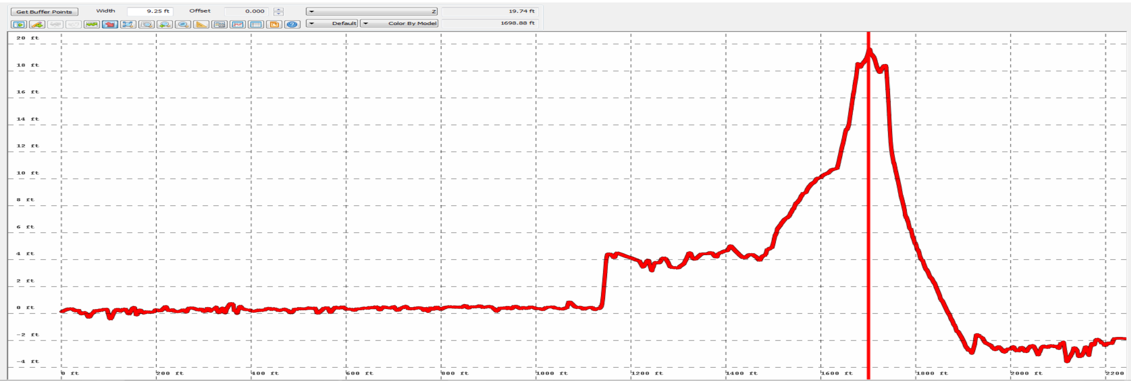
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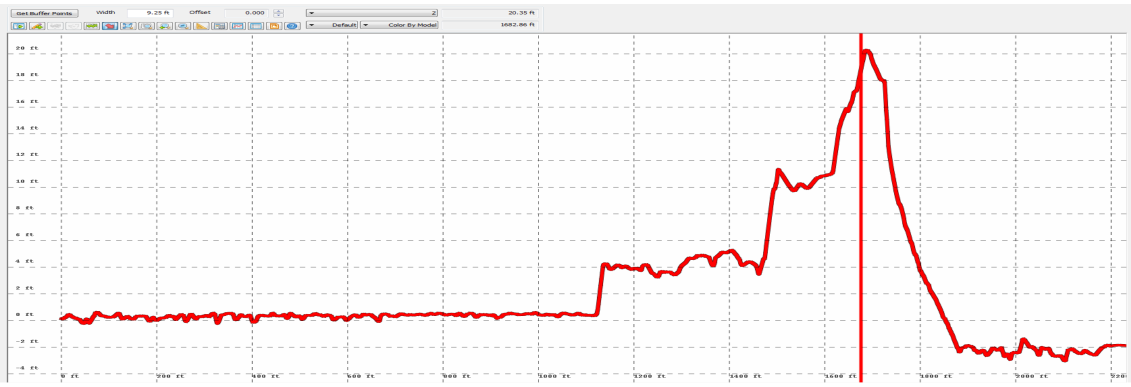
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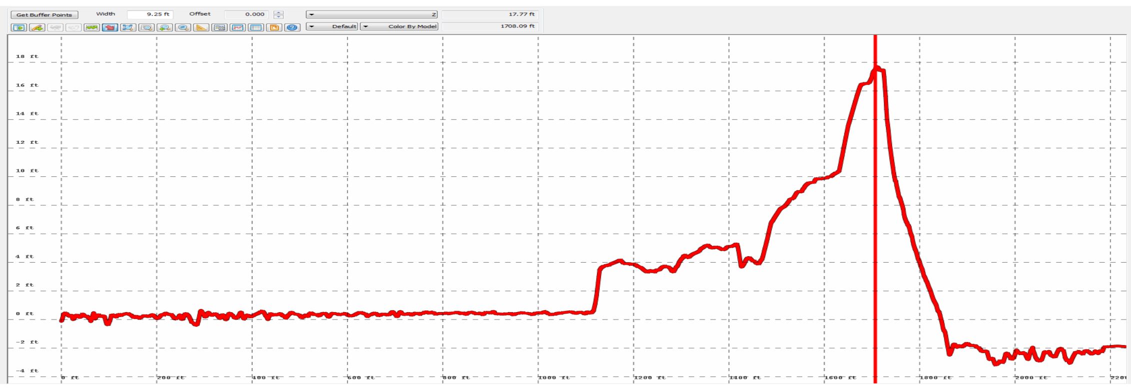
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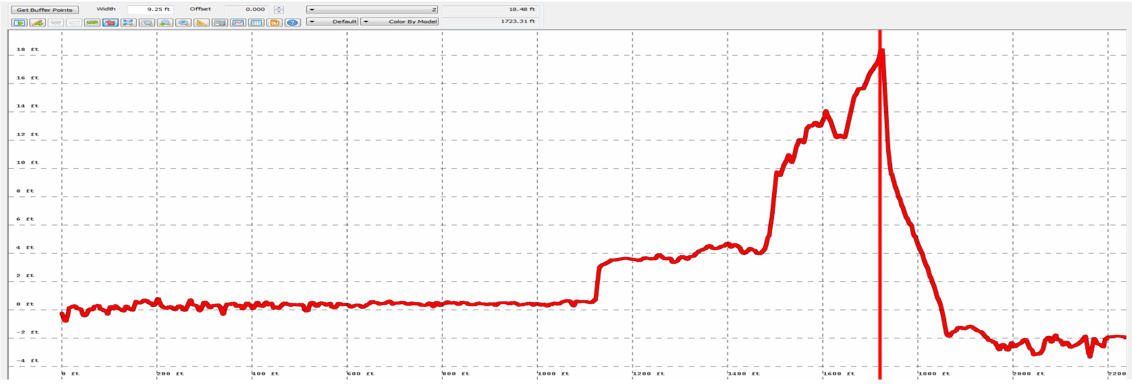

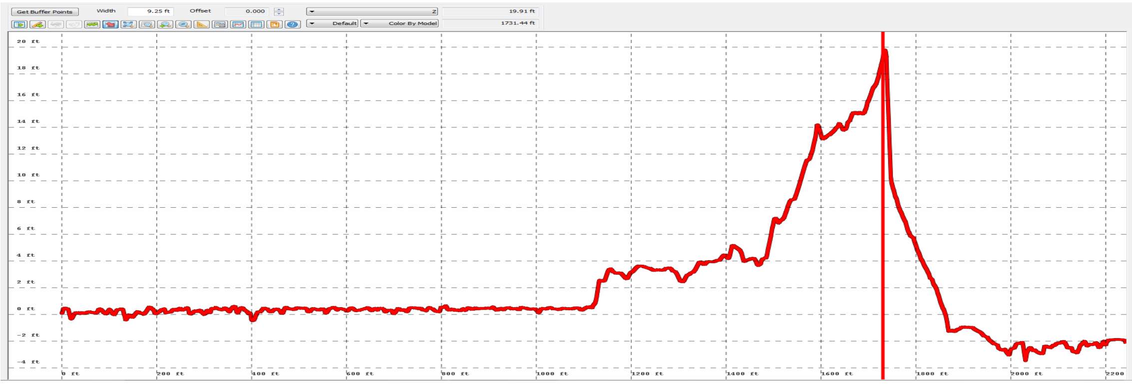

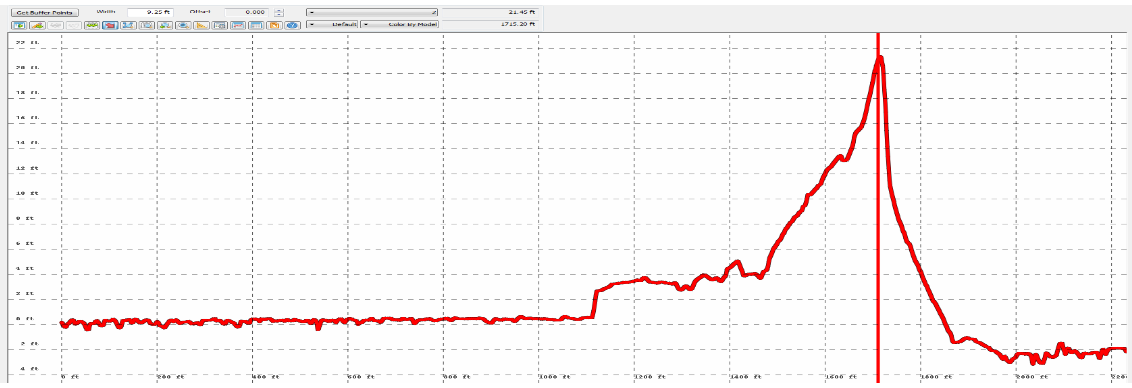

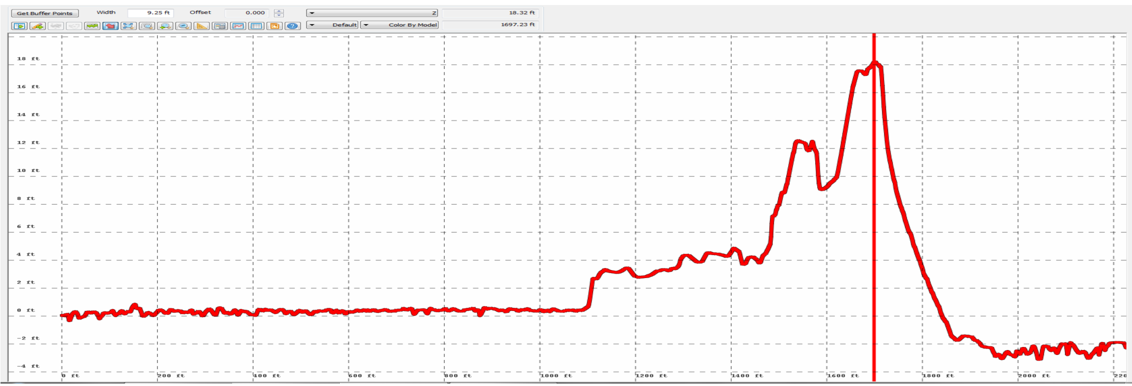

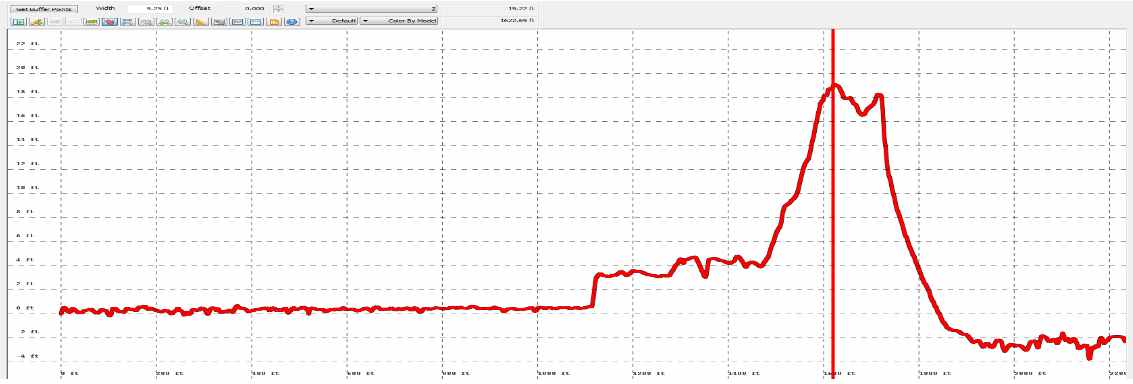

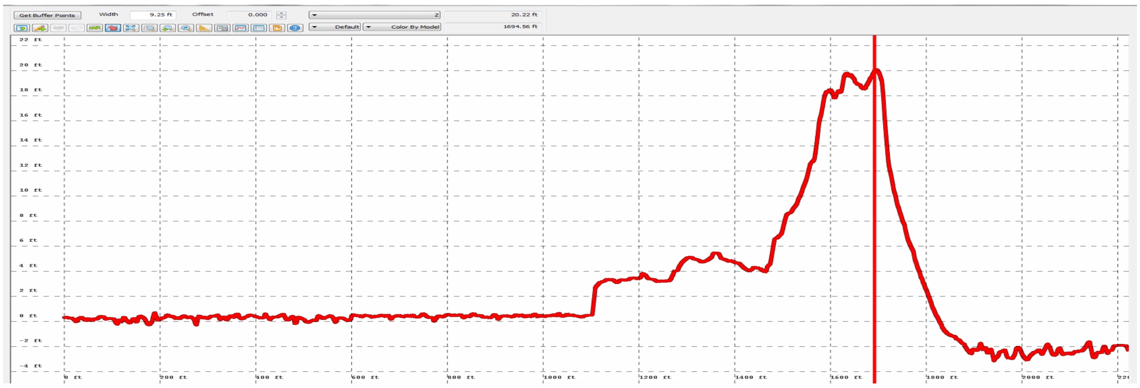

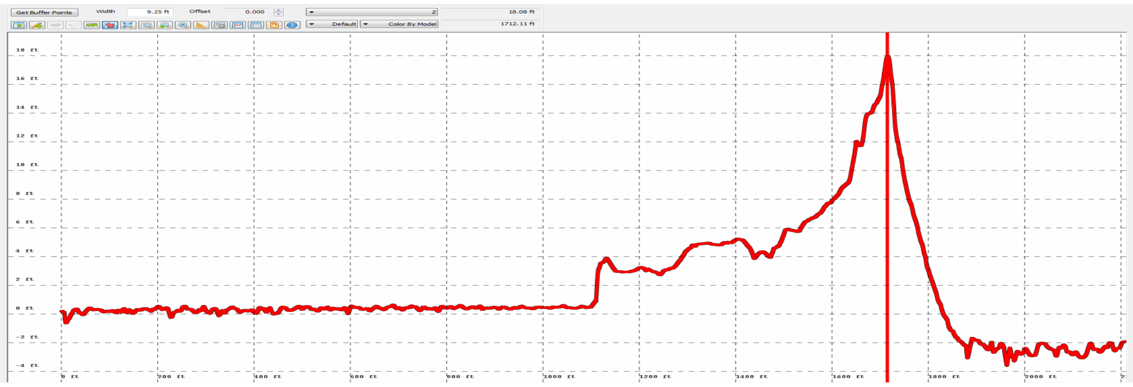

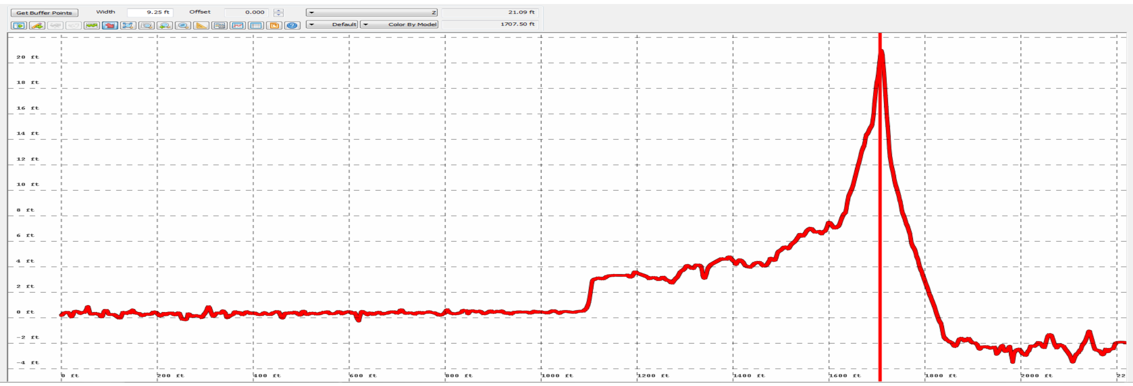

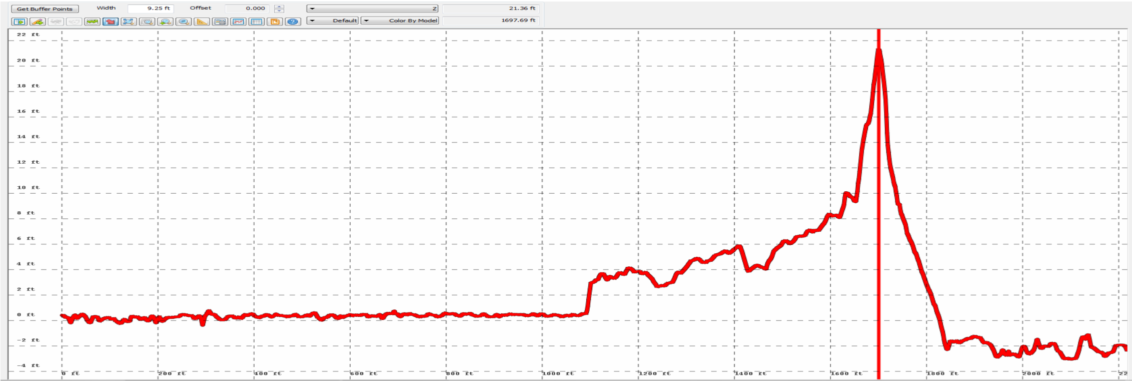
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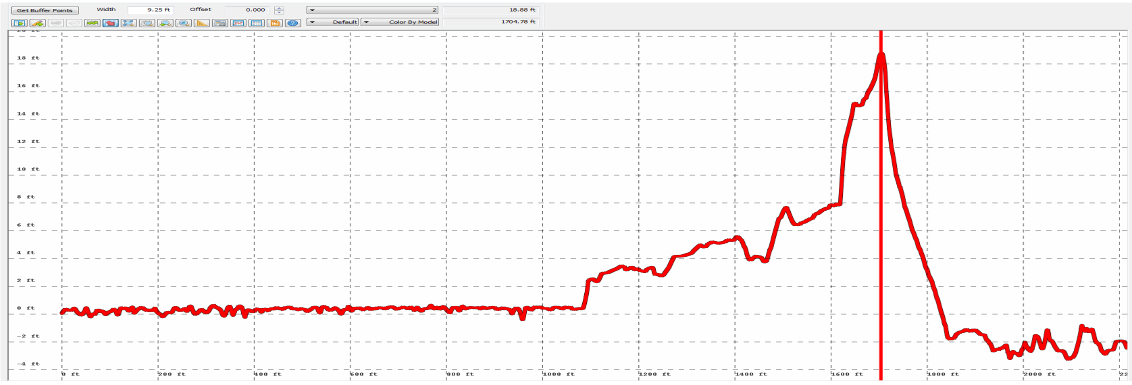
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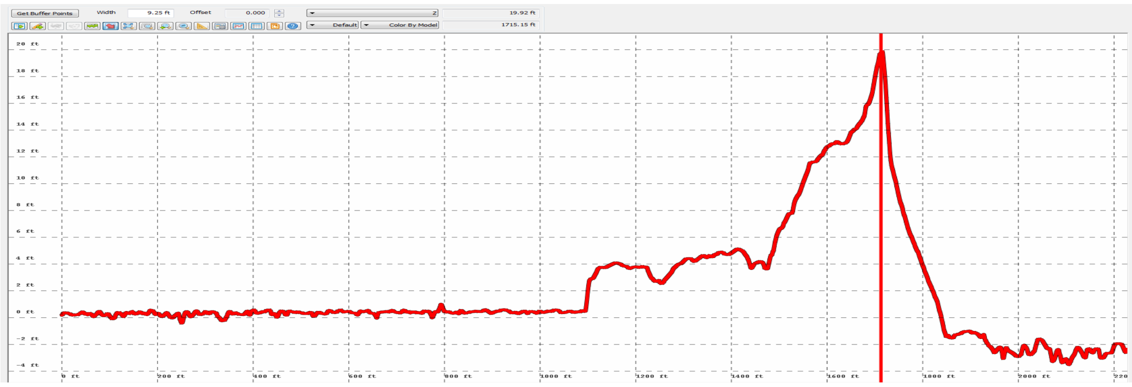
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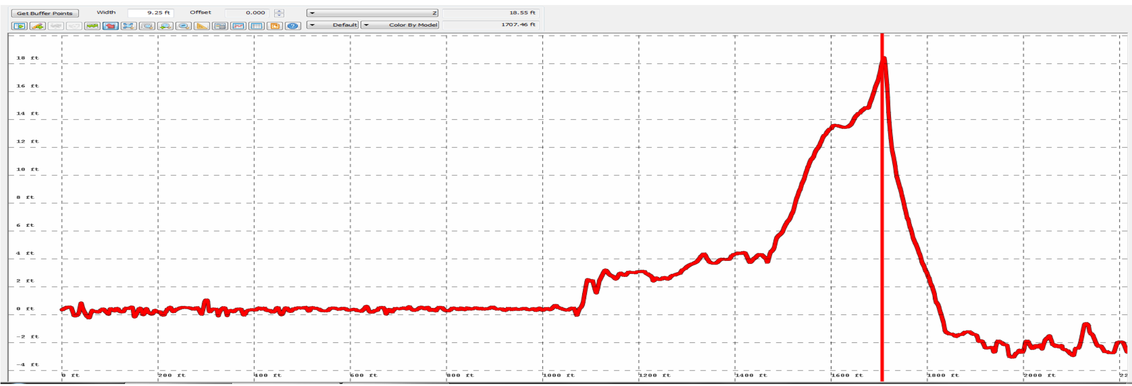
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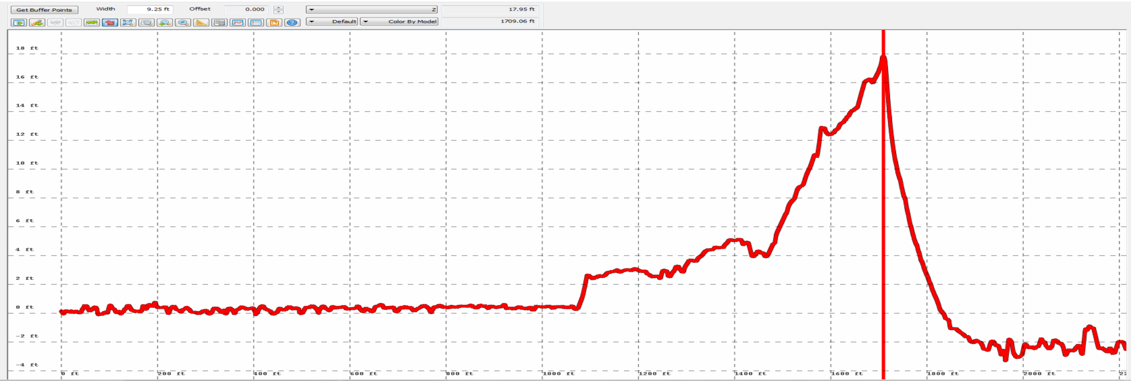
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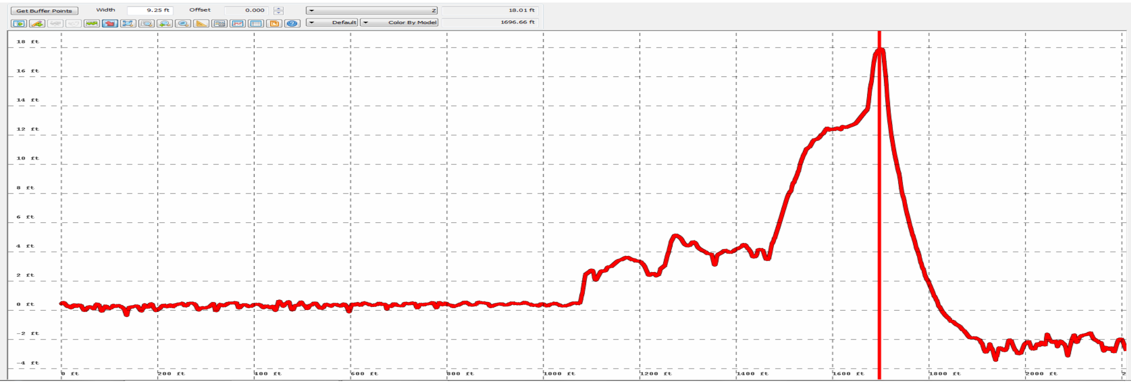
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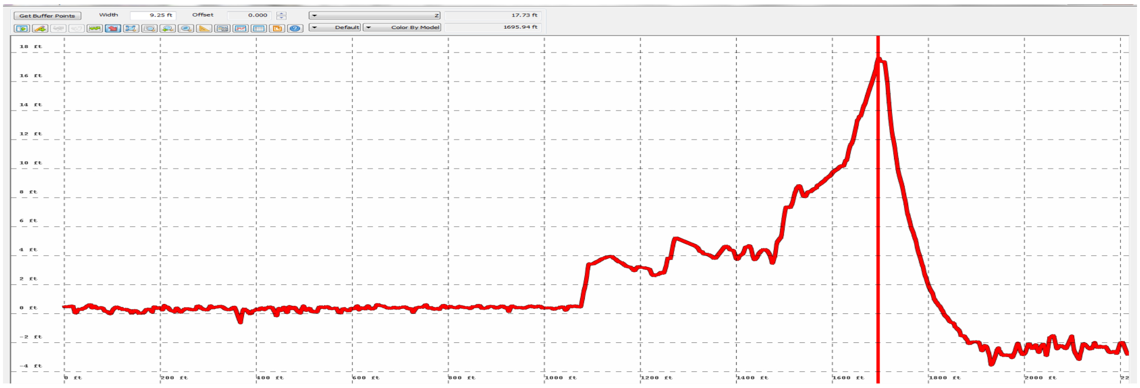
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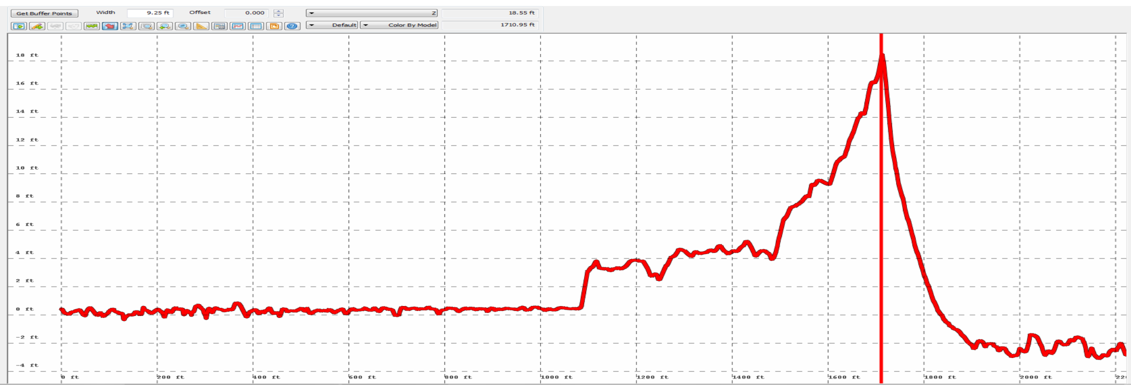
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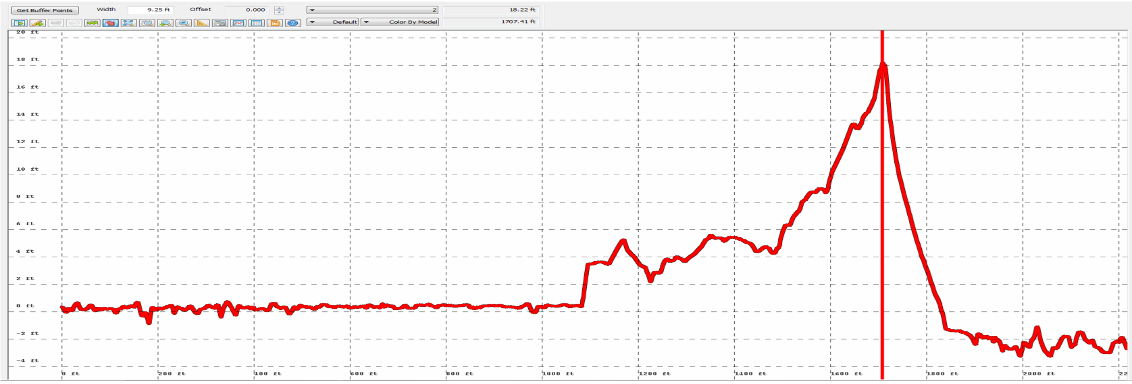

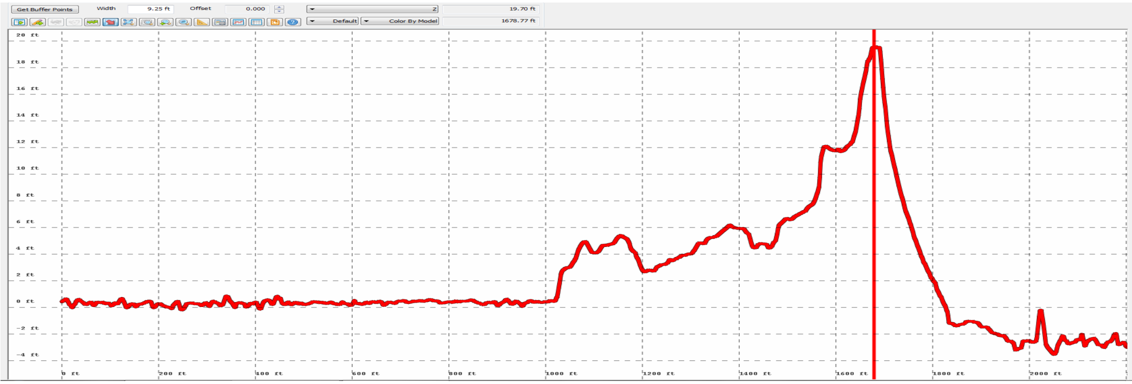

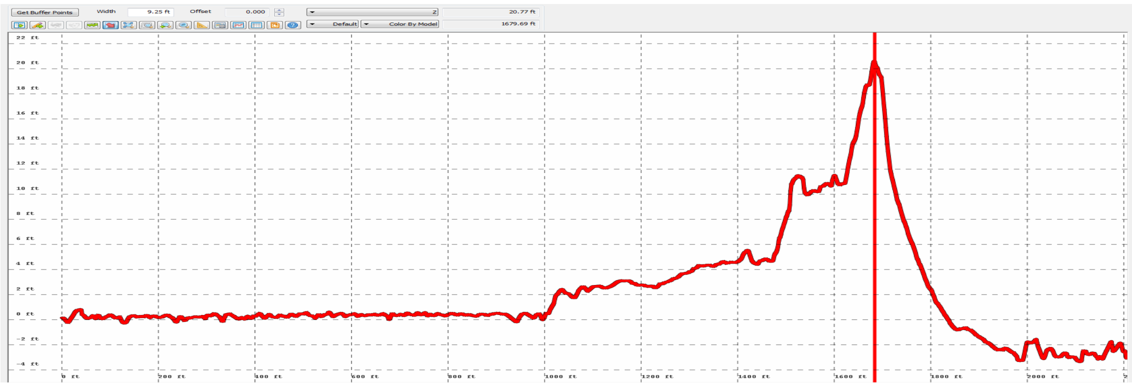

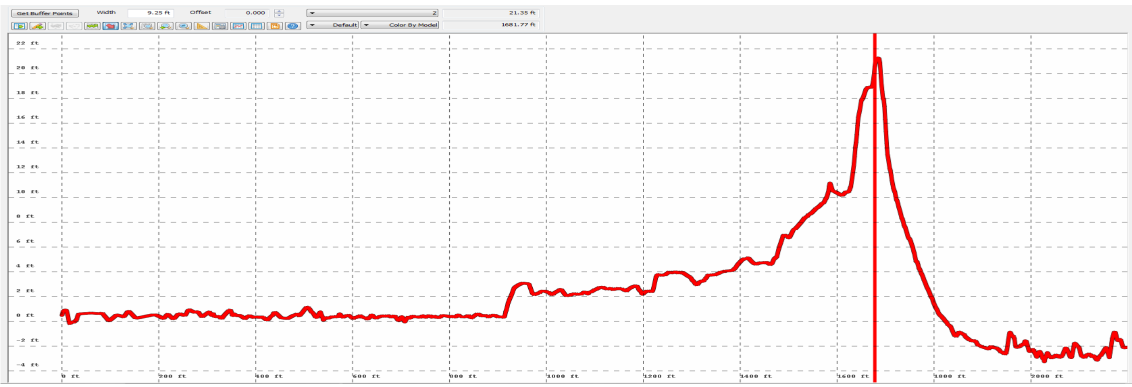

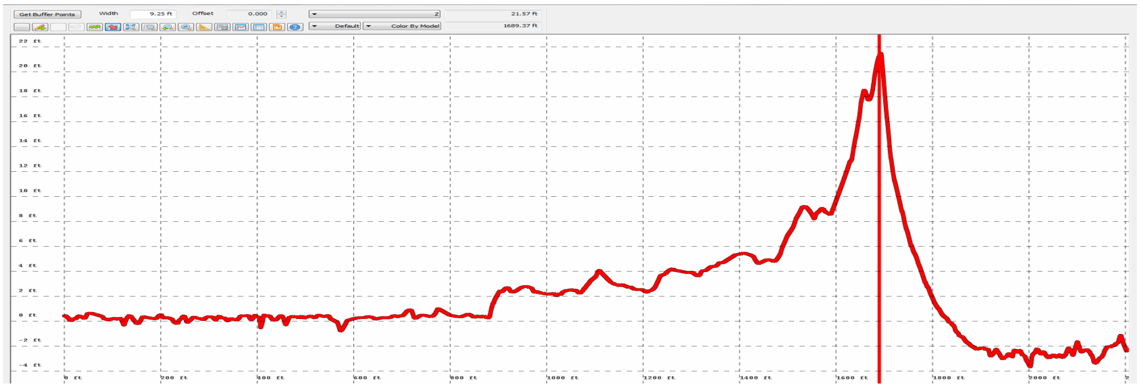

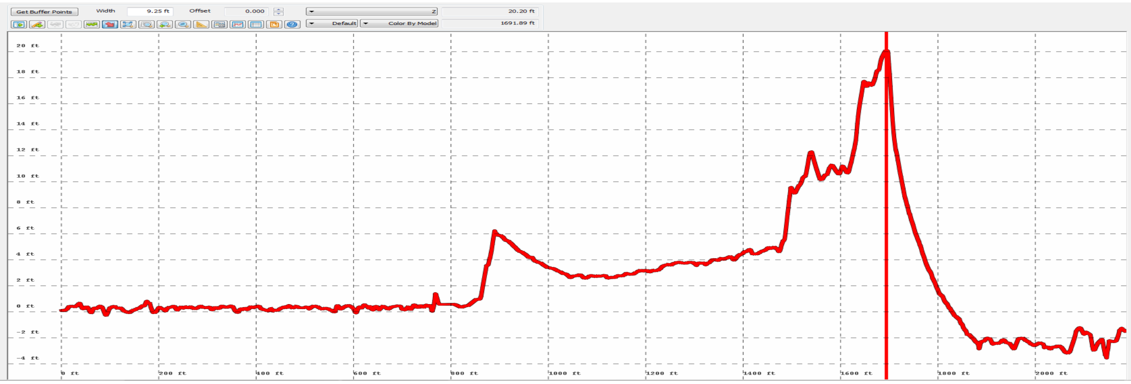

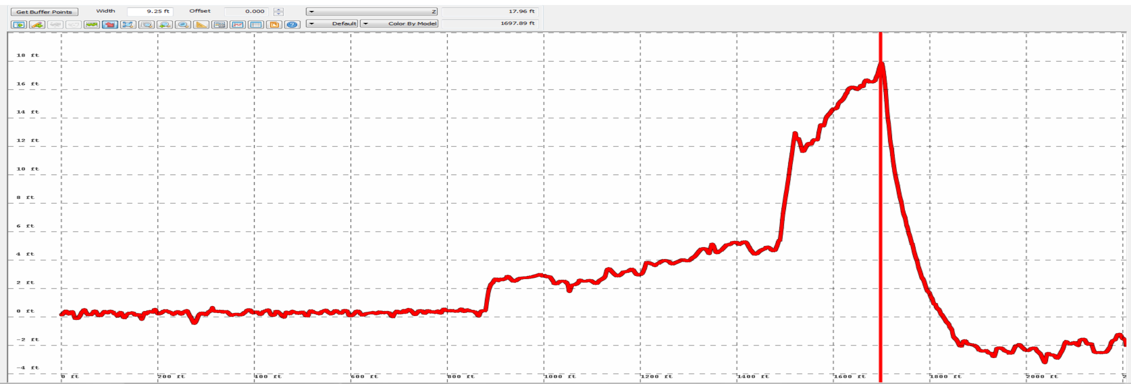

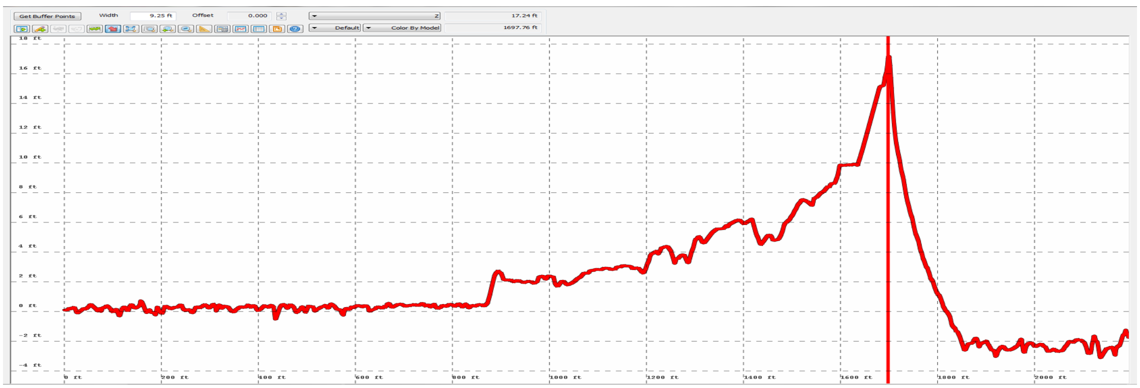

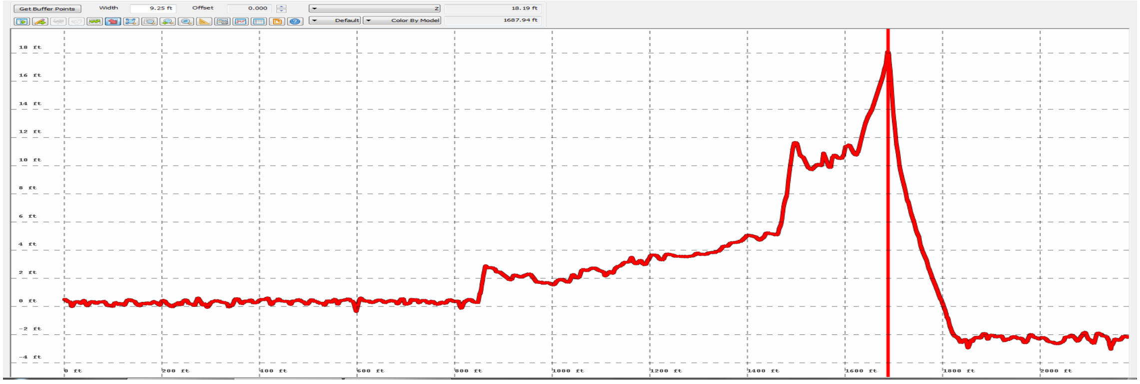
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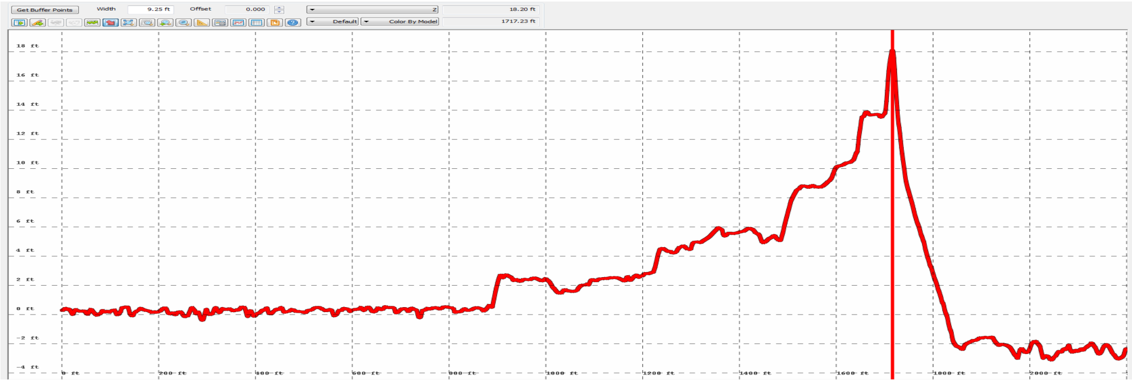
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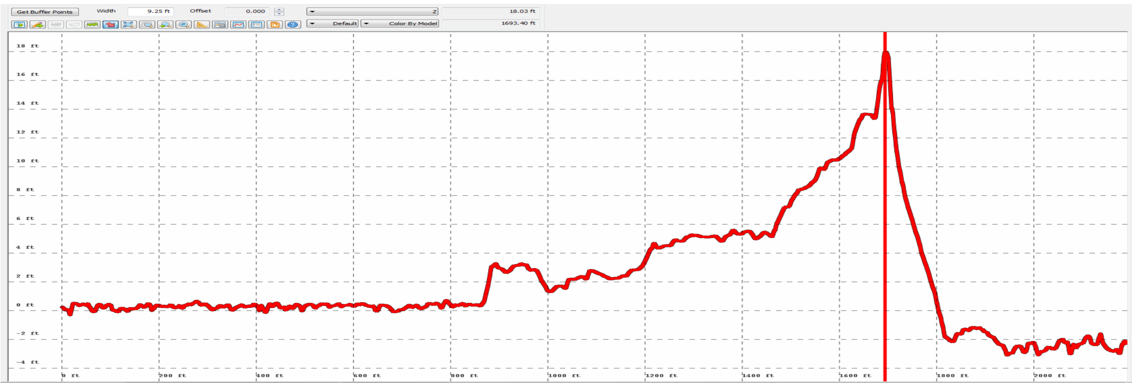
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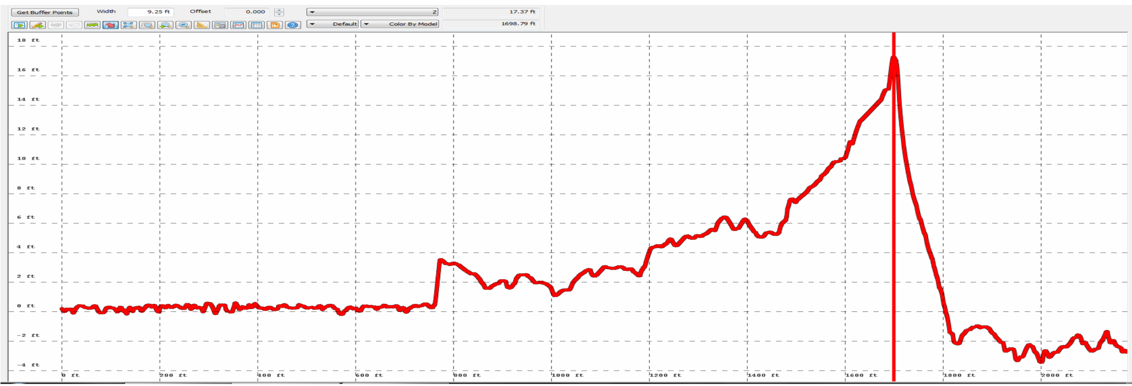
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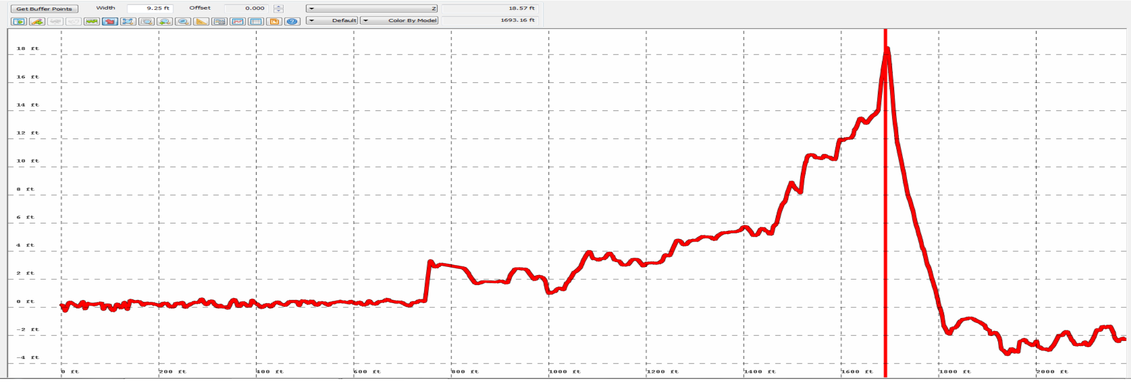
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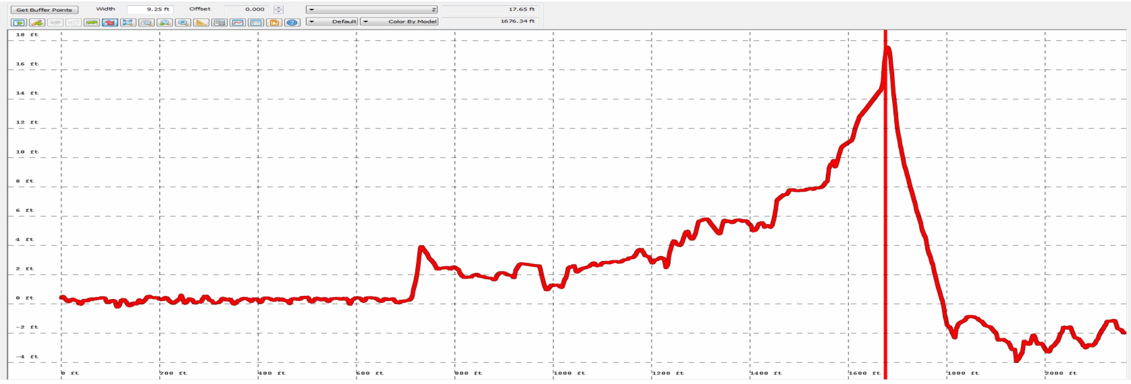
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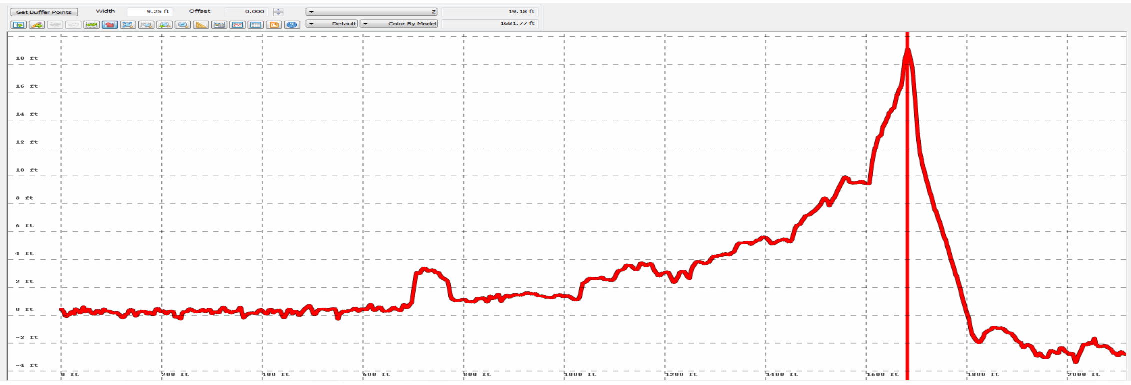
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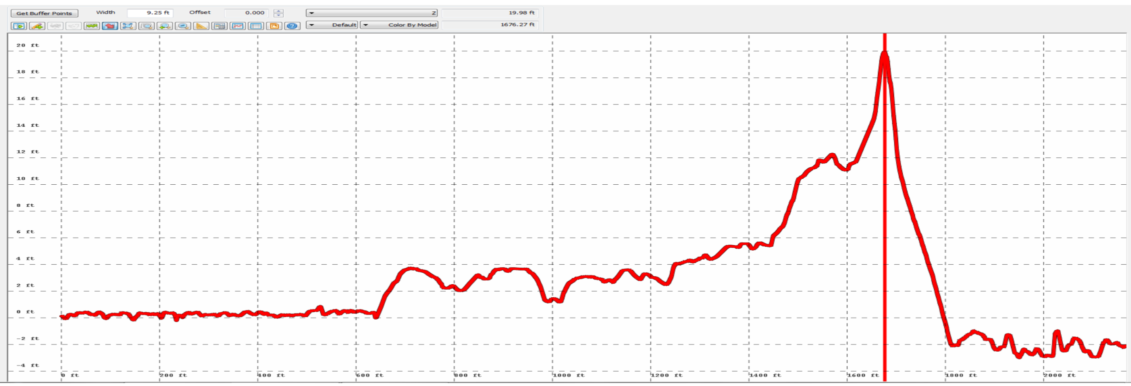
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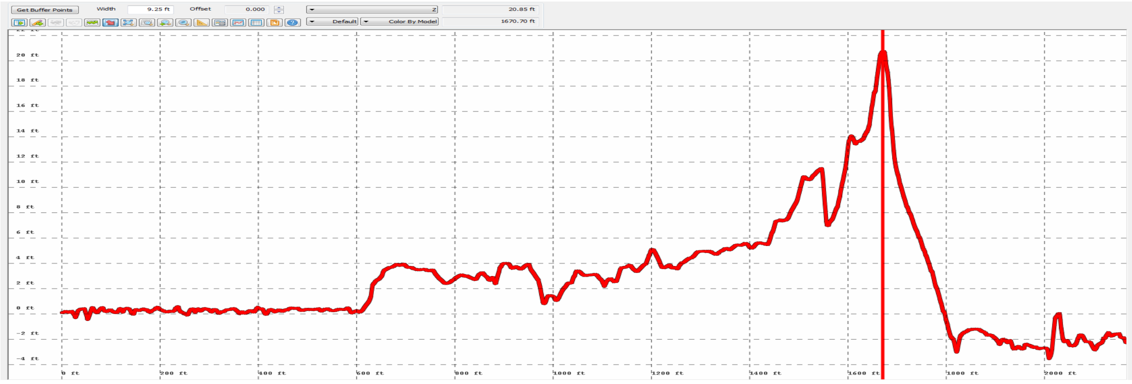

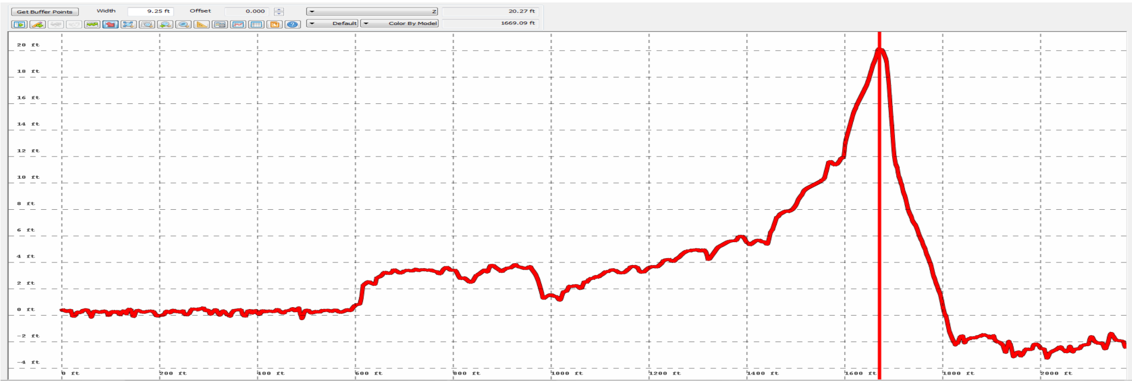

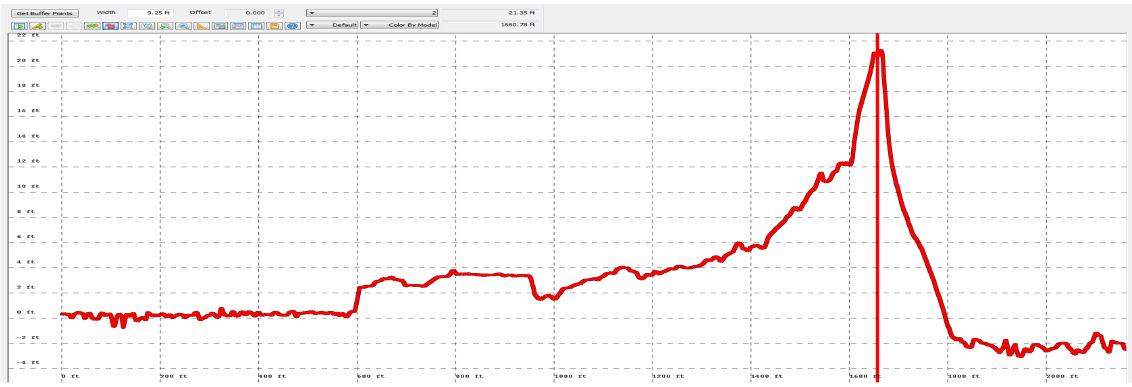

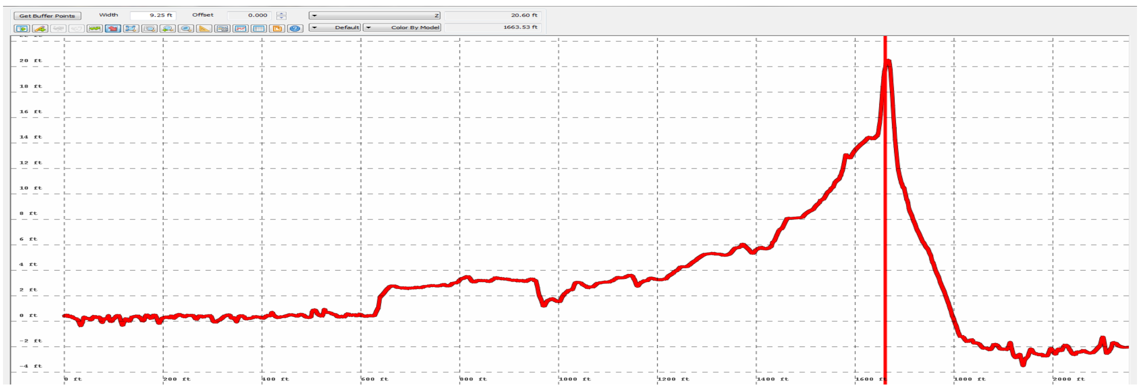

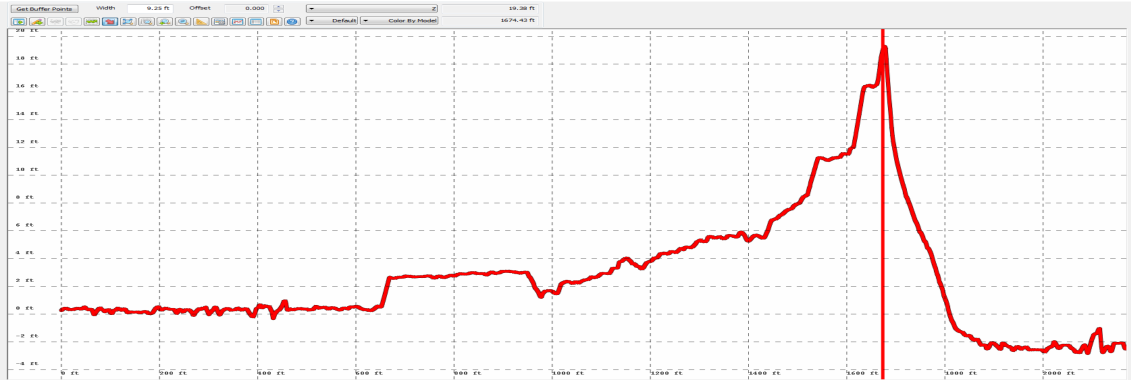
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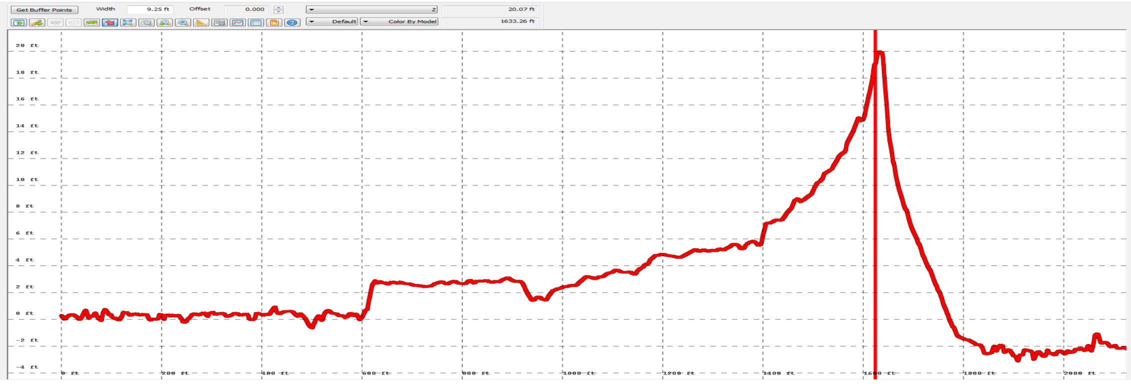
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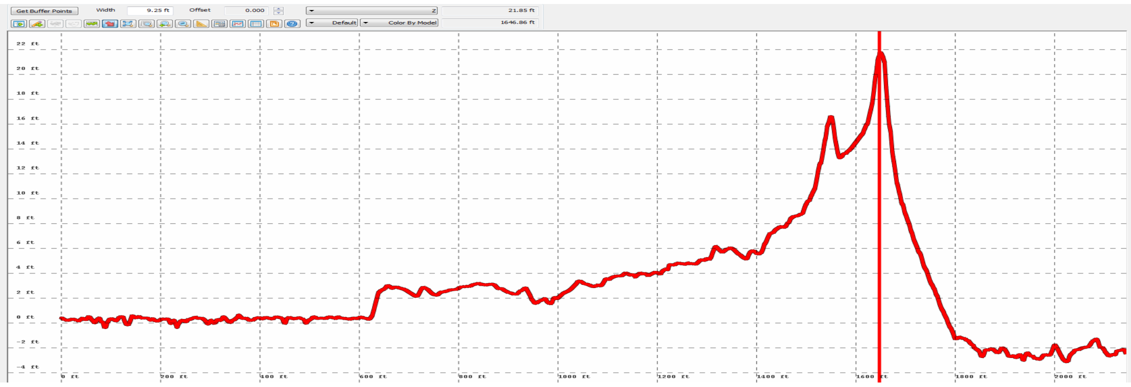
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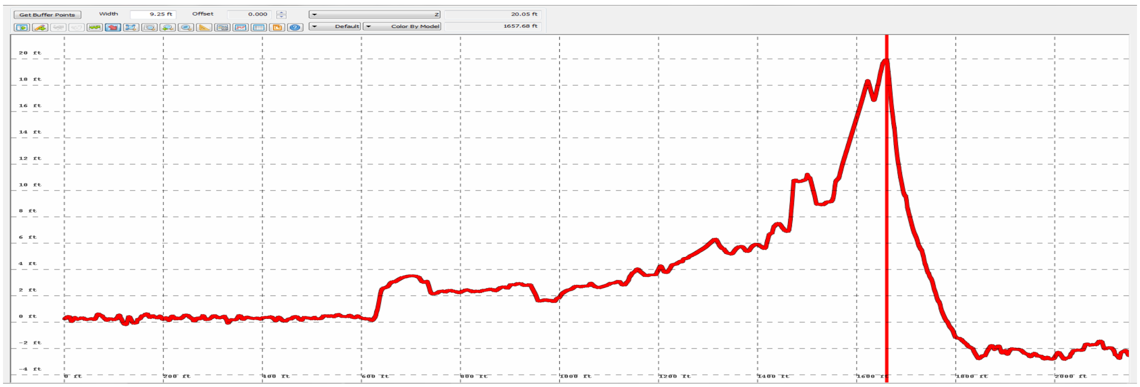
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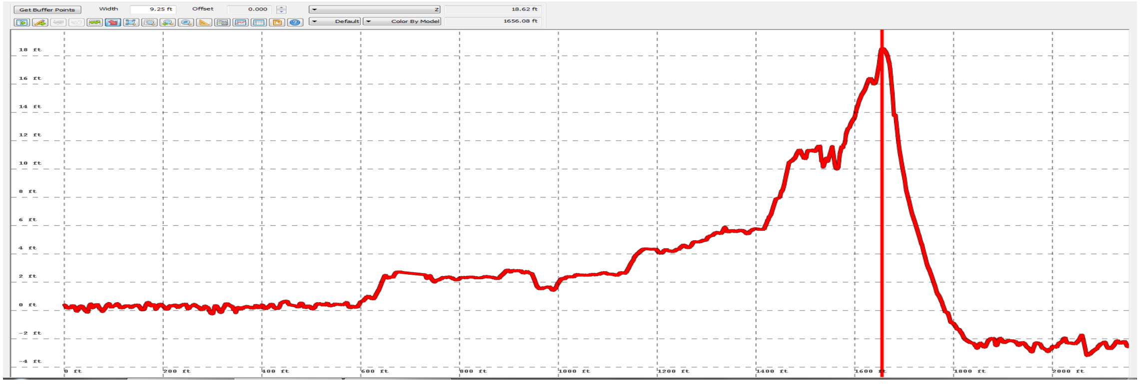

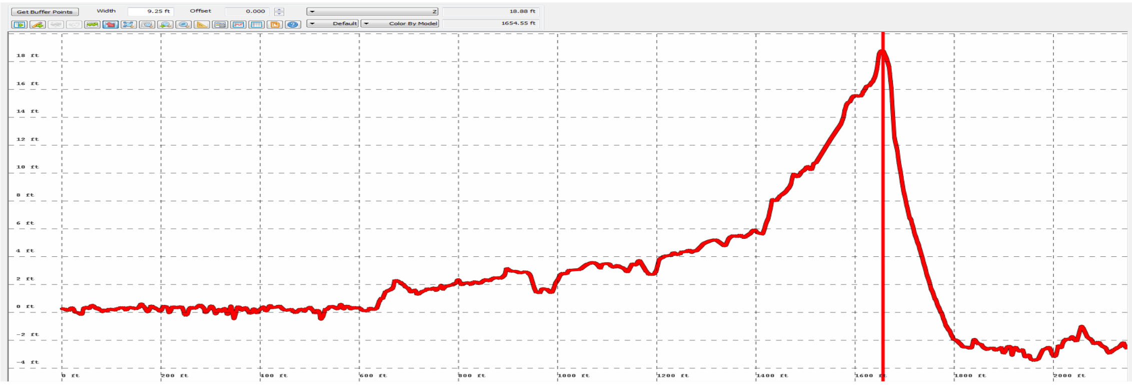

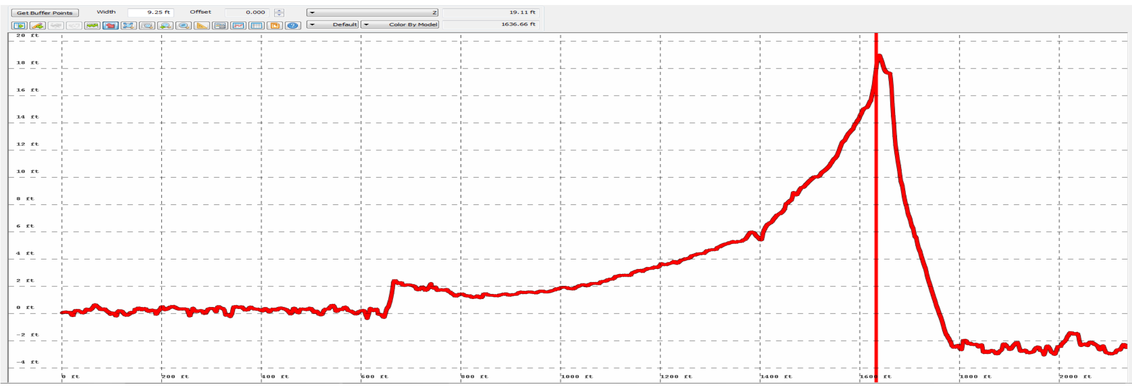

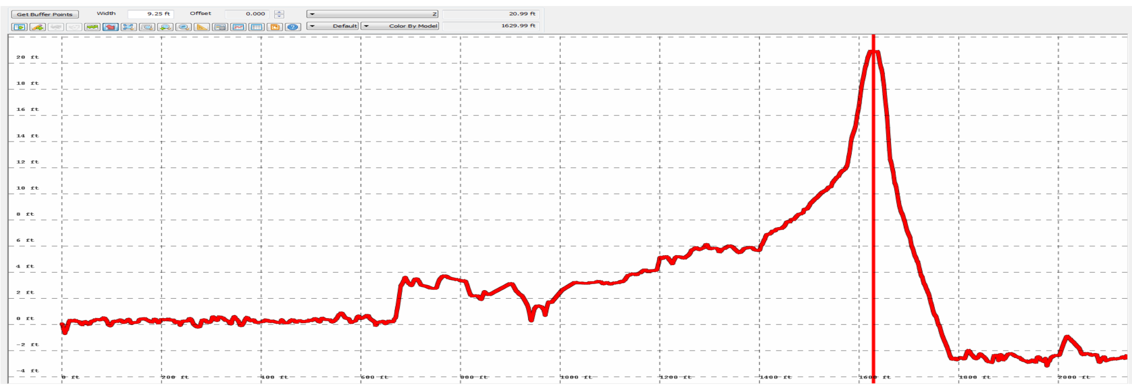

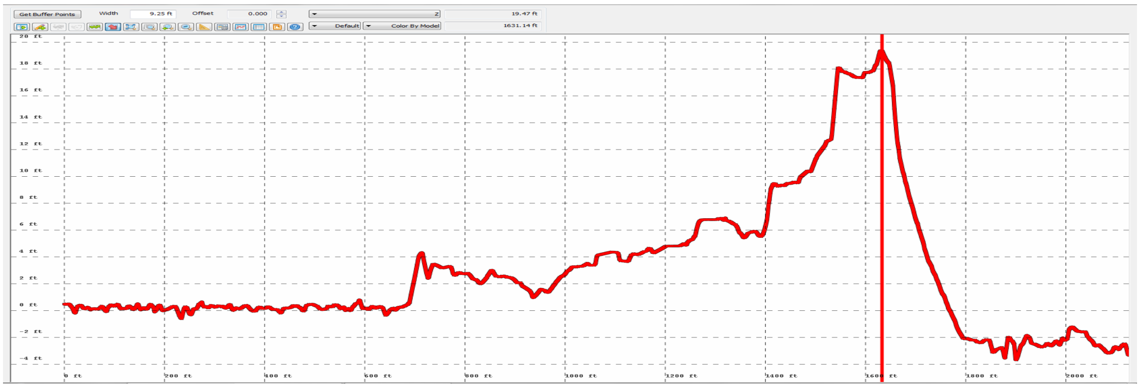

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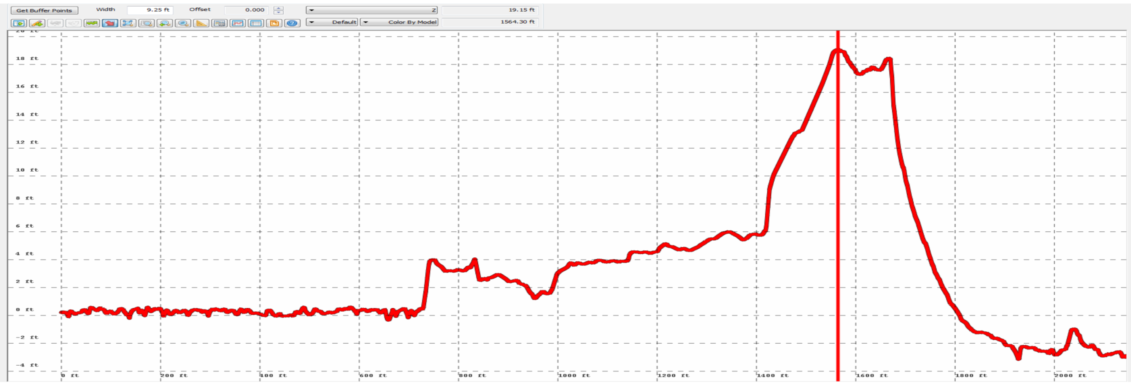

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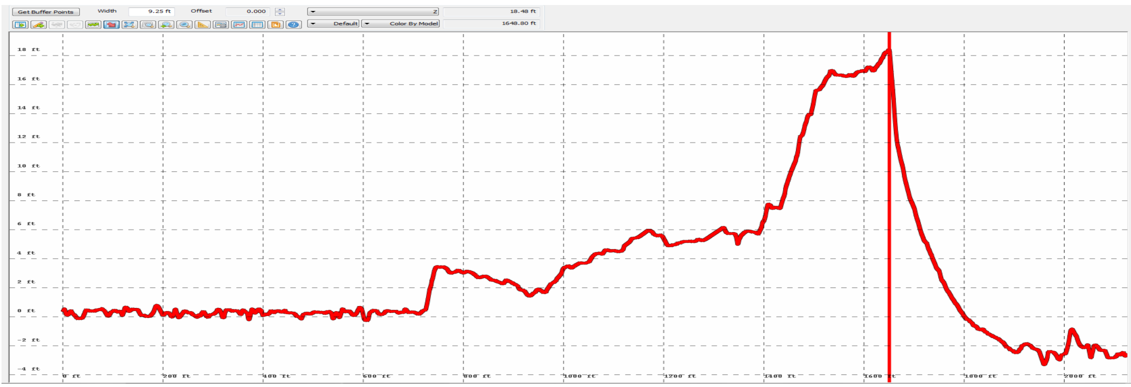

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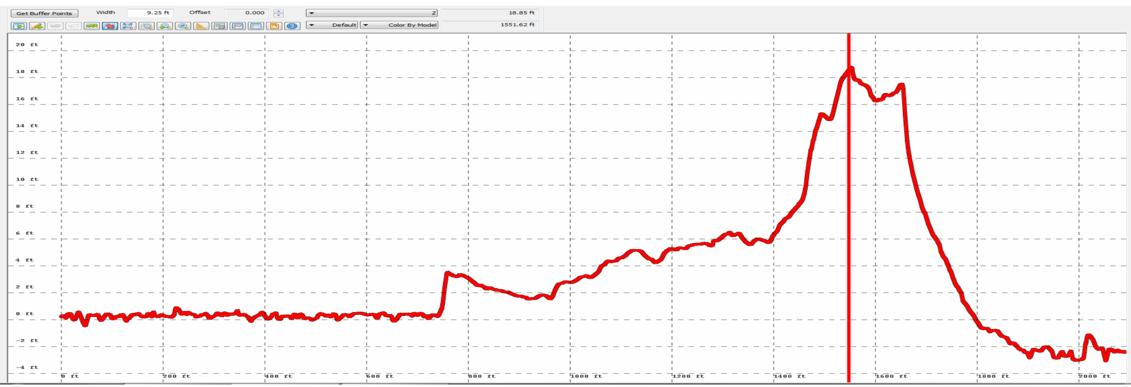

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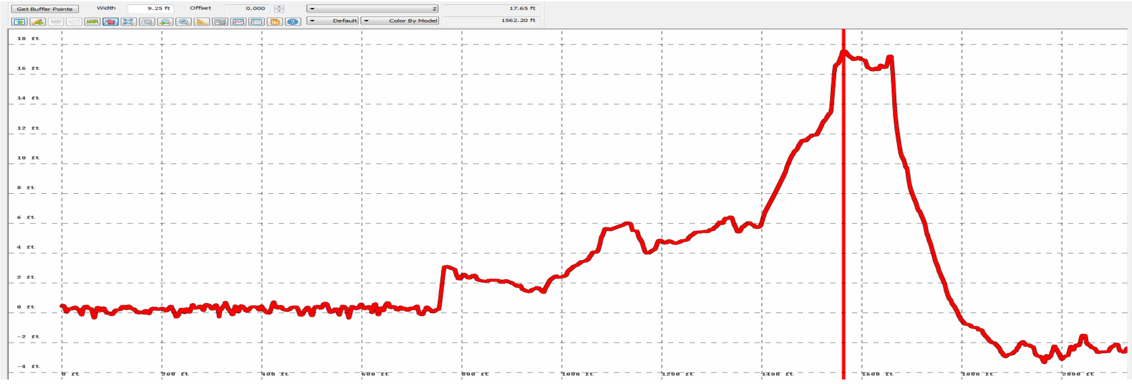

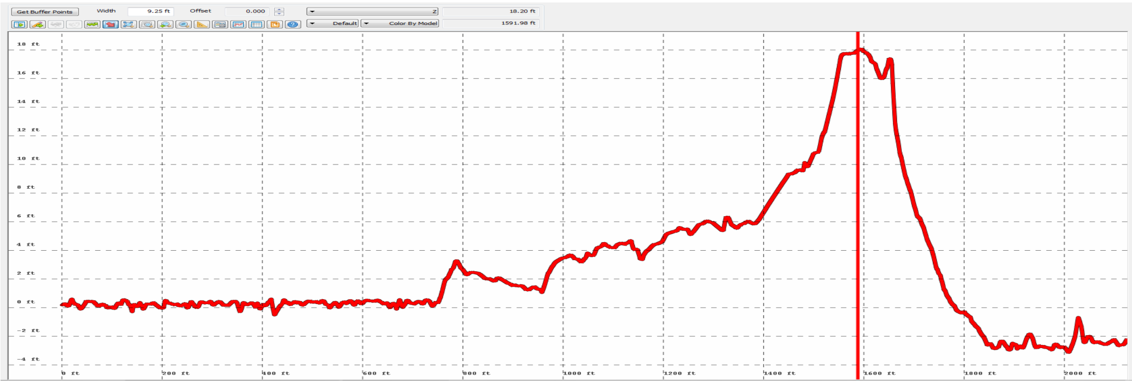

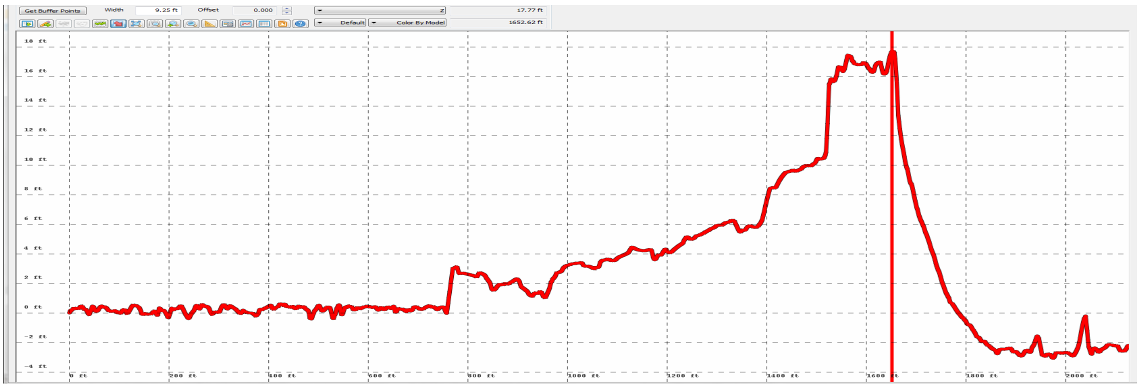

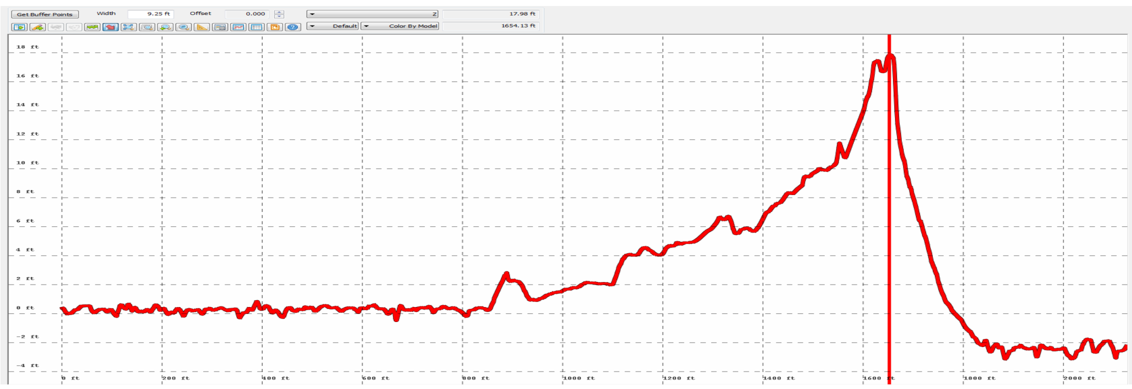

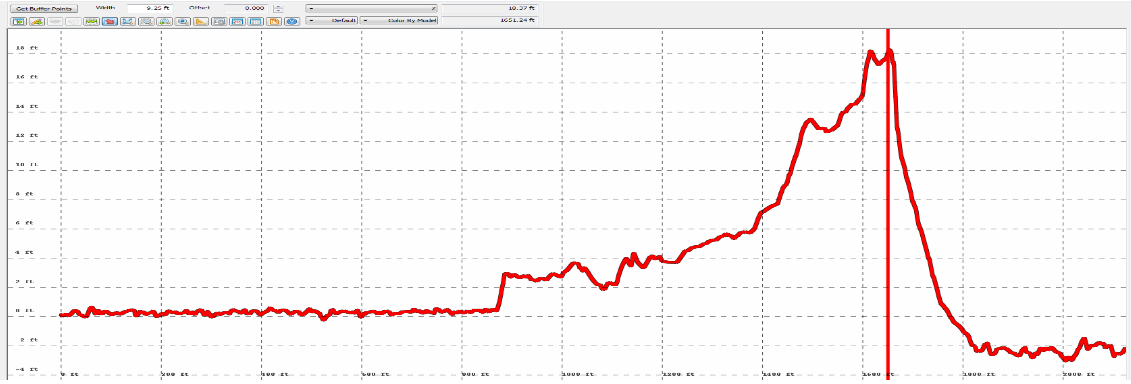

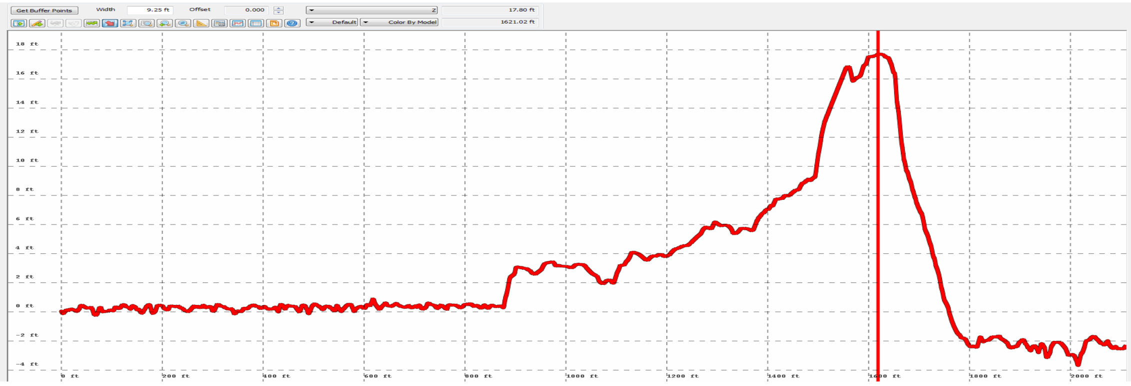

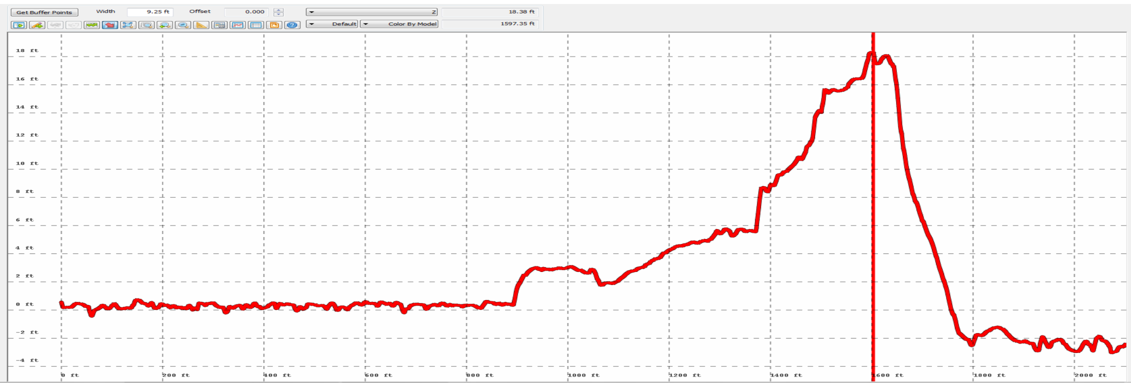

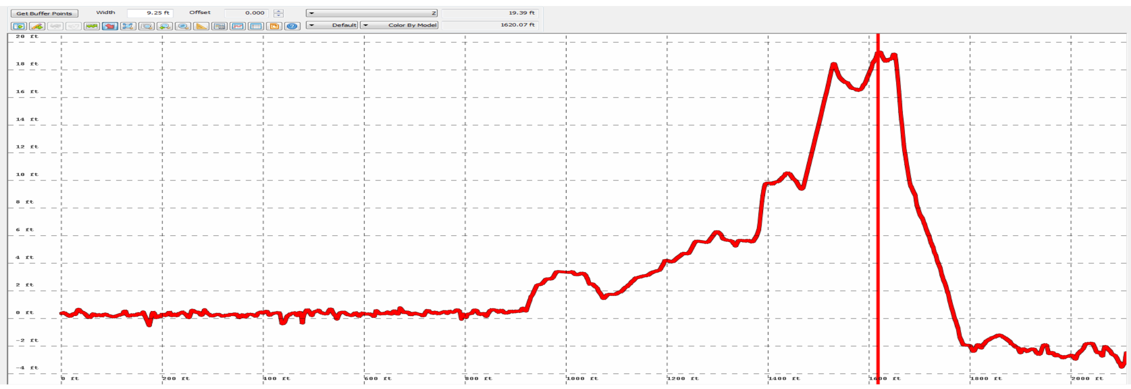

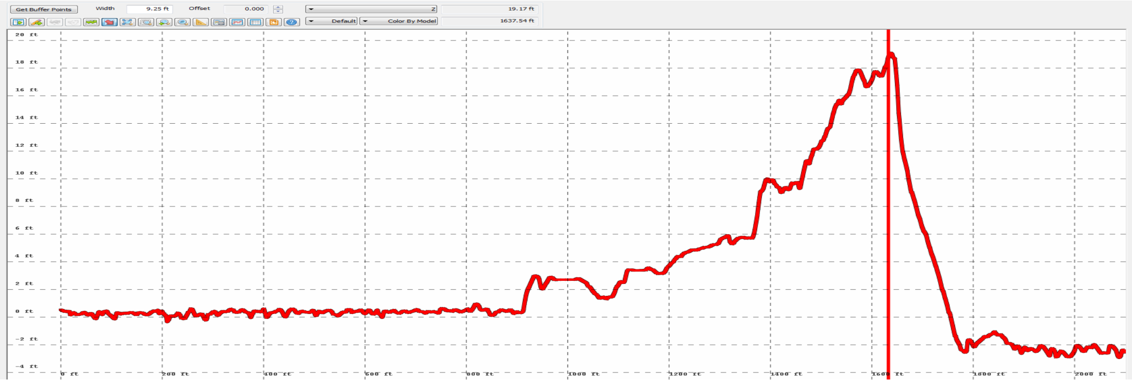

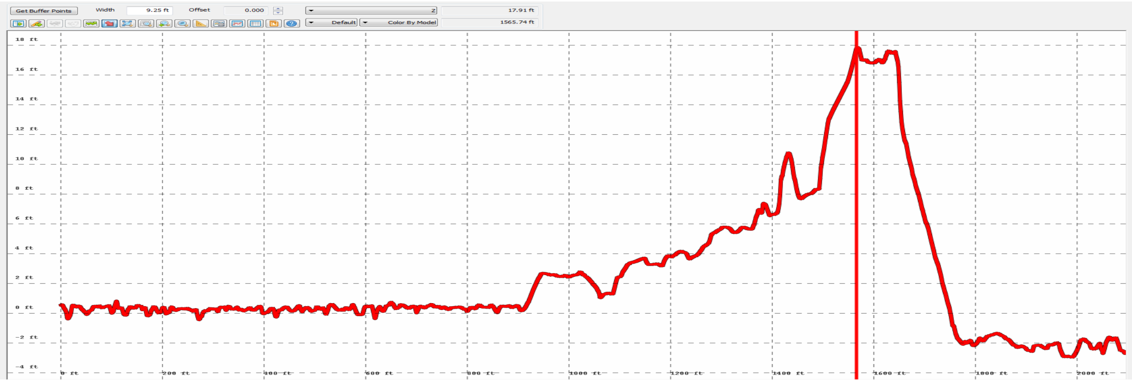

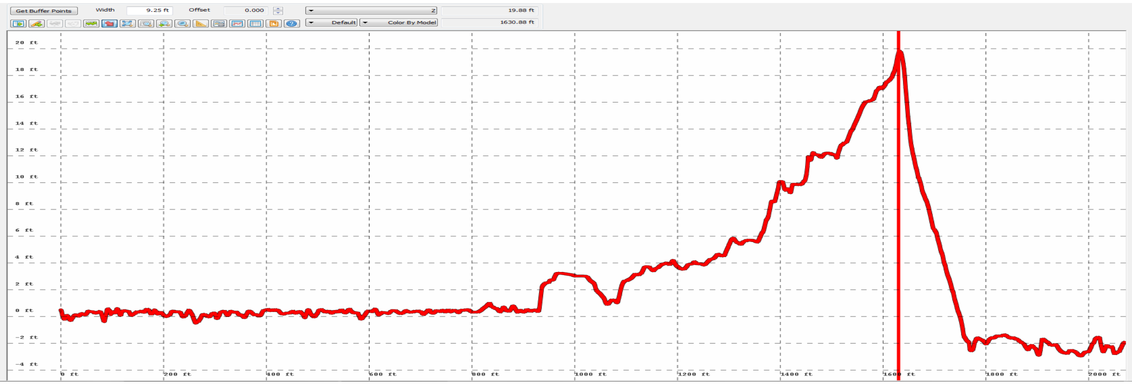

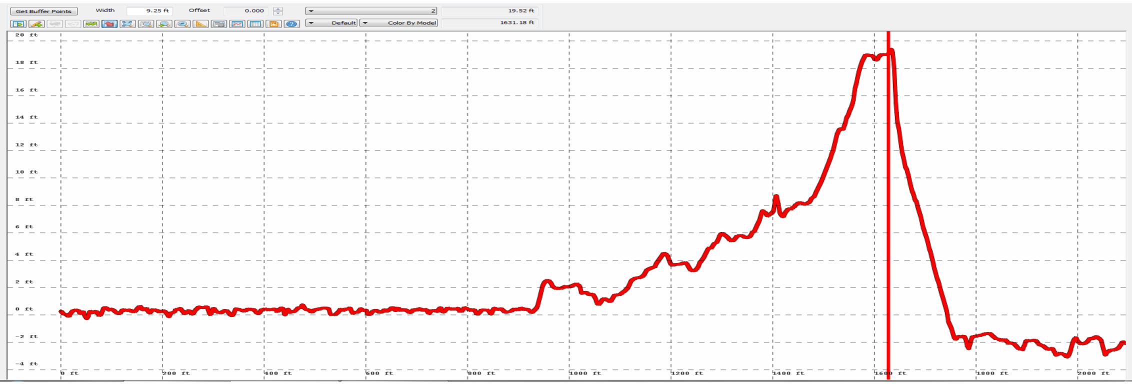

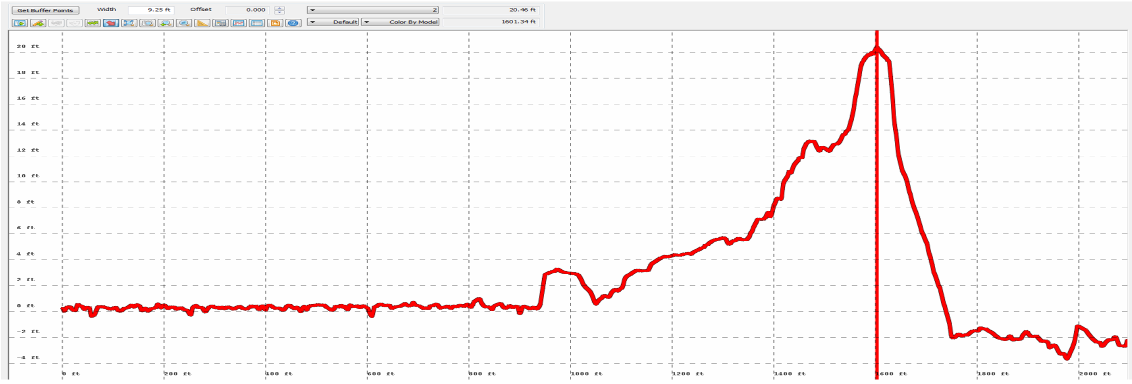
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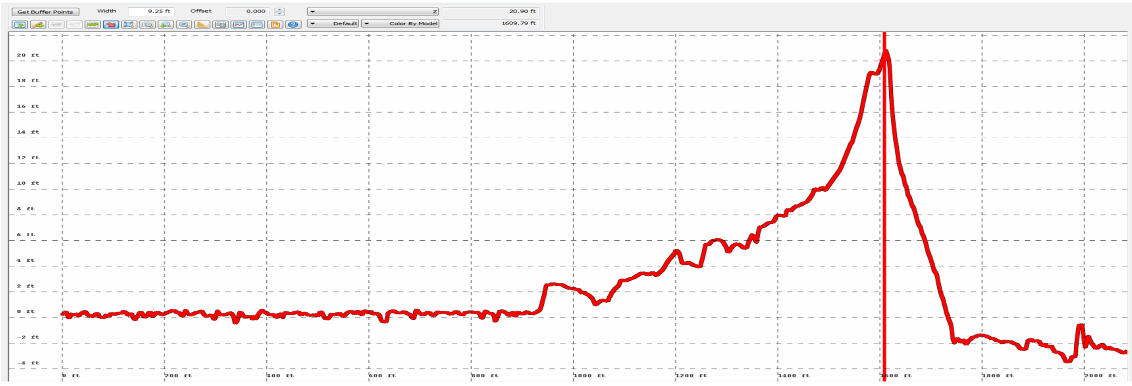
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4 ft
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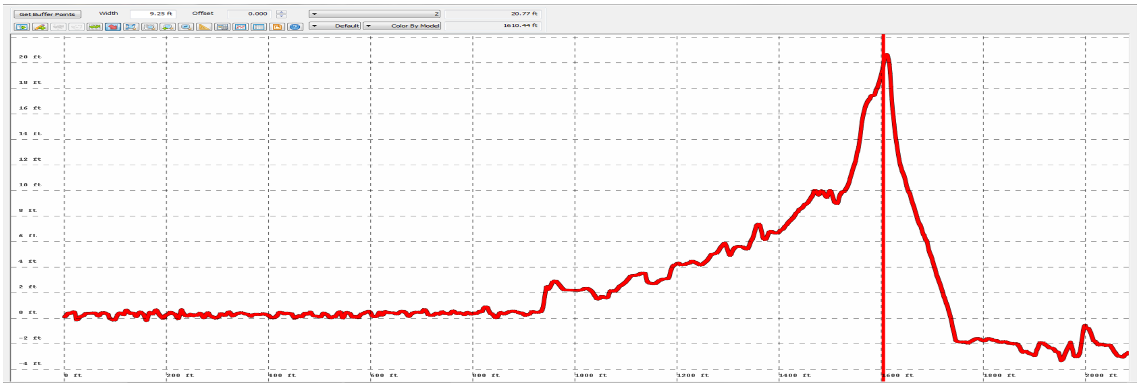
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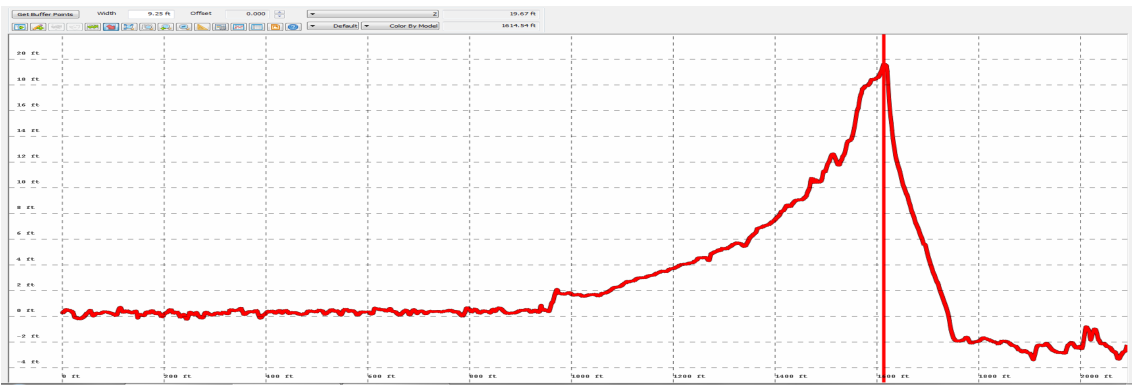
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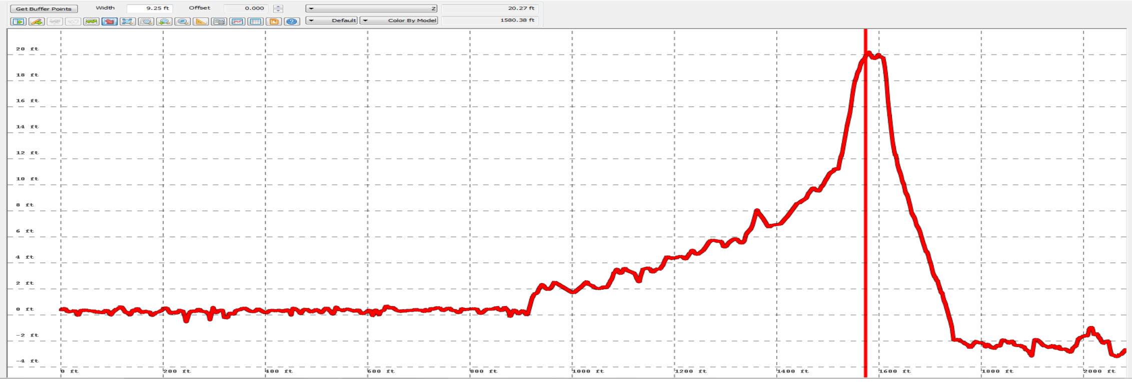

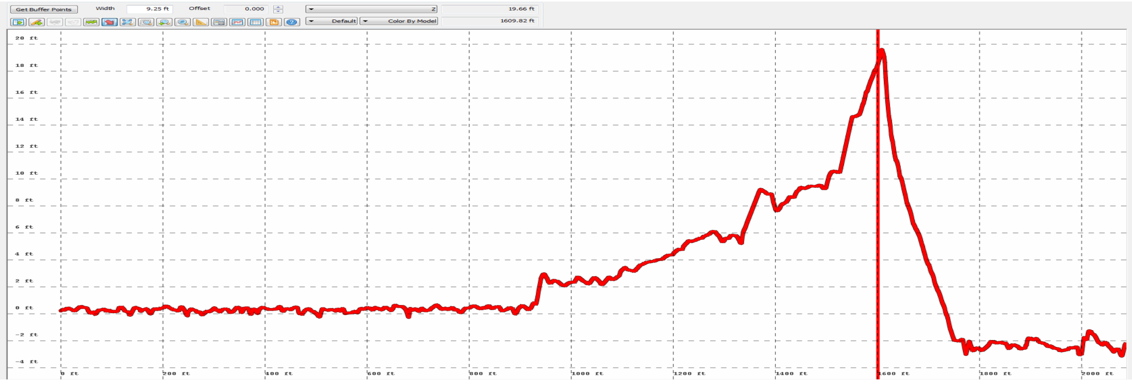

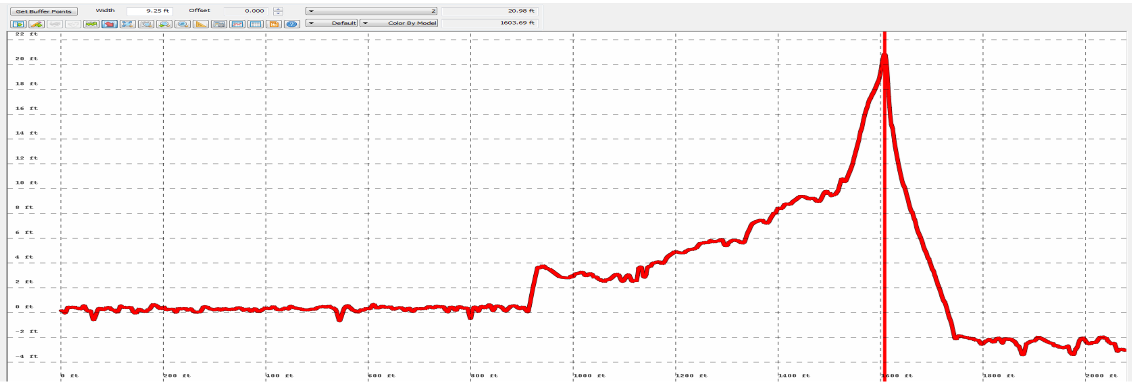

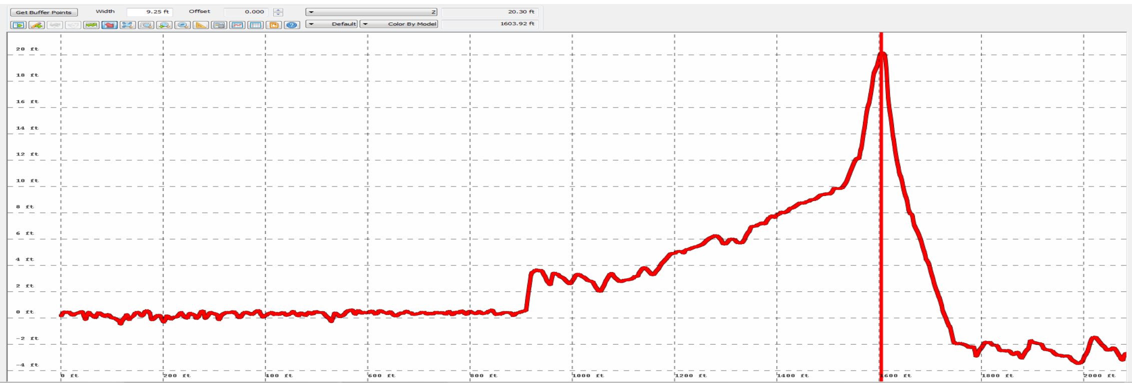

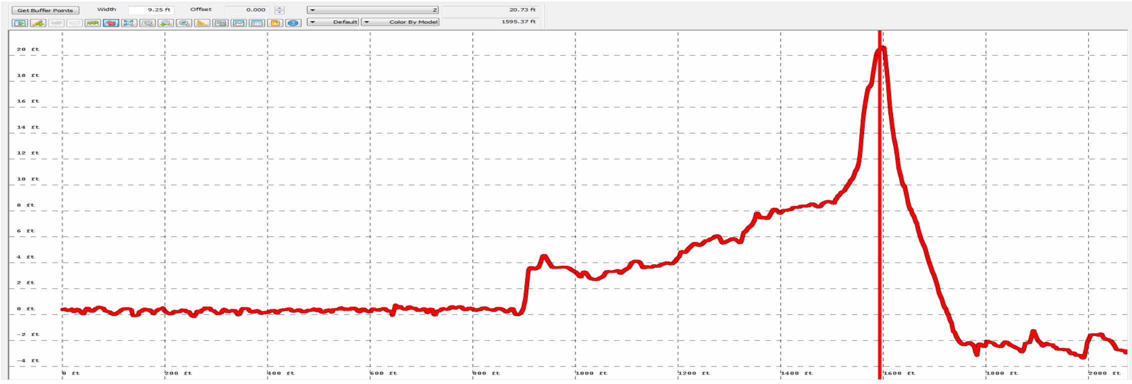

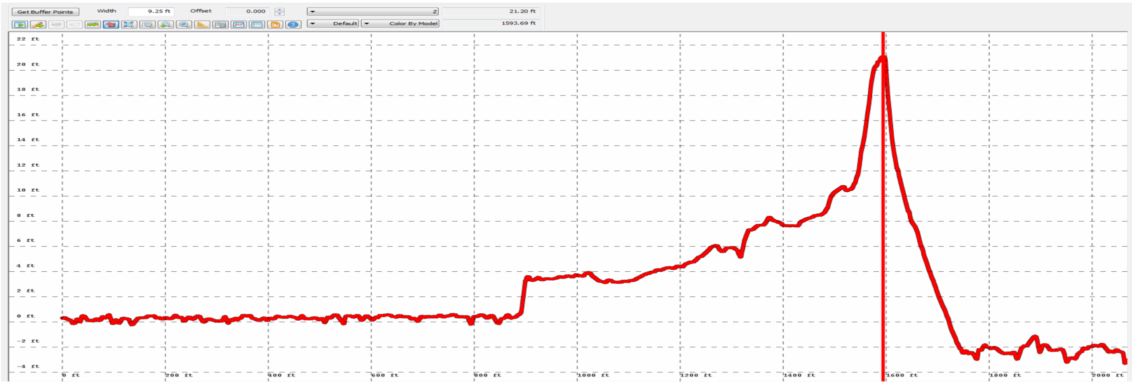

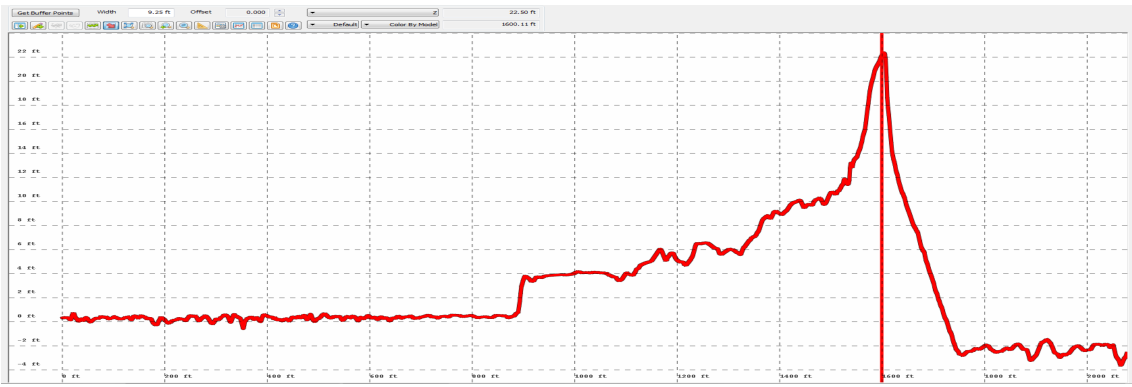

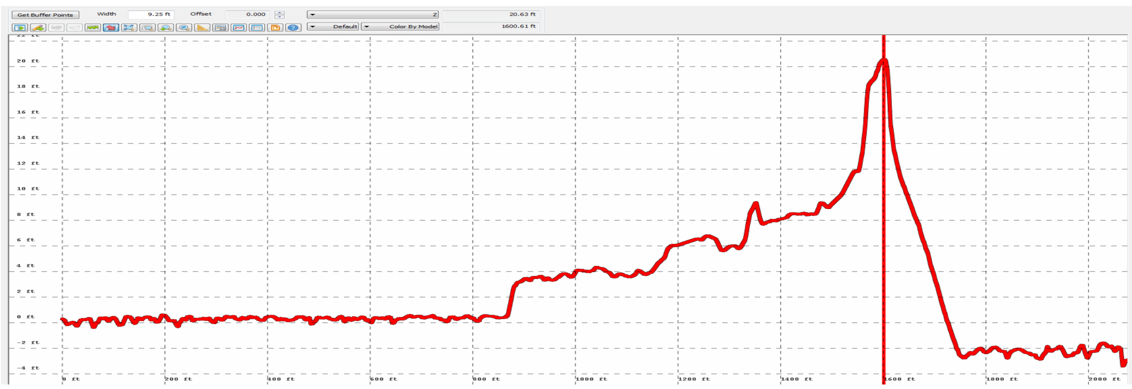

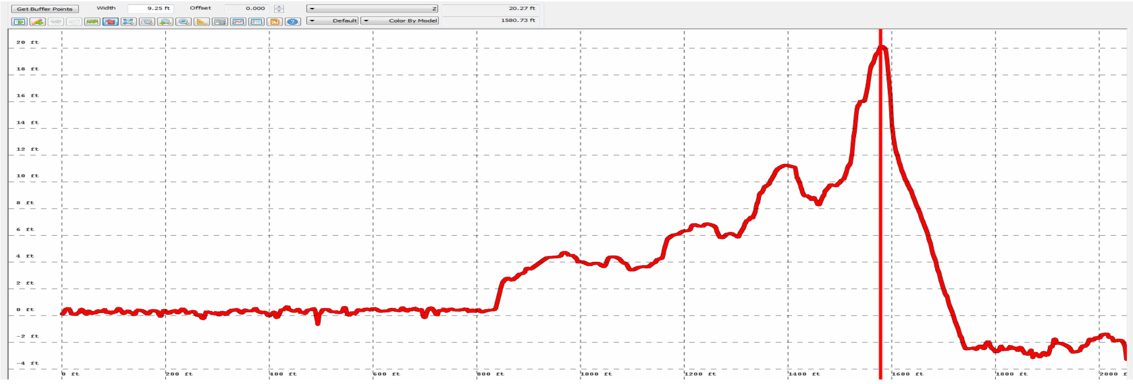
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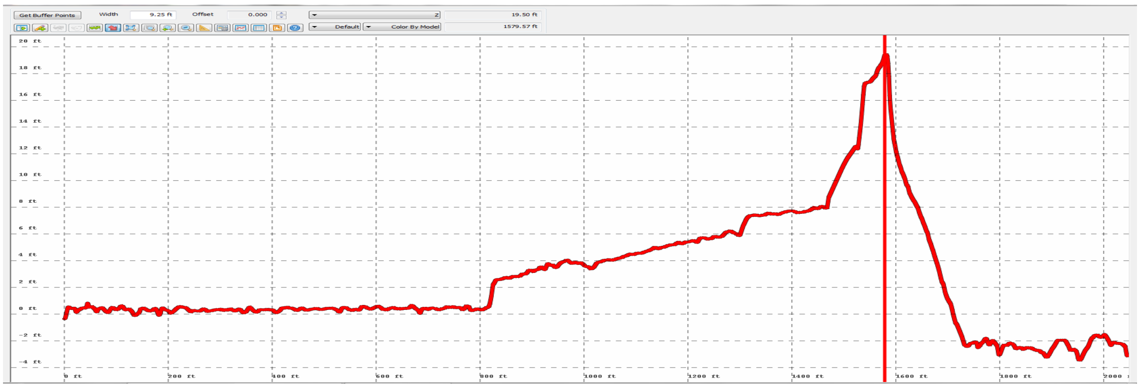
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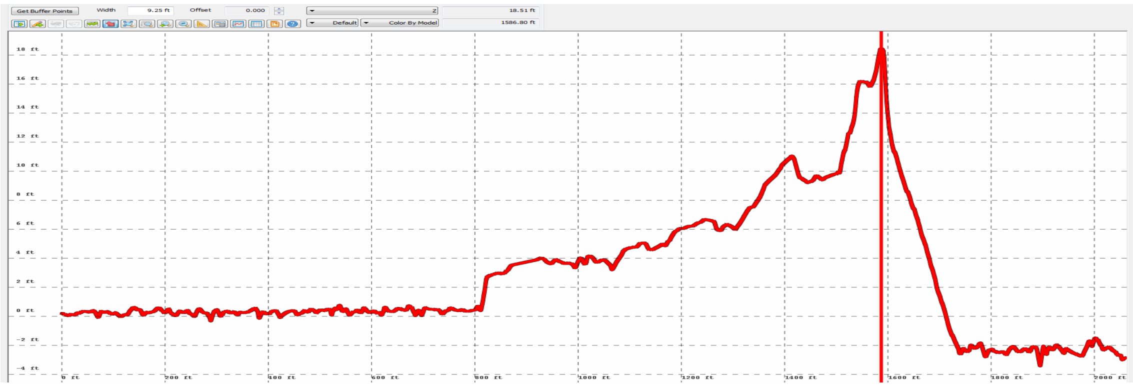
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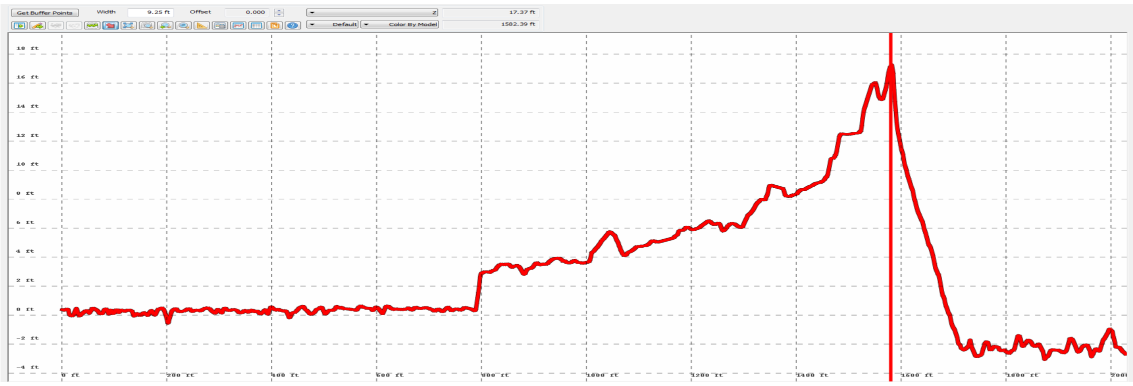
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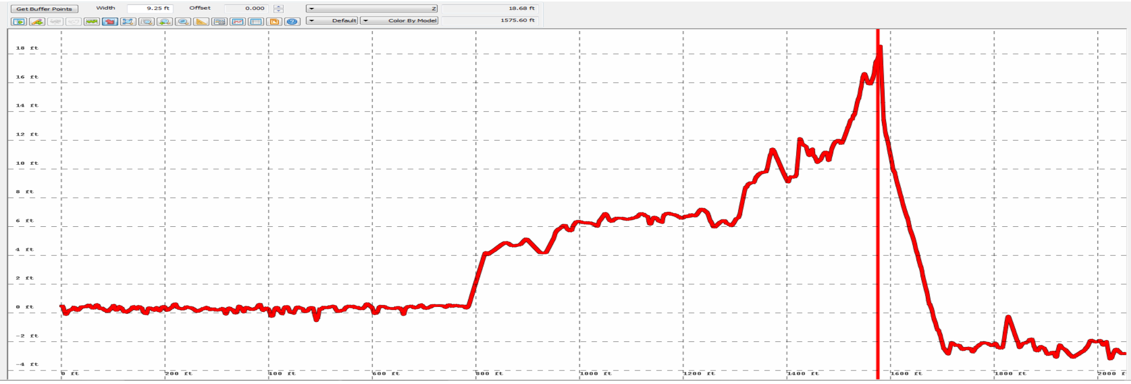

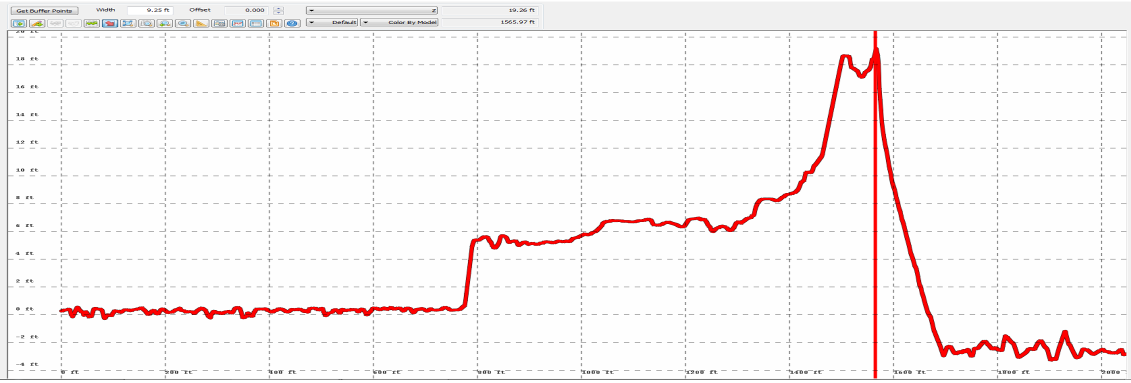

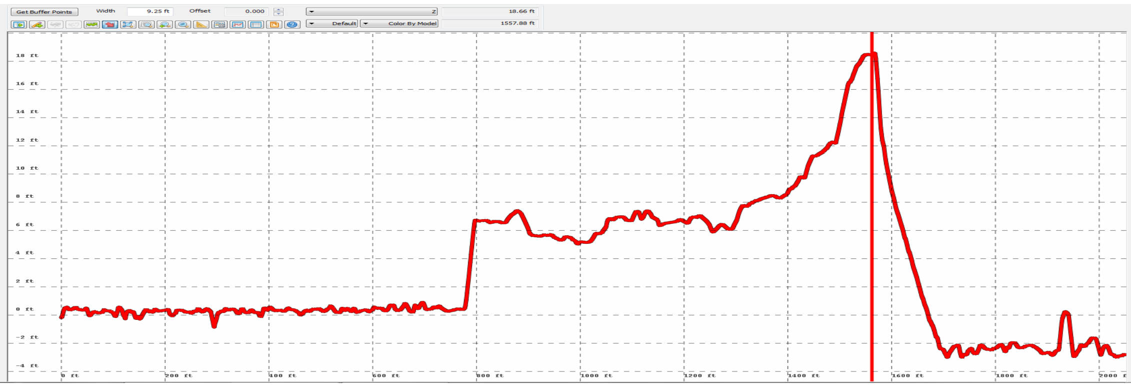

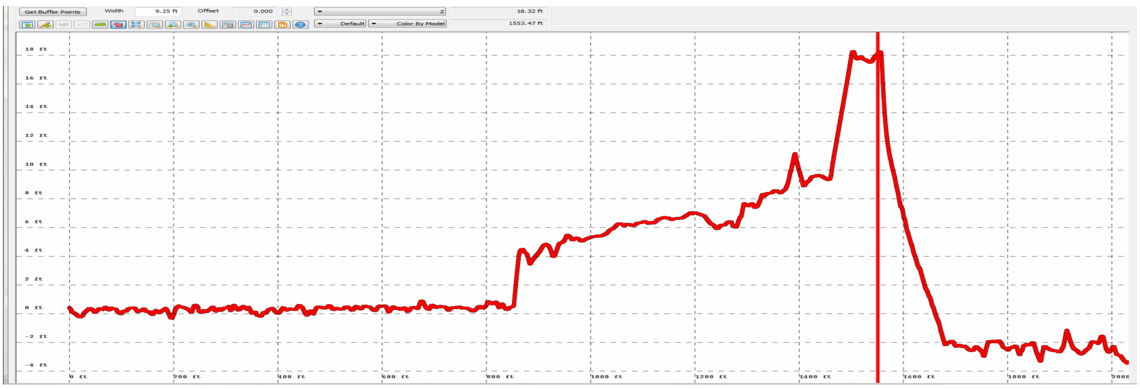

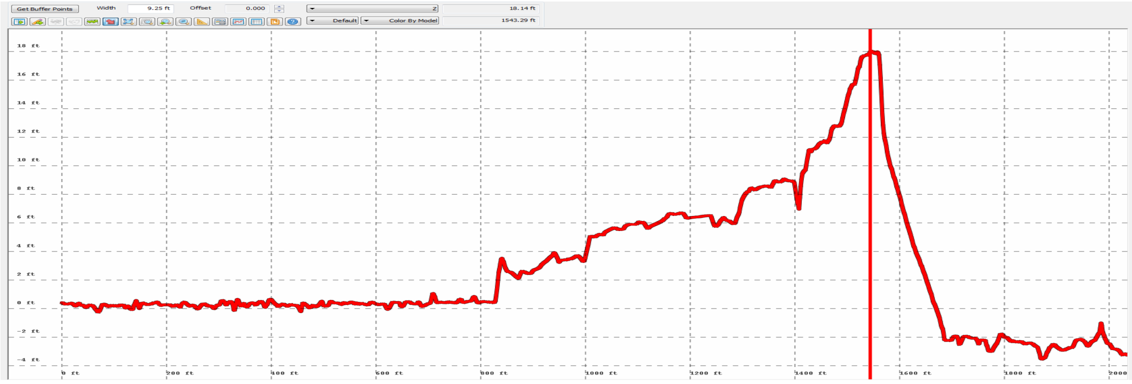

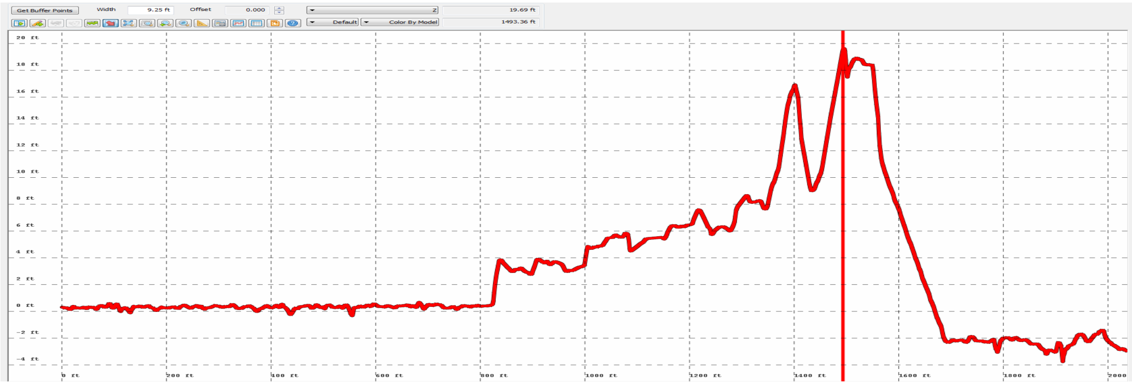

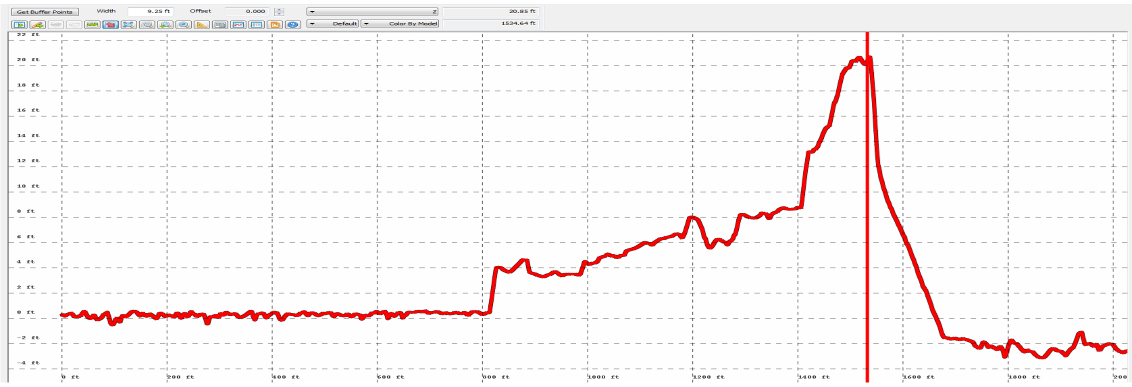

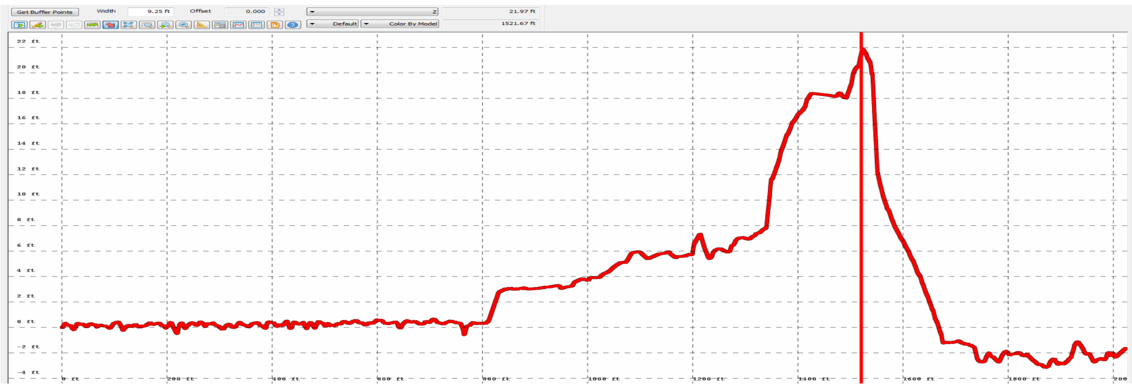

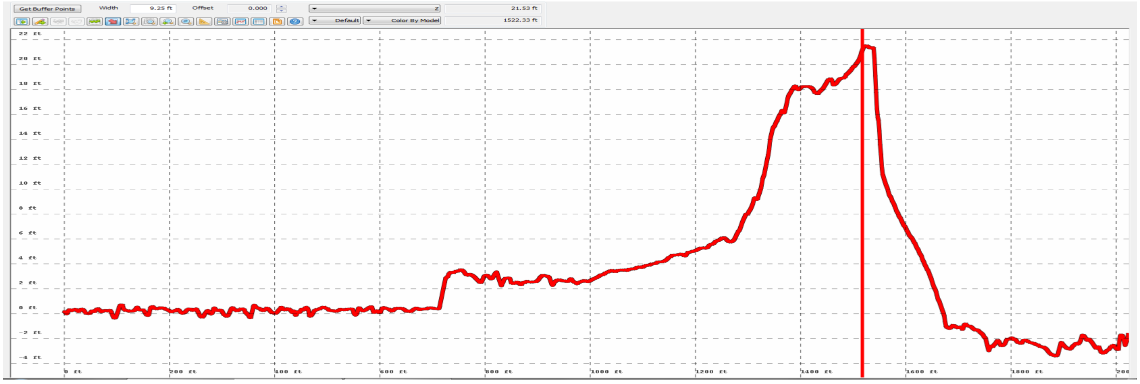

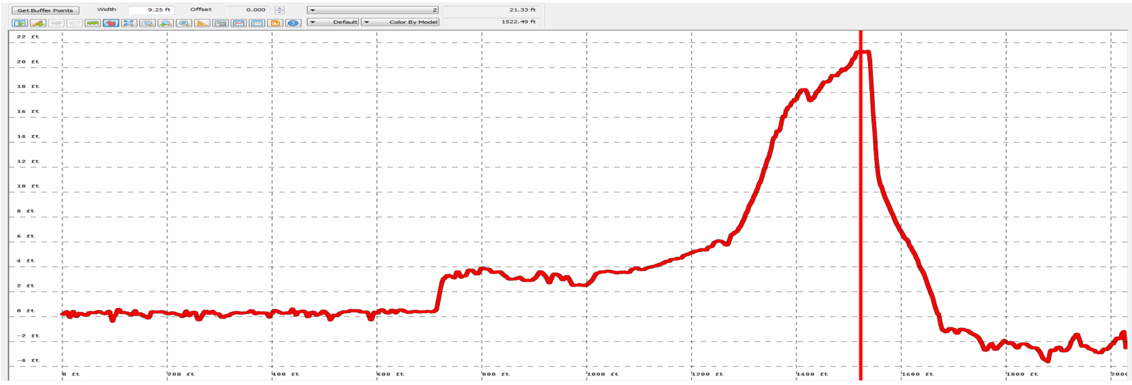

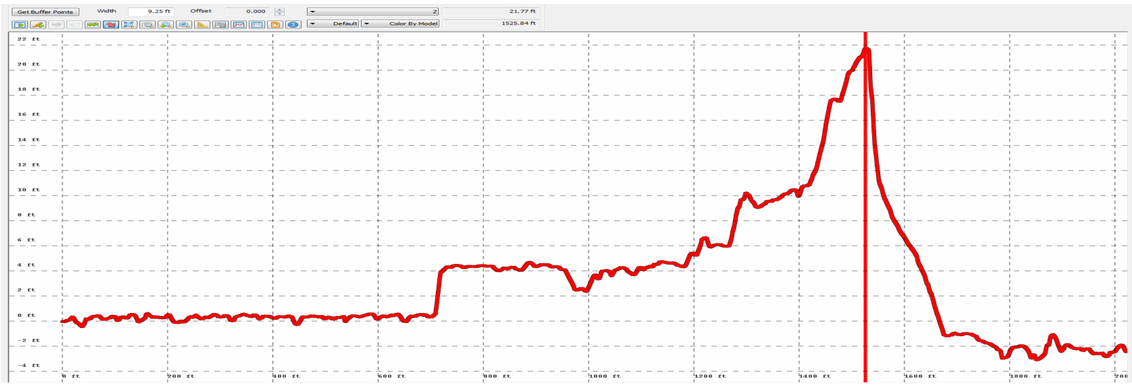

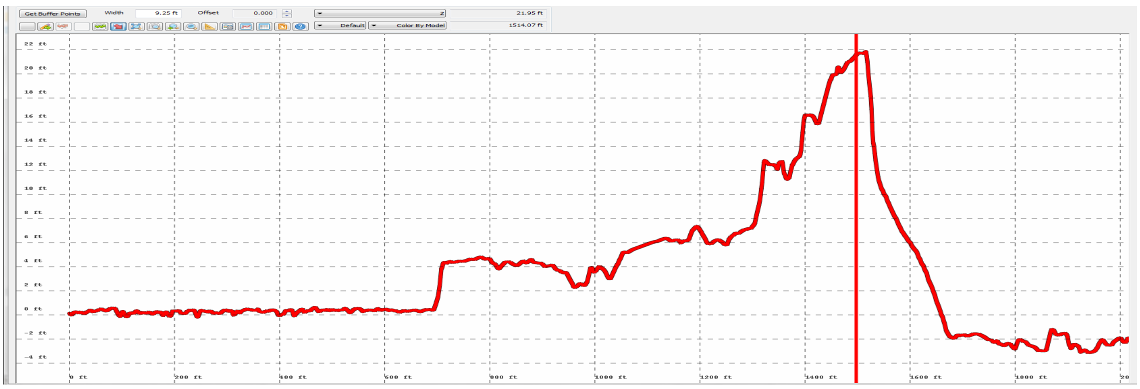

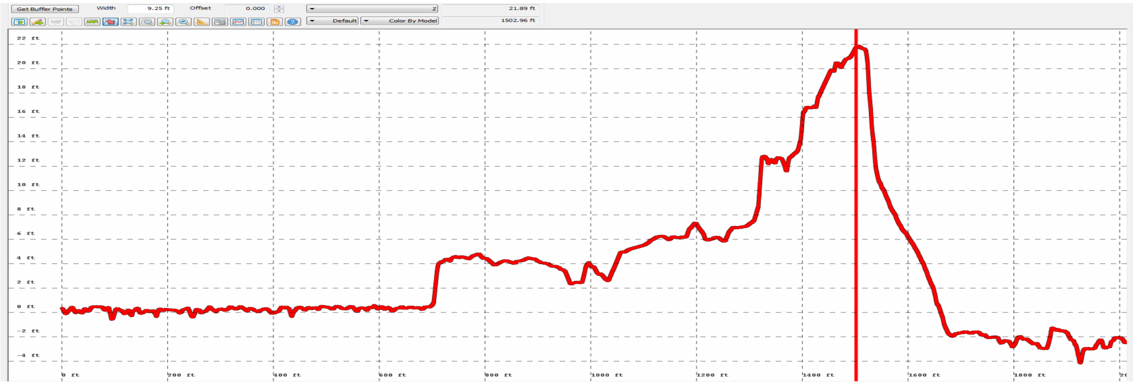
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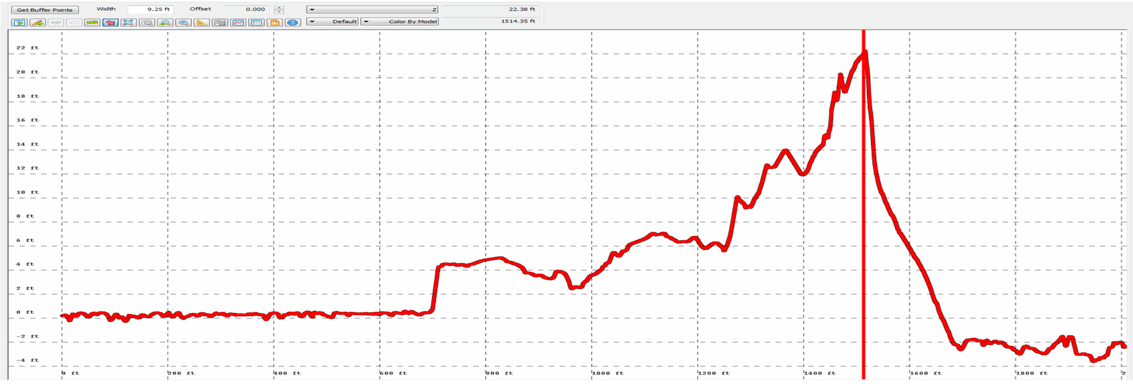
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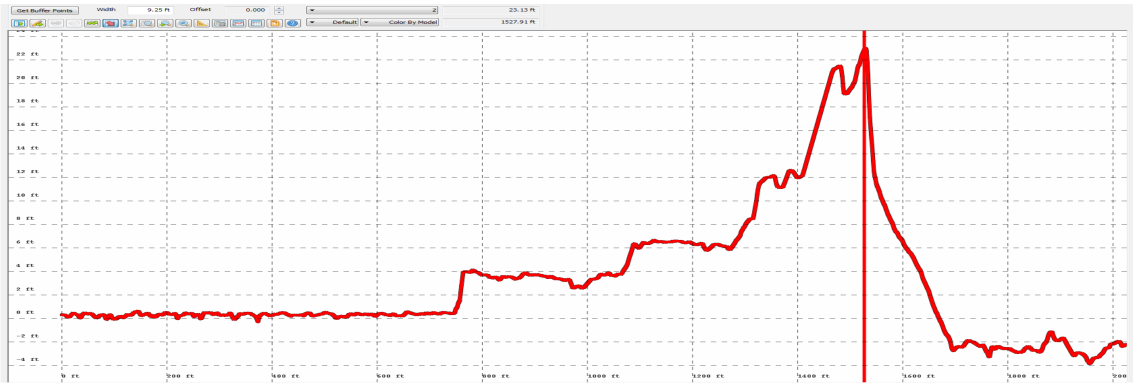
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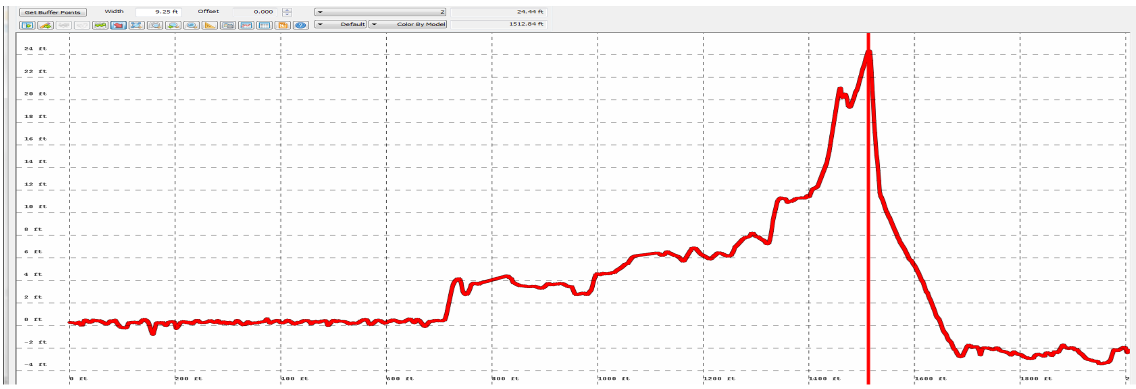
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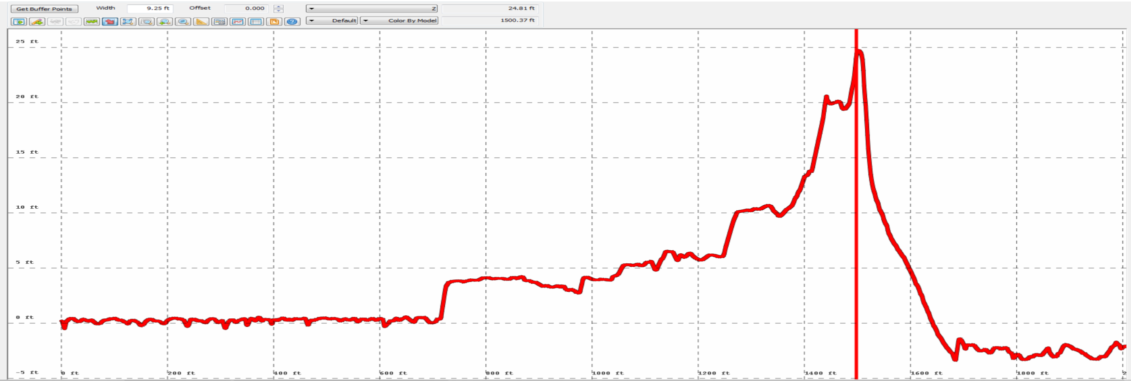

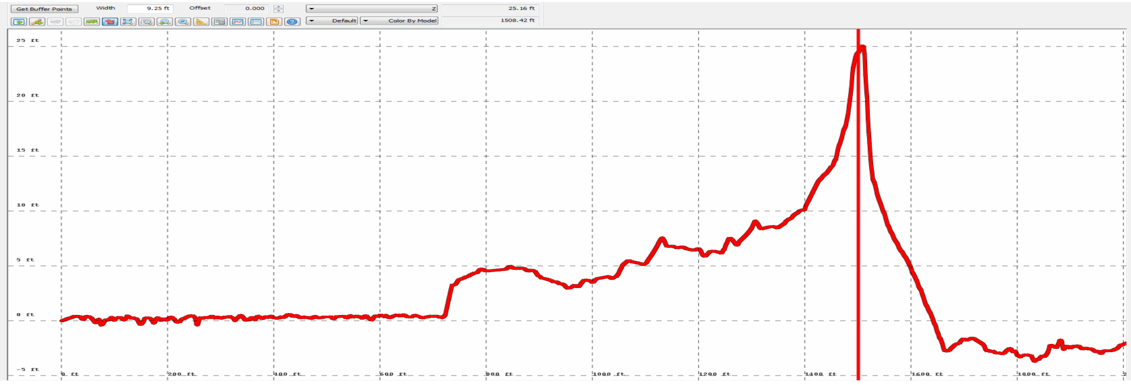

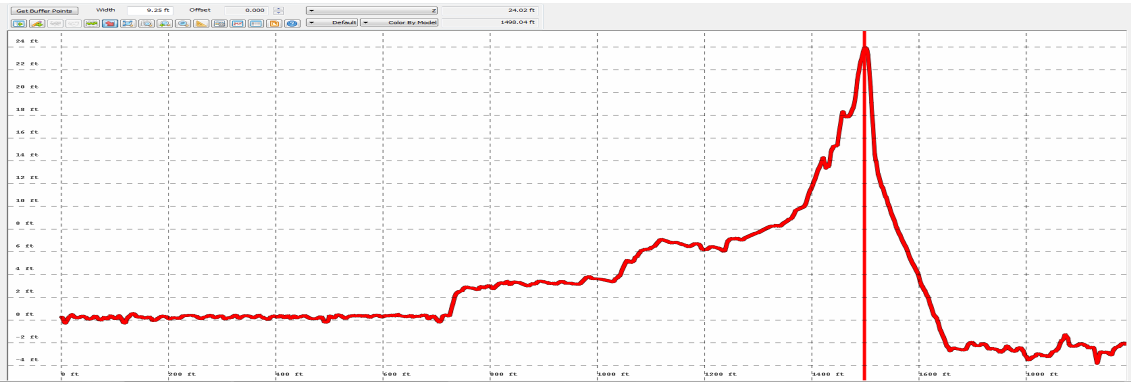

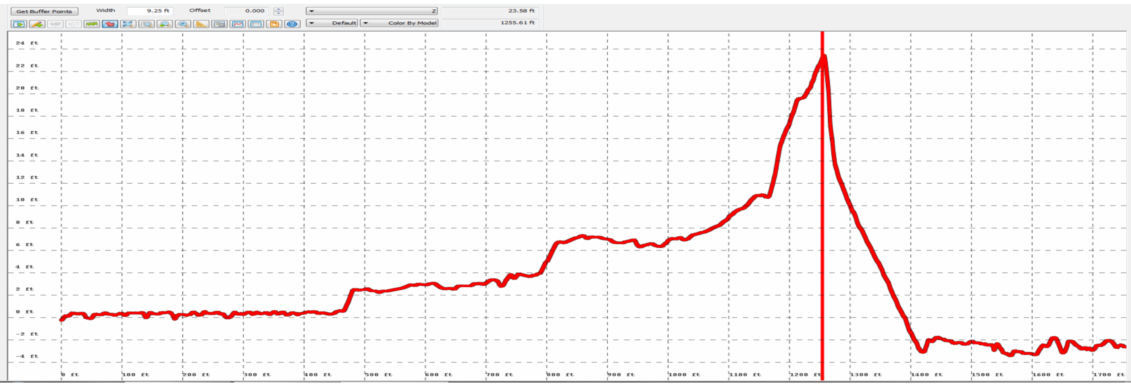

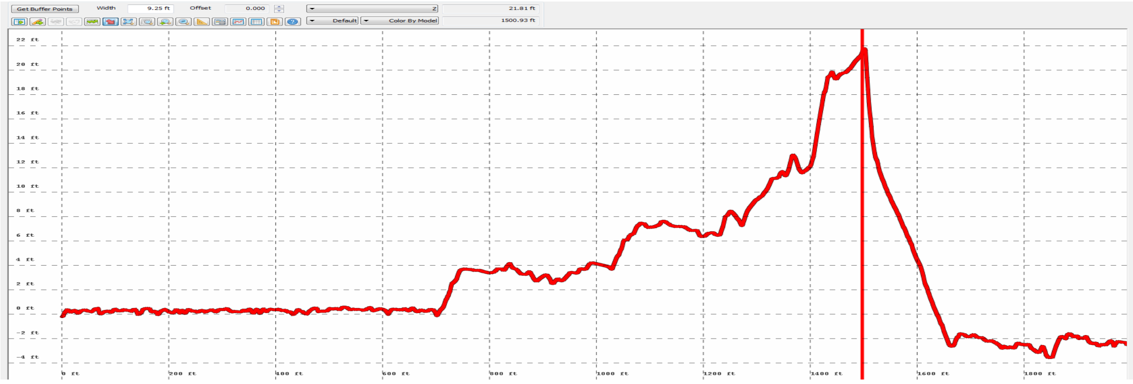
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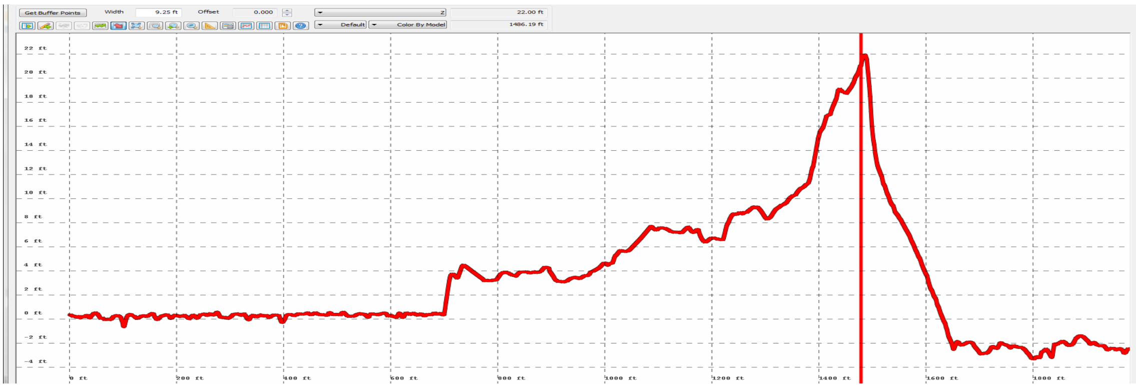
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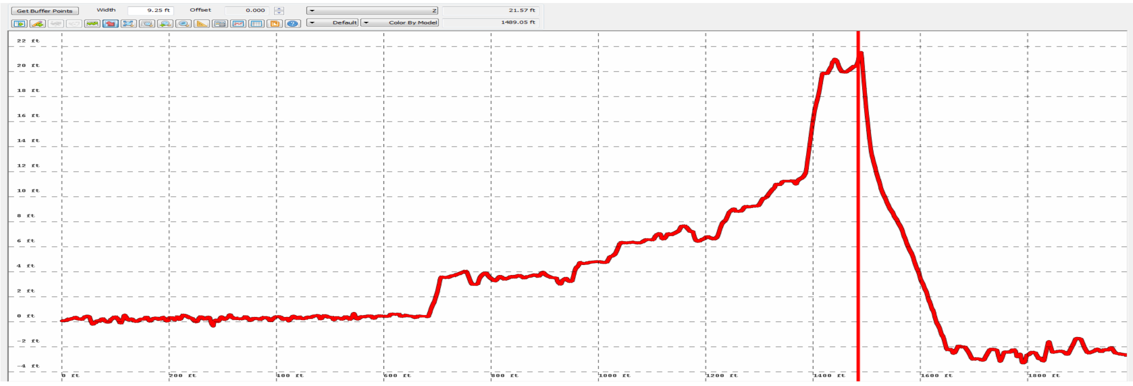
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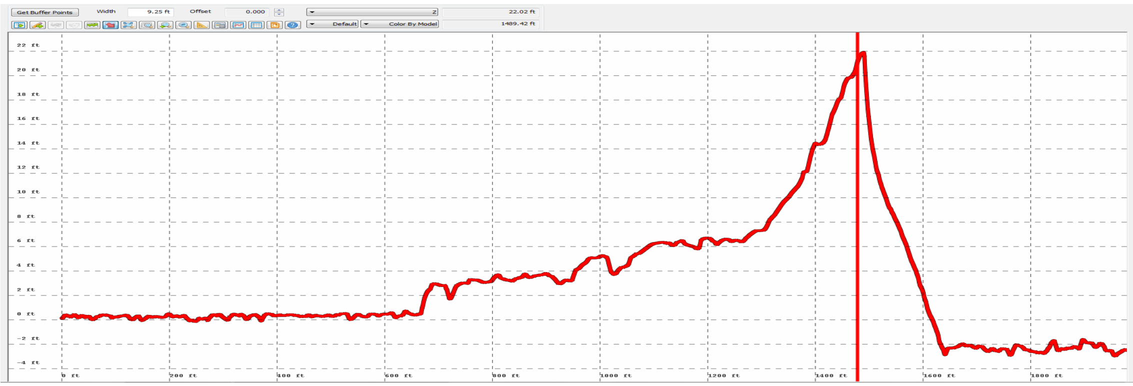
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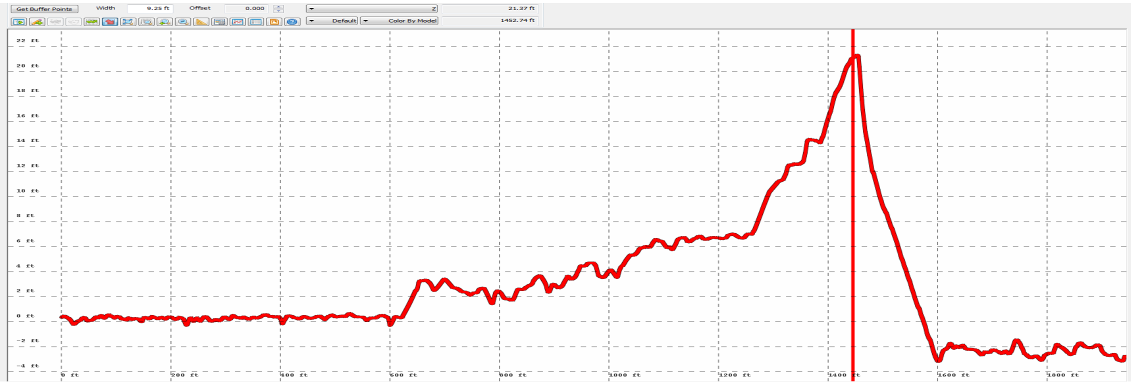

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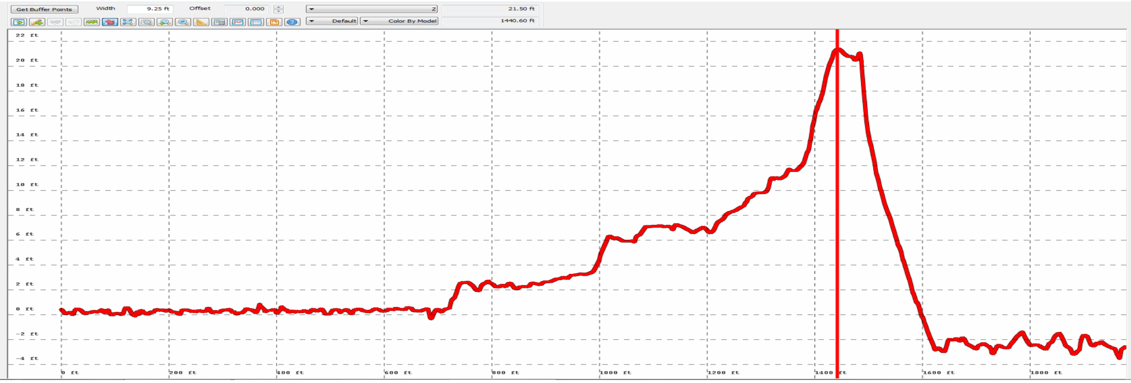

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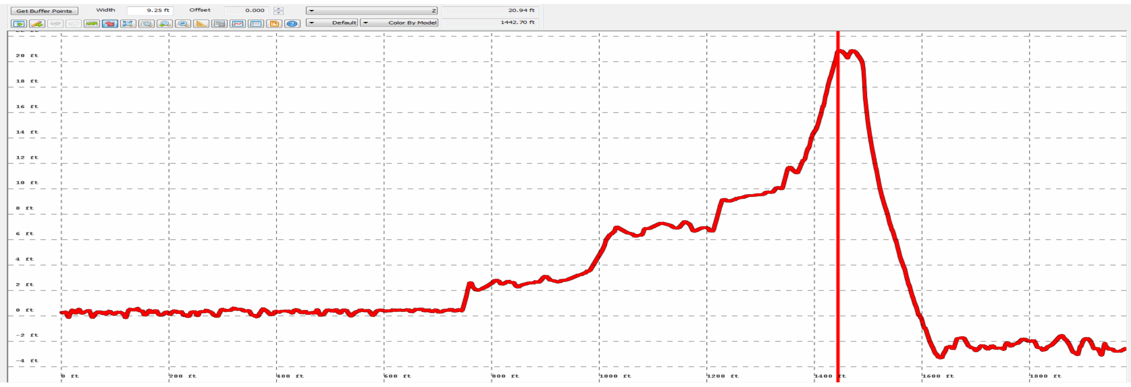

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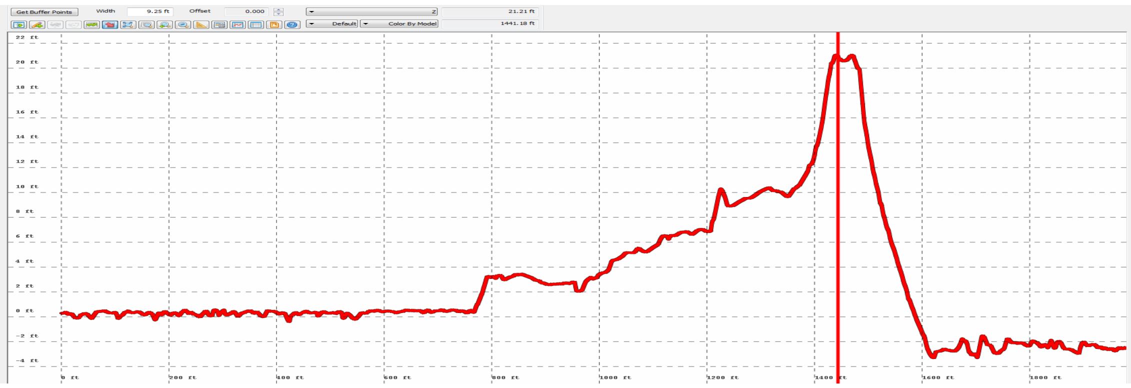

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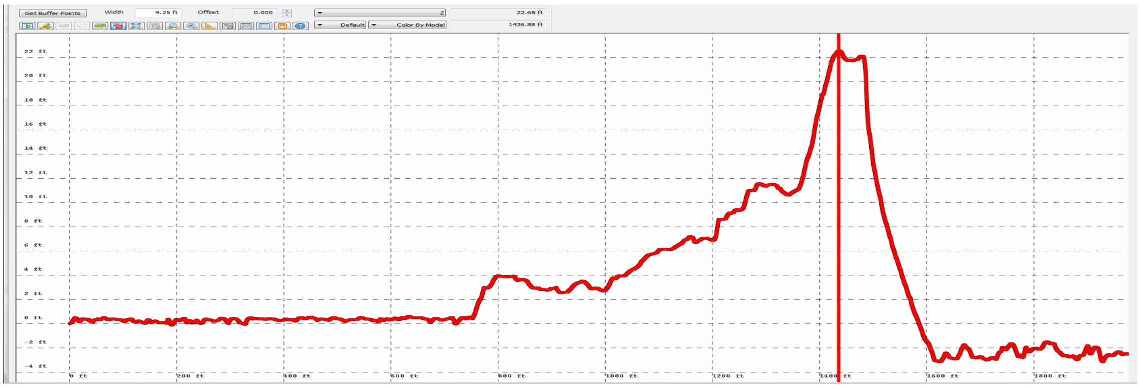
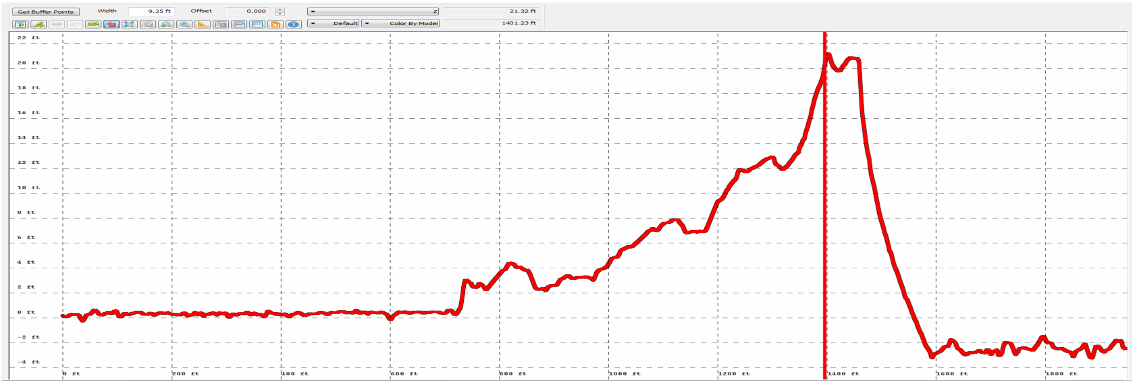
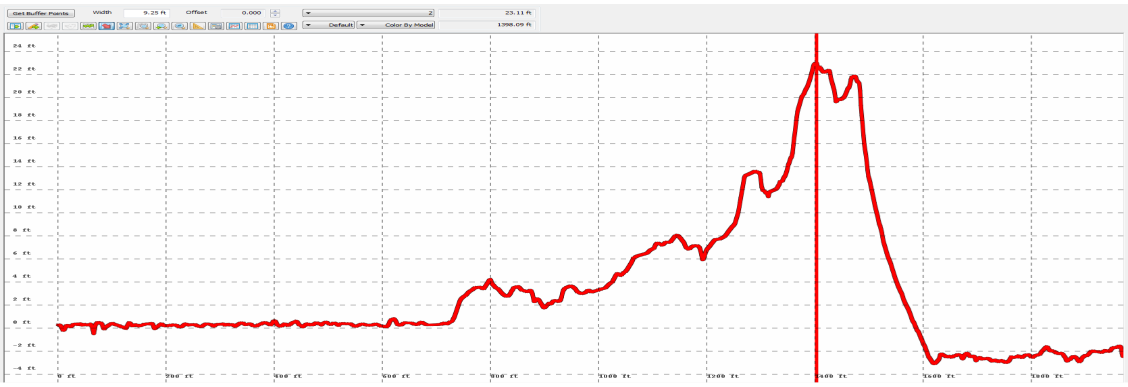
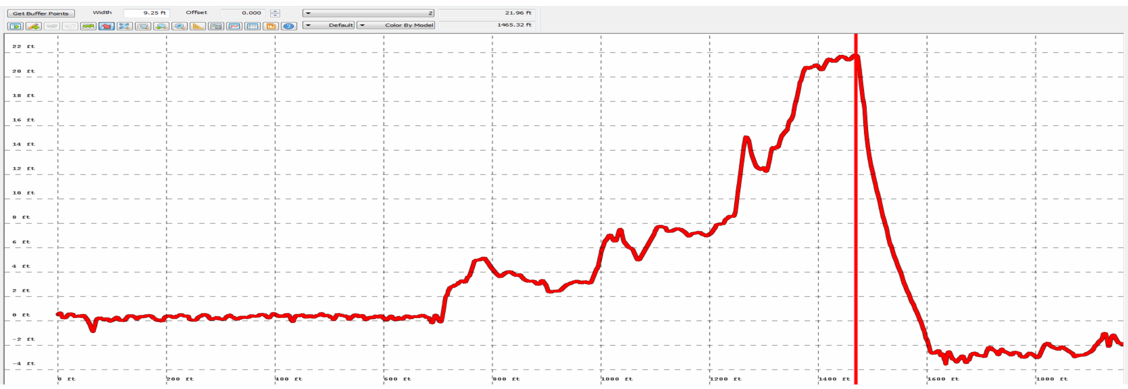
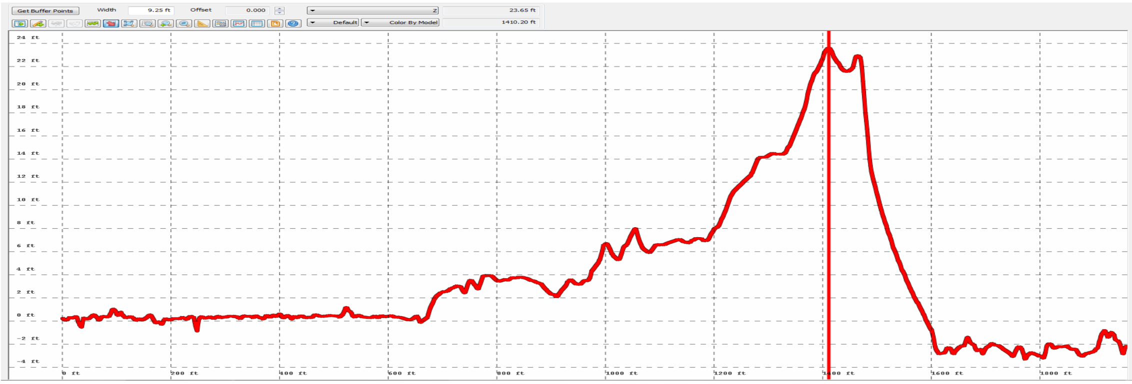
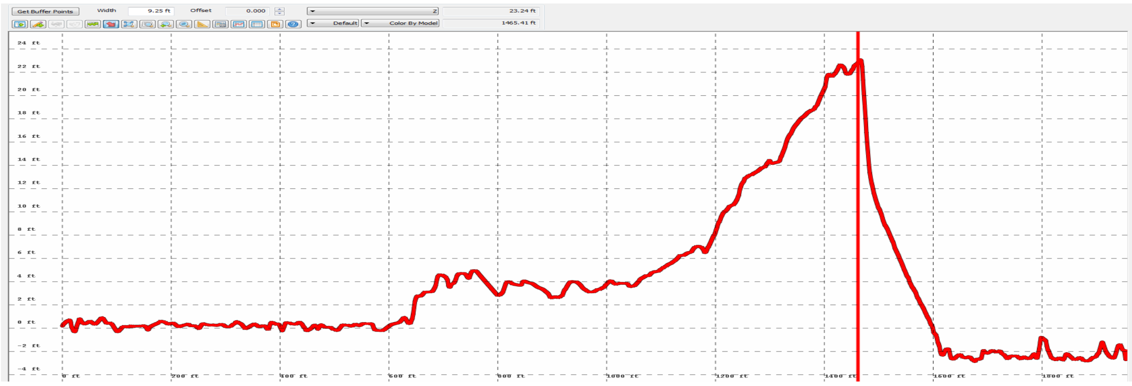


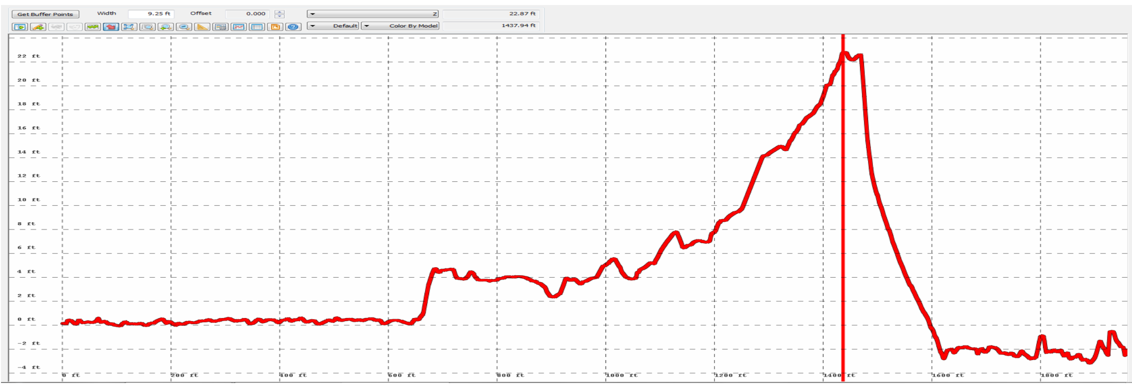


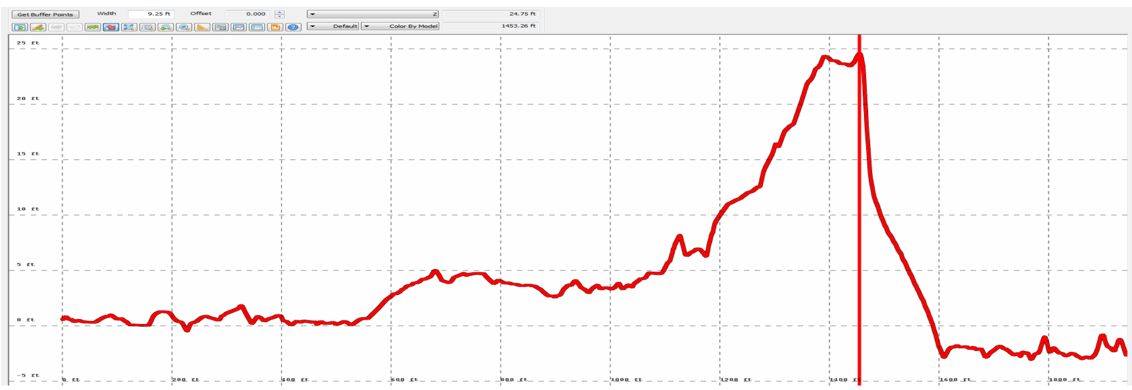




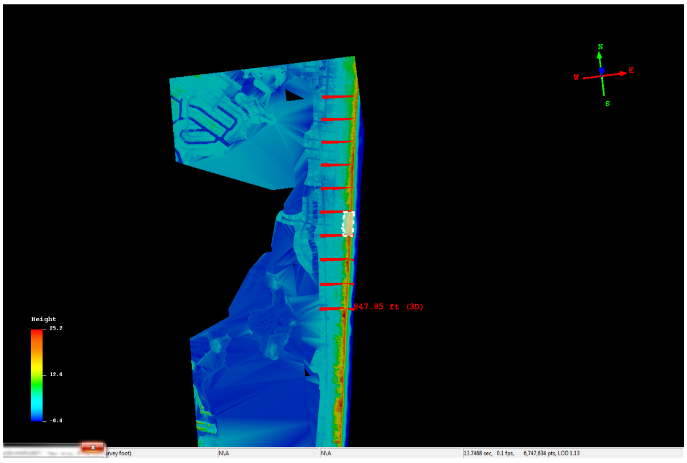


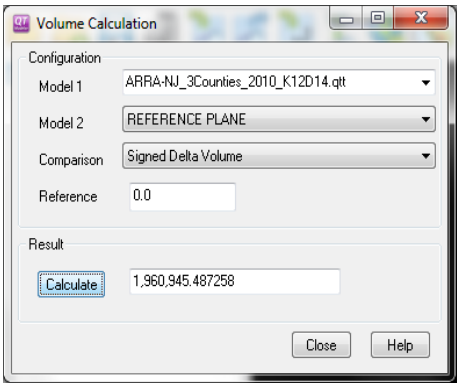






Appendix B – Volume Calculations Along Shoreline

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Comparison
Signed Delta Volume
Reference
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Result
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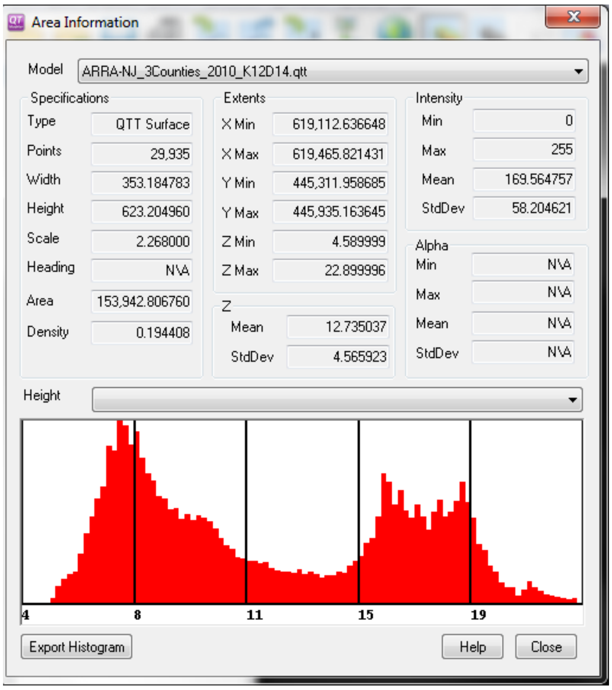
Close
Help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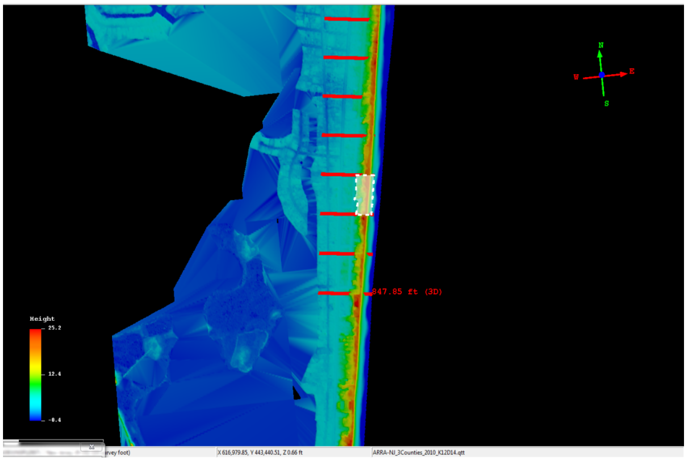
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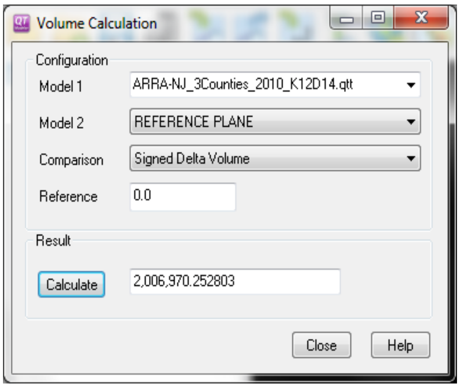
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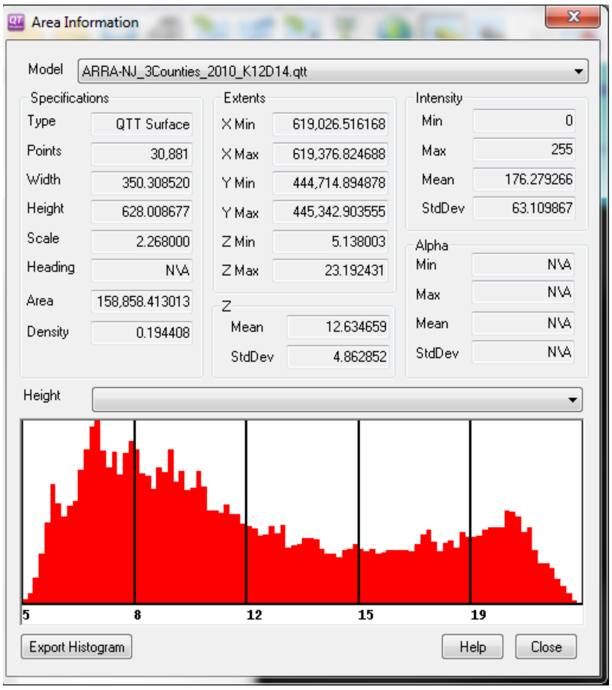
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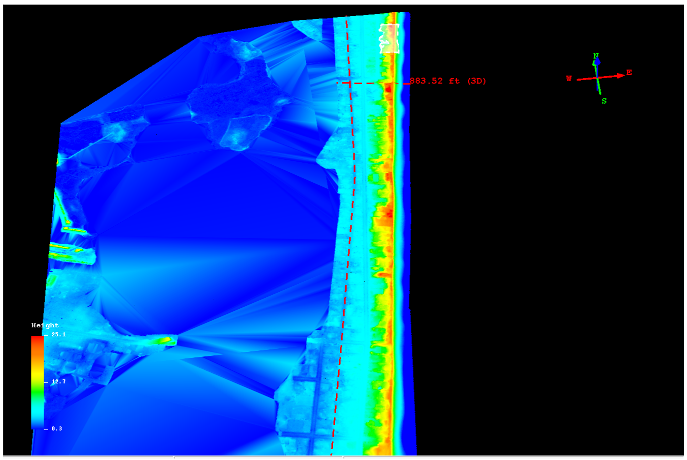
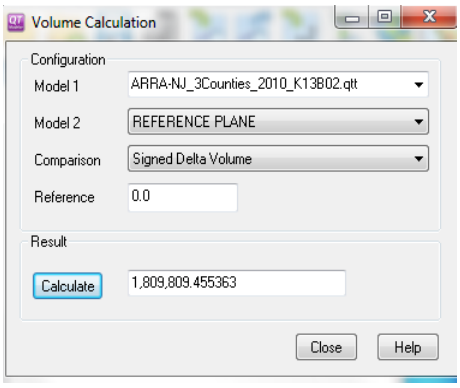
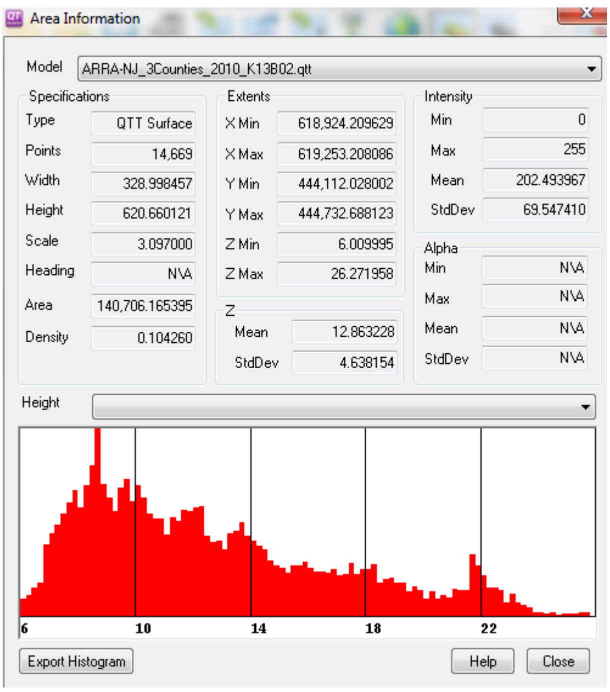
350.308520
Height
628.008677
Scale
2.268000
Heading
N\A
Area
158,858.413013
Density
0.194408
Extents
X Min
619,026.516168
X Max
619,376.824688
Y Min
444,714.894878
Y Max
445,342.903555
Z Min
5.138003
Z Max
23.192431
Z
Mean
12.634659
StdDev
4.862852
Intensity
Min
0
Max
255
Mean
176.279266
StdDev
63.109867
Alpha
Min
N\A
Max
N\A
Mean
N\A
StdDev
N\A
Height
5
8
12
15
19
Export Histogram
Help
Close




Volume Calculation
Configuration
Model 1
ARRA-NJ_3Counties_2010_K13B02.qtt
Model 2
REFERENCE PLANE
Comparison
Signed Delta Volume
Reference
0.0
Result
Calculate
1,809,809.455363
Close
Help


Area Information
Model
ARRA-NJ_3Counties_2010_K13B02.qtt
Specifications
Type
QTT Surface
Points
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Width
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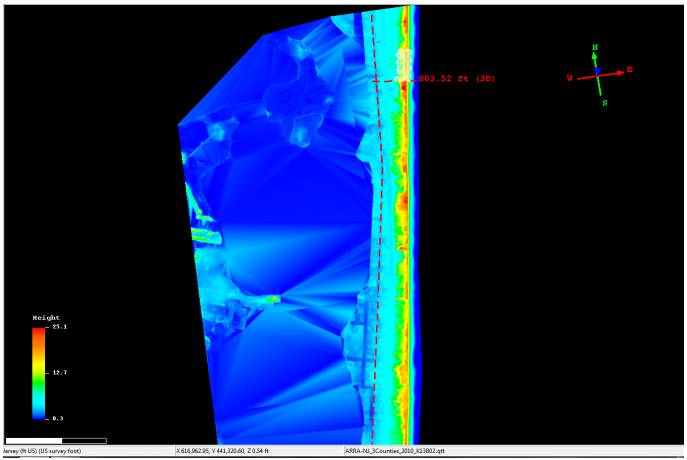
Height
620.660121
Scale
3.097000
Heading
N\A
Area
140,706.165395
Density
0.104260
Extents
X Min
618,924.209629
X Max
619,253.208086
Y Min
444,112.028002
Y Max
444,732.688123
Z Min
6.009995
Z Max
26.271958
Z
Mean
12.863228
StdDev
4.638154
Intensity
Min
0
Max
255
Mean
202.493967
StdDev
69.547410
Alpha
Min
N\A
Max
N\A
Mean
N\A
StdDev
N\A
Height
6
10
14
18
22
Export Histogram
Help
Close


Height
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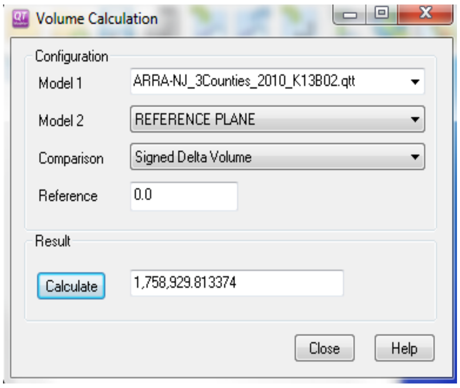
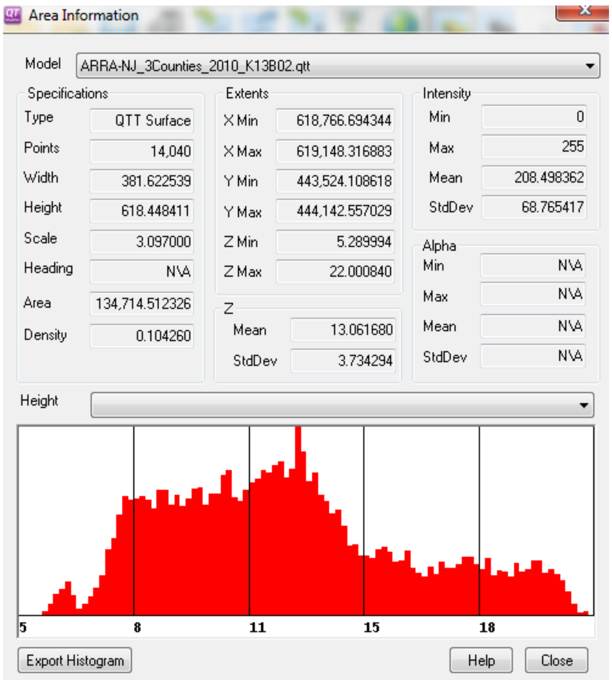
12.7
0.3


Volume Calculation
Configuration
Model 1
ARRA-NJ_3Counties_2010_K13B02.qtt
Model 2
REFERENCE PLANE
Comparison
Signed Delta Volume
Reference
0.0
Result
Calculate
1,758,929.813374
Close
Help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Model
ARRA-NJ_3Counties_2010_K13B02.qtt
Specifications
Type
QTT Surface
Points
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Width
381.622539
Height
618.448411
Scale
3.097000
Heading
N\A
Area
134,714.512326
Density
0.104260
Extents
X Min
618,766.694344
X Max
619,148.316883
Y Min
443,524.108618
Y Max
444,142.557029
Z Min
5.289994
Z Max
22.000840
Z
Mean
13.061680
StdDev
3.734294
Intensity
Min
0
Max
255
Mean
208.498362
StdDev
68.765417
Alpha
Min
N\A
Max
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Mean
N\A
StdDev
N\A
Height
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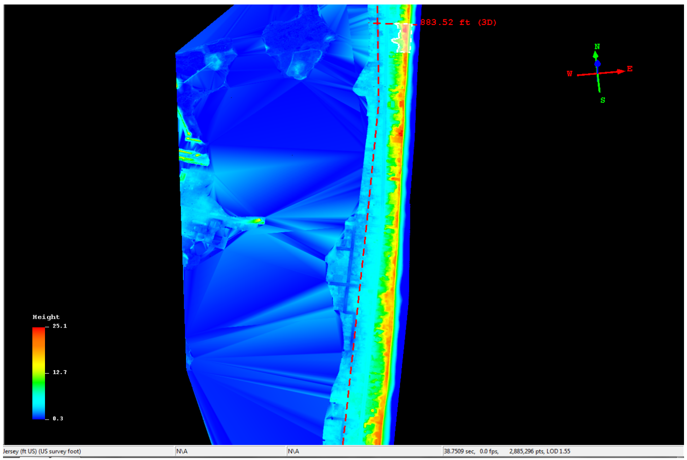
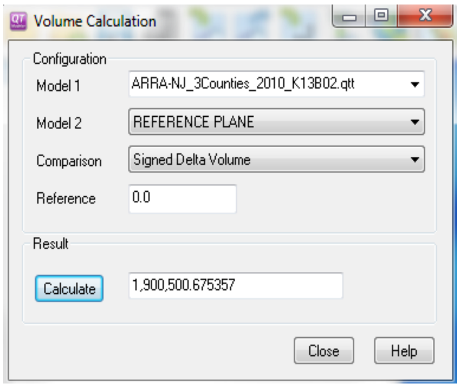
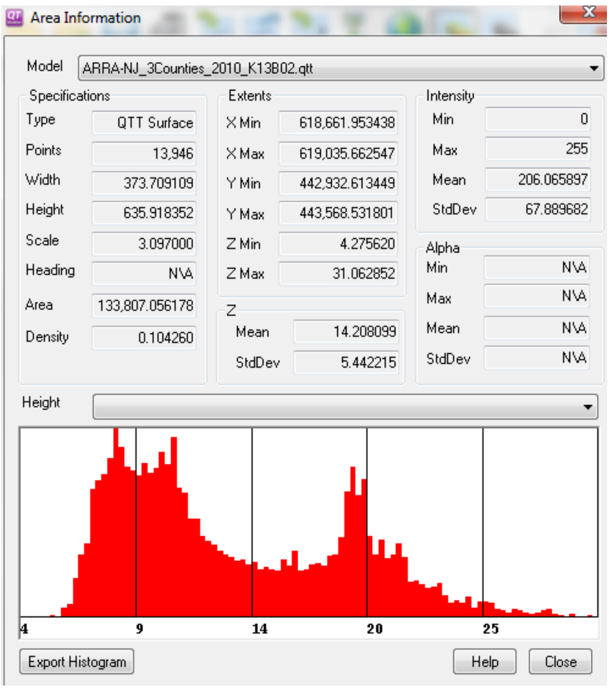
18
Export Histogram
Help
Close


Height


Volume Calculation
Configuration
Model 1
ARRA-NJ_3Counties_2010_K13B02.qtt
Model 2
REFERENCE PLANE
Comparison
Signed Delta Volume
Reference
0.0
Result
Calculate
1,900,500.675357
Close
Help


Area Information
Model
ARRA-NJ_3Counties_2010_K13B02.qtt
Specifications
Type
QTT Surface
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Width
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Height
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Scale
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Heading
N\A
Area
133,807.056178
Density
0.104260
Extents
X Min
618,661.953438
X Max
619,035.662547
Y Min
442,932.613449
Y Max
443,568.531801
Z Min
4.275620
Z Max
31.062852
Z
Mean
14.208099
StdDev
5.442215
Intensity
Min
0
Max
255
Mean
206.065897
StdDev
67.889682
Alpha
Min
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Max
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Mean
N\A
StdDev
N\A
Height
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9
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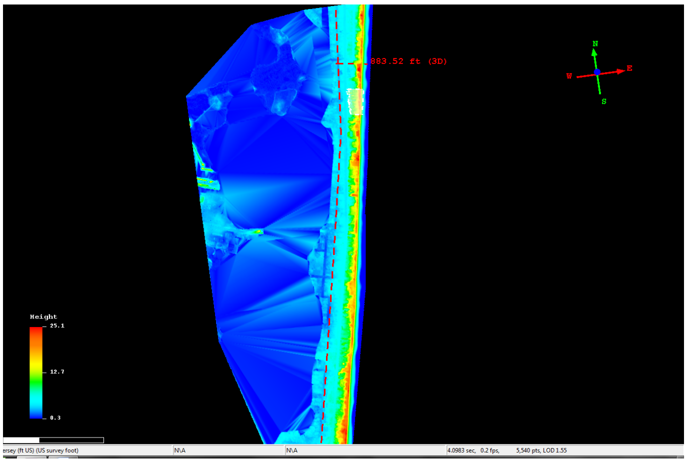
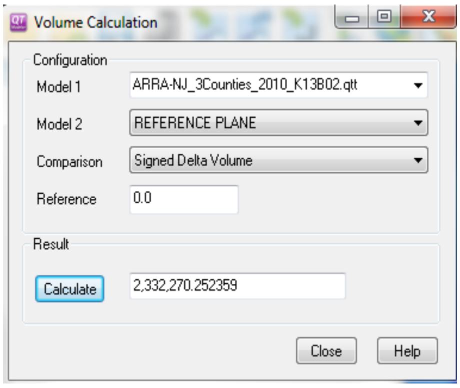
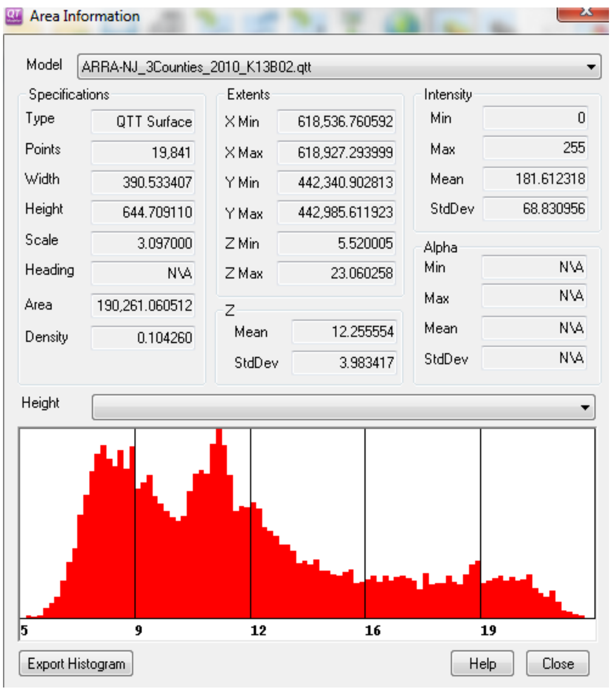
20
25
Export Histogram
Help
Close




Volume Calculation
Configuration
Model 1
ARRA-NJ_3Counties_2010_K13B02.qtt
Model 2
REFERENCE PLANE
Comparison
Signed Delta Volume
Reference
0.0
Result
Calculate
2,332,270.252359
Close
Help


Area Information
Model
ARRA-NJ_3Counties_2010_K13B02.qtt
Specifications
Type
QTT Surface
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Width
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Height
644.709110
Scale
3.097000
Heading
N\A
Area
190,261.060512
Density
0.104260
Extents
X Min
618,536.760592
X Max
618,927.293999
Y Min
442,340.902813
Y Max
442,985.611923
Z Min
5.520005
Z Max
23.060258
Z
Mean
12.255554
StdDev
3.983417
Intensity
Min
0
Max
255
Mean
181.612318
StdDev
68.830956
Alpha
Min
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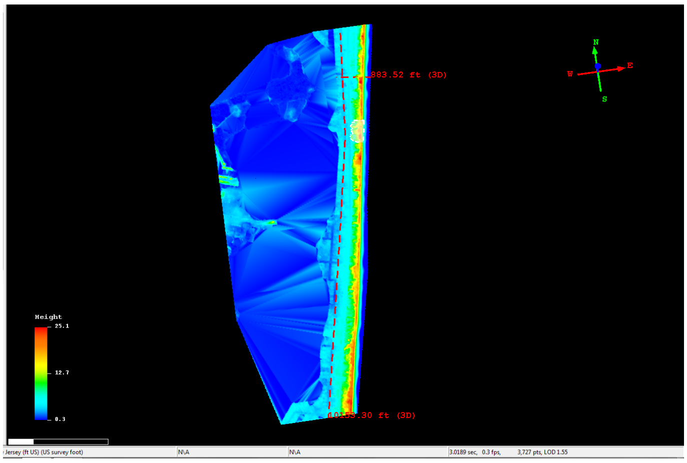
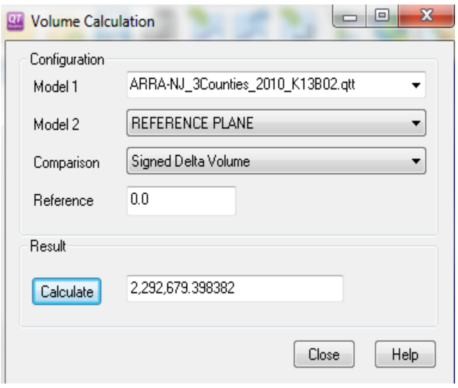
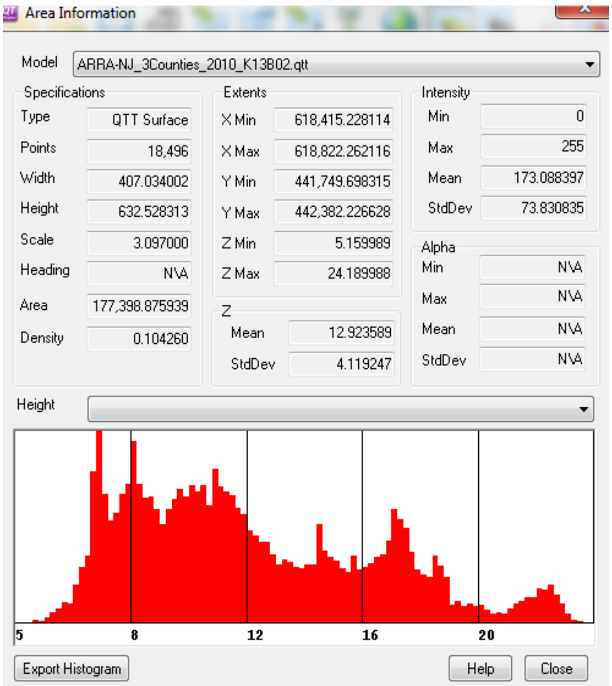
N\A
Mean
N\A
StdDev
N\A
Height
5
9
12
16
19
Export Histogram
Help
Close


883.52 ft (3D)
Height


Volume Calculation
Configuration
Model 1
ARRA-NJ_3Counties_2010_K13B02.qtt
Model 2
REFERENCE PLANE
Comparison
Signed Delta Volume
Reference
0.0
Result
Calculate
2,292,679.398382
Close
Help


Area Information
Model
ARRA-NJ_3Counties_2010_K13B02.qtt
Specifications
Type
QTT Surface
Points
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Width
407.034002
Height
632.528313
Scale
3.097000
Heading
N\A
Area
177,398.875939
Density
0.104260
Extents
X Min
618,415.228114
X Max
618,822.262116
Y Min
441,749.698315
Y Max
442,382.226628
Z Min
5.159989
Z Max
24.189988
Z
Mean
12.923589
StdDev
4.119247
Intensity
Min
0
Max
255
Mean
173.088397
StdDev
73.830835
Alpha
Min
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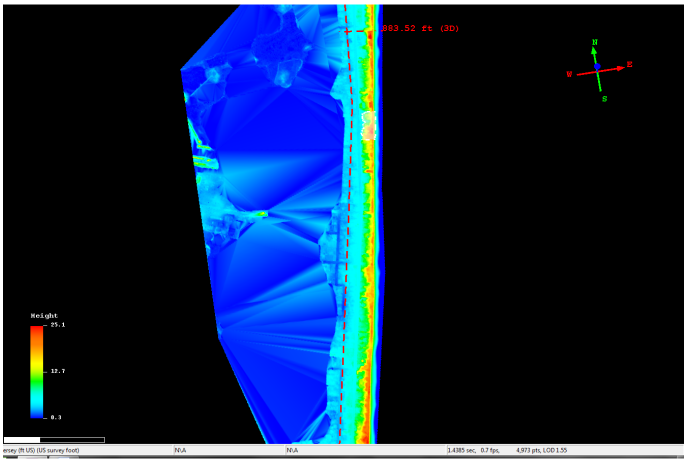
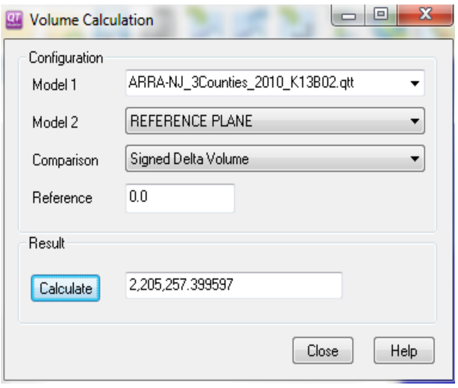
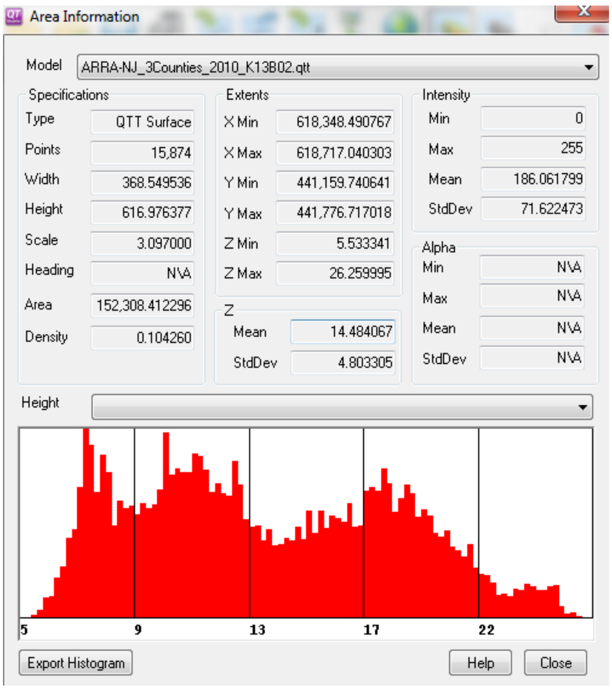
Max
N\A
Mean
N\A
StdDev
N\A
Height
5
8
12
16
20
Export Histogram
Help
Close

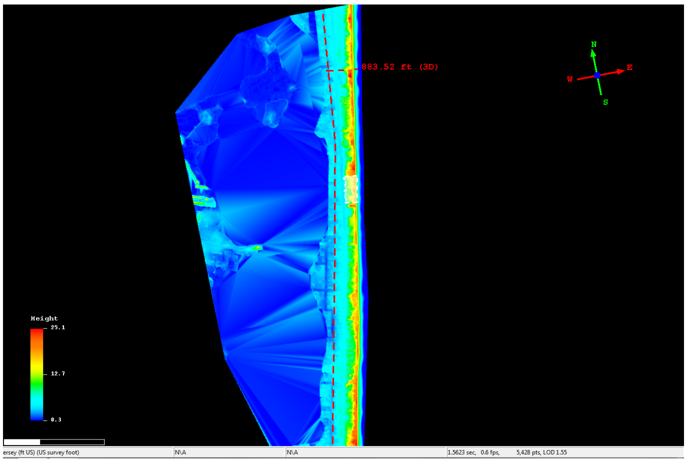


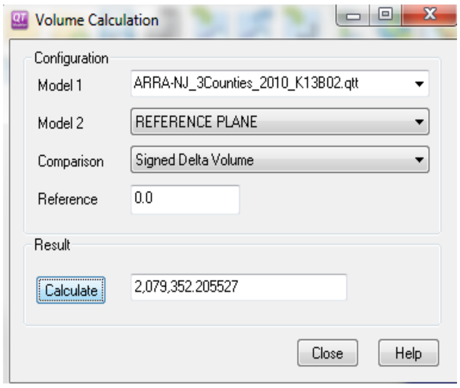


Volume Calculation
Configuration
Model 1
ARRA-NJ_3Counties_2010_K13B02.qtt
Model 2
REFERENCE PLANE
Comparison
Signed Delta Volume
Reference
0.0
Result
Calculate
2,205,257.399597
Close
Help



Area Information
Model
ARRA-NJ_3Counties_2010_K13B02.qtt
Specifications
Type QTT Surface
Points 15,874
Width 368.549536
Height 616.976377
Scale 3.097000
Heading N\A
Area 152,308.412296
Density 0.104260
Extents
X Min 618,348.490767
X Max 618,717.040303
Y Min 441,159.740641
Y Max 441,776.717018
Z Min 5.533341
Z Max 26.259995
Z
Mean 14.484067
StdDev 4.803305
Intensity
Min 0
Max 255
Mean 186.061799
StdDev 71.622473
Alpha
Min N\A
Max N\A
Mean N\A
StdDev N\A
Height
5
9
13
17
22
Export Histogram
Help
Close


Height


Volume Calculation
Configuration
Model 1
ARRA-NJ_3Counties_2010_K13B02.qtt
Model 2
REFERENCE PLANE
Comparison
Signed Delta Volume
Reference
0.0
Result
Calculate
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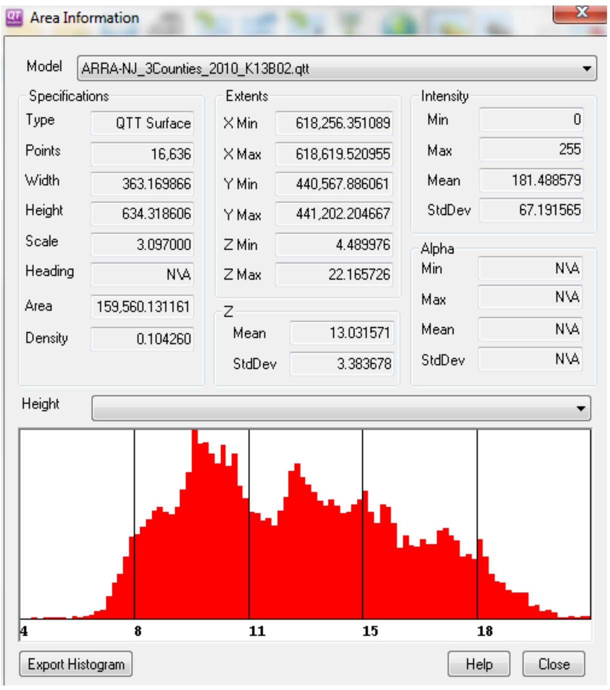
Close
Help


Area Information
Model
ARRA-NJ_3Counties_2010_K13B02.qtt
Specifications
Type
QTT Surface
Points
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Width
363.169866
Height
634.318606
Scale
3.097000
Heading
N\A
Area
159,560.131161
Density
0.104260
Extents
X Min
618,256.351089
X Max
618,619.520955
Y Min
440,567.886061
Y Max
441,202.204667
Z Min
4.489976
Z Max
22.165726
Z
Mean
13.031571
StdDev
3.383678
Intensity
Min
0
Max
255
Mean
181.488579
StdDev
67.191565
Alpha
Min
N\A
Max
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Mean
N\A
StdDev
N\A
Height
4
8
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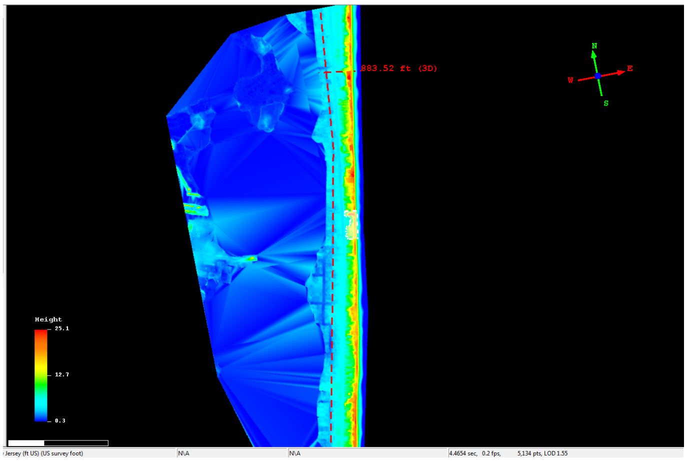
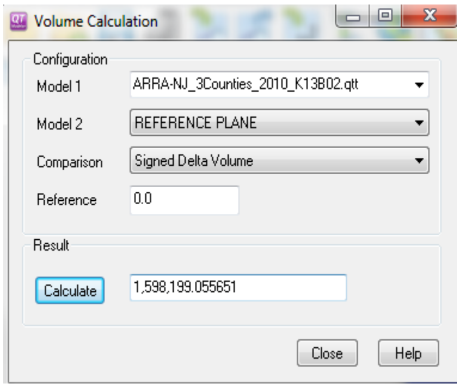
15
18
Export Histogram
Help
Close


883.52 ft (3D)
Height
25.1
12.7
0.3


Volume Calculation
Configuration
Model 1
ARRA-NJ_3Counties_2010_K13B02.qtt
Model 2
REFERENCE PLANE
Comparison
Signed Delta Volume
Reference
0.0
Result
Calculate
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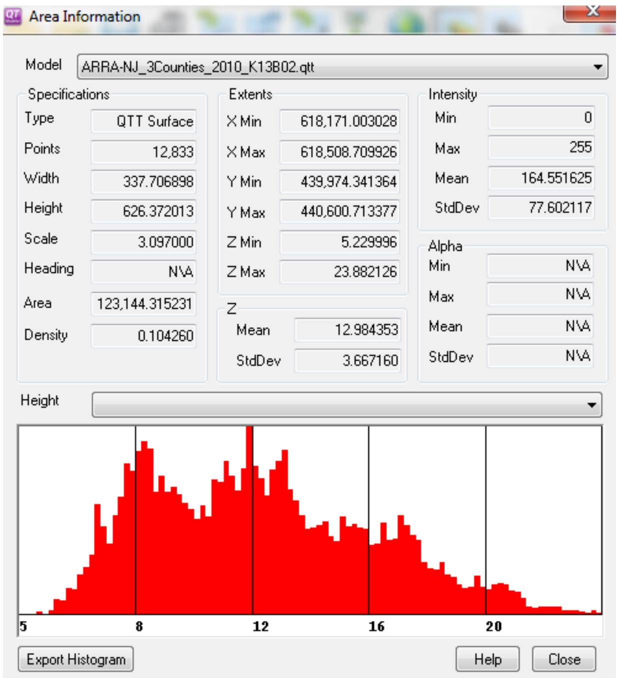
Close
Help


Area Information
Model
ARRA-NJ_3Counties_2010_K13B02.qtt
Specifications
Type
QTT Surface
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Width
337.706898
Height
626.372013
Scale
3.097000
Heading
N\A
Area
123,144.315231
Density
0.104260
Extents
X Min
618,171.003028
X Max
618,508.709926
Y Min
439,974.341364
Y Max
440,600.713377
Z Min
5.229996
Z Max
23.882126
Z
Mean
12.984353
StdDev
3.667160
Intensity
Min
0
Max
255
Mean
164.551625
StdDev
77.602117
Alpha
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Max
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Mean
N\A
StdDev
N\A
Height
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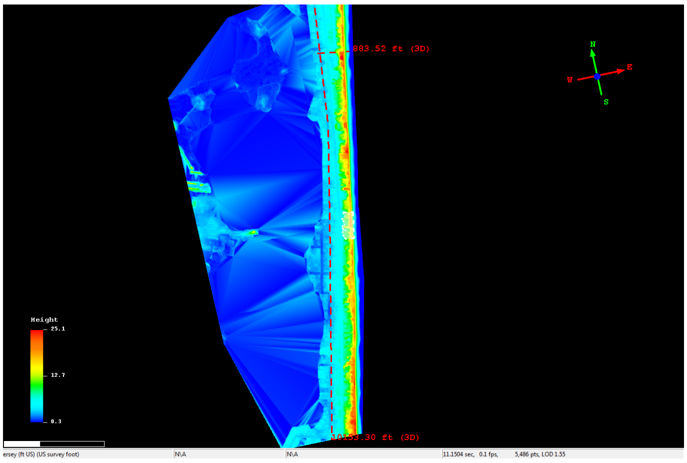
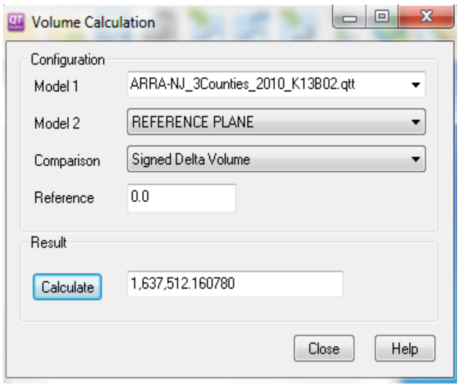
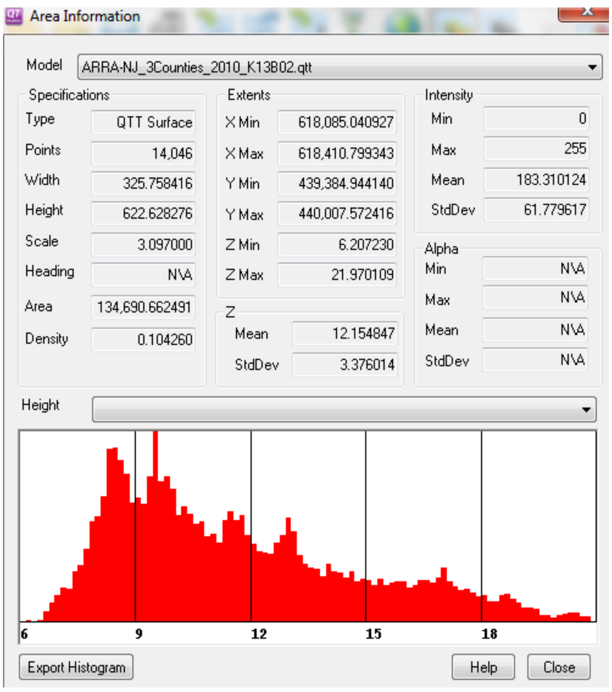
8
12
16
20
Export Histogram
Help
Close


483.52 ft (3D)
Height


Volume Calculation
Configuration
Model 1
ARRA-NJ_3Counties_2010_K13B02.qtt
Model 2
REFERENCE PLANE
Comparison
Signed Delta Volume
Reference
0.0
Result
Calculate
1,637,512.160780
Close
Help


Area Information
Model
ARRA-NJ_3Counties_2010_K13B02.qtt
Specifications
Type
QTT Surface
Points
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Width
325.758416
Height
622.628276
Scale
3.097000
Heading
N\A
Area
134,690.662491
Density
0.104260
Extents
X Min
618,085.040927
X Max
618,410.799343
Y Min
439,384.944140
Y Max
440,007.572416
Z Min
6.207230
Z Max
21.970109
Z
Mean
12.154847
StdDev
3.376014
Intensity
Min
0
Max
255
Mean
183.310124
StdDev
61.779617
Alpha
Min
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Max
N\A
Mean
N\A
StdDev
N\A
Height
6
9
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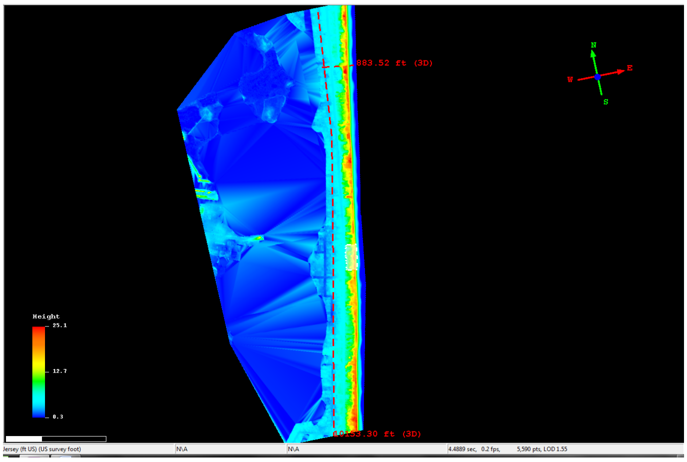
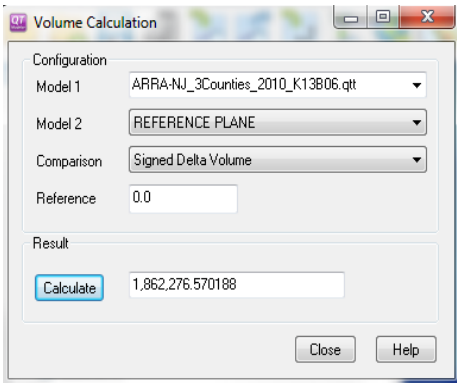
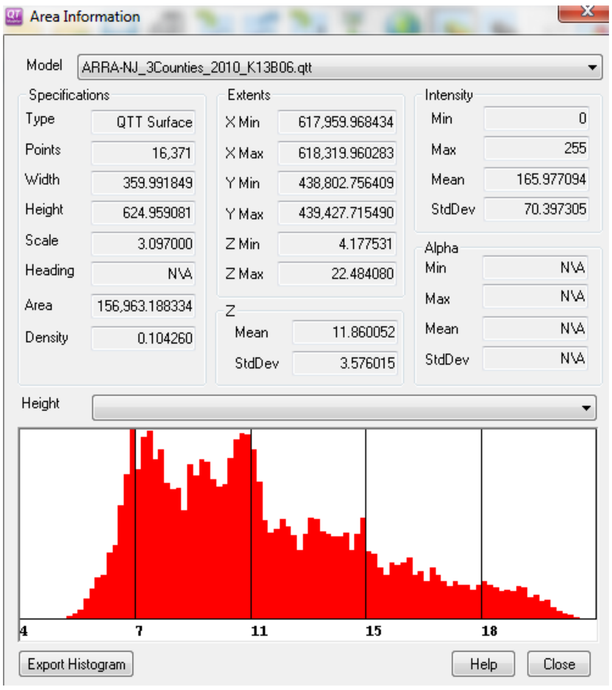
18
Export Histogram
Help
Close




Volume Calculation
Configuration
Model 1
ARRA-NJ_3Counties_2010_K13B06.qtt
Model 2
REFERENCE PLANE
Comparison
Signed Delta Volume
Reference
0.0
Result
Calculate
1,862,276.570188
Close
Help


Area Information
Model
ARRA-NJ_3Counties_2010_K13B06.qtt
Specifications
Type
QTT Surface
Points
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Width
359.991849
Height
624.959081
Scale
3.097000
Heading
N\A
Area
156,963.188334
Density
0.104260
Extents
X Min
617,959.968434
X Max
618,319.960283
Y Min
438,802.756409
Y Max
439,427.715490
Z Min
4.177531
Z Max
22.484080
Z
Mean
11.860052
StdDev
3.576015
Intensity
Min
0
Max
255
Mean
165.977094
StdDev
70.397305
Alpha
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Max
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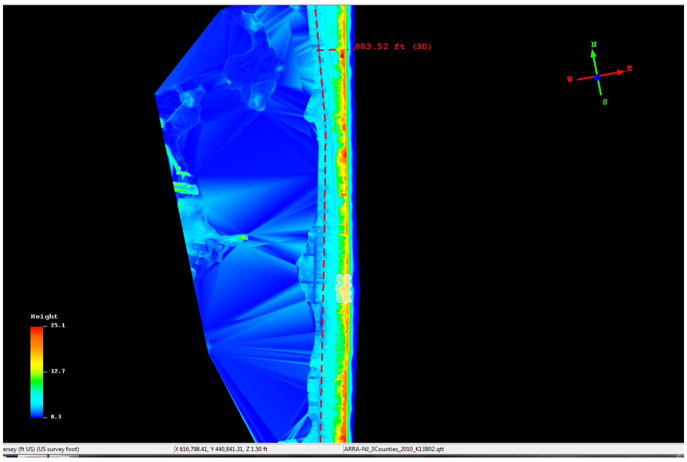
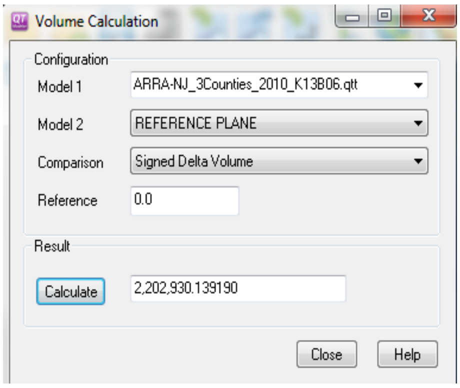
Mean
N\A
StdDev
N\A
Height
4
7
11
15
18
Export Histogram
Help
Close




Volume Calculation
Configuration
Model 1
ARRA-NJ_3Counties_2010_K13B06.qtt
Model 2
REFERENCE PLANE
Comparison
Signed Delta Volume
Reference
0.0
Result
Calculate
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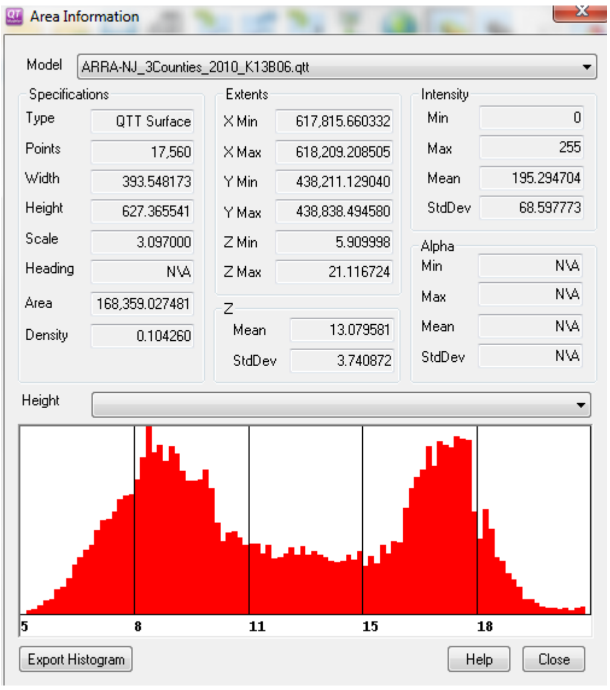
Close
Help


Area Information
Model
ARRA-NJ_3Counties_2010_K13B06.qtt
Specifications
Type
QTT Surface
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Width
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Height
627.365541
Scale
3.097000
Heading
N\A
Area
168,359.027481
Density
0.104260
Extents
X Min
617,815.660332
X Max
618,209.208505
Y Min
438,211.129040
Y Max
438,838.494580
Z Min
5.909998
Z Max
21.116724
Z
Mean
13.079581
StdDev
3.740872
Intensity
Min
0
Max
255
Mean
195.294704
StdDev
68.597773
Alpha
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Max
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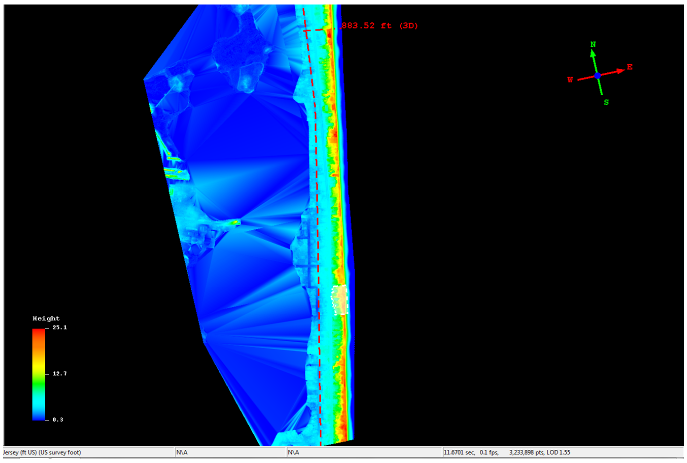
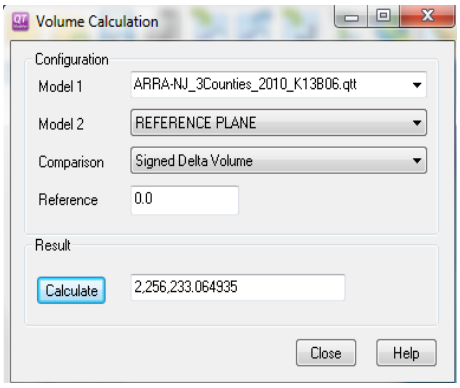
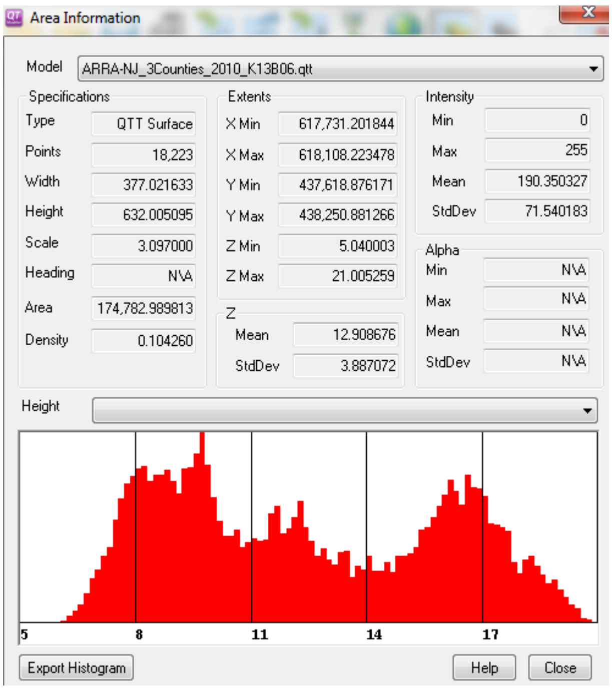
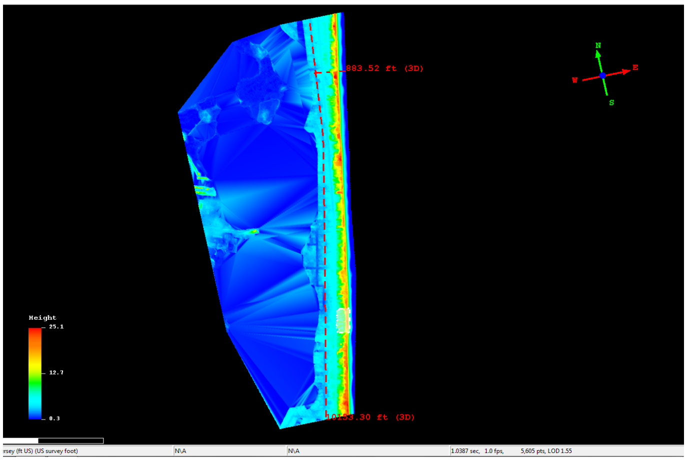
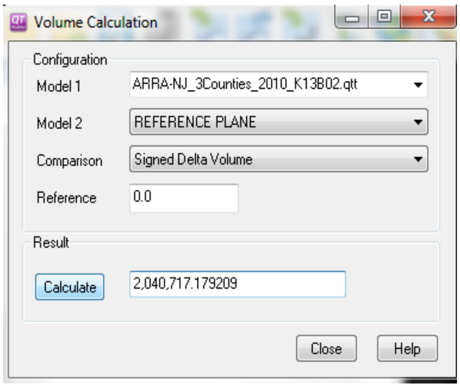
Mean
N\A
StdDev
N\A
Height
5
8
11
15
18
Export Histogram
Help
Close

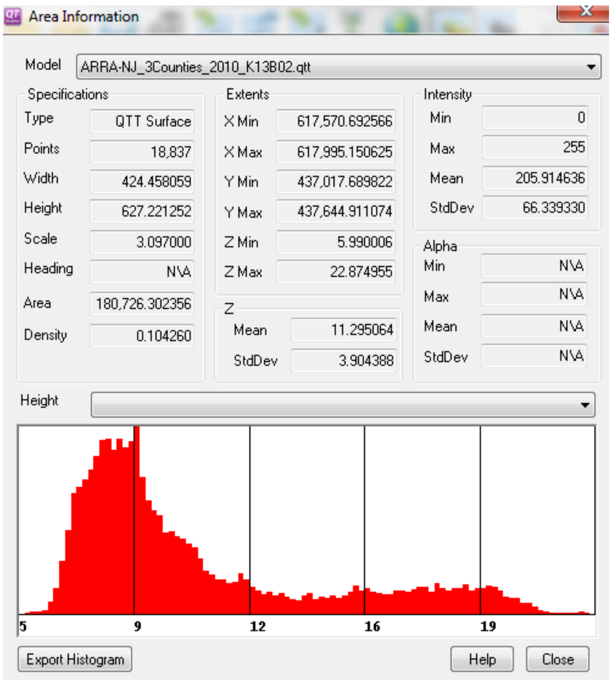


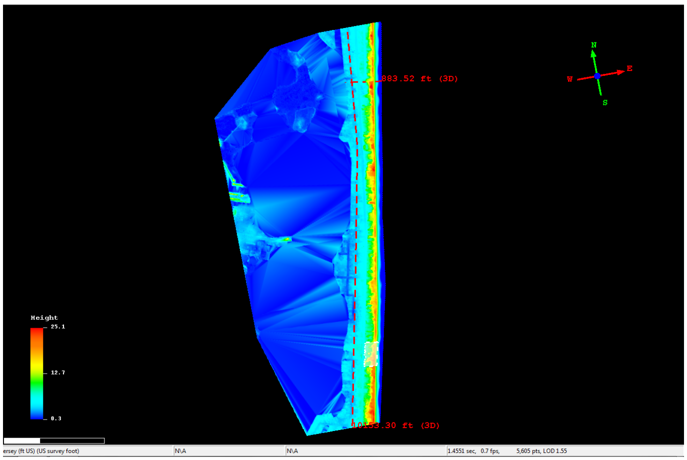

Volume Calculation
Configuration
Model 1
ARRA-NJ_3Counties_2010_K13B06.qtt
Model 2
REFERENCE PLANE
Comparison
Signed Delta Volume
Reference
0.0
Result
Calculate
2,256,233.064935
Close
Help

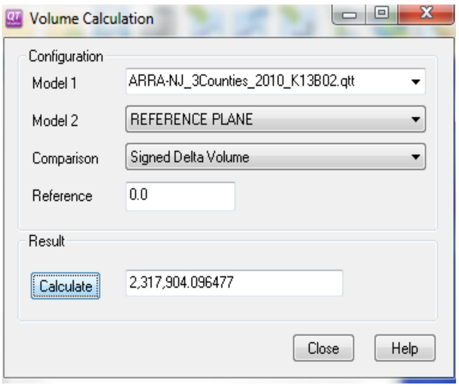

Area Information
Model
ARRA-NJ_3Counties_2010_K13B06.qtt
Specifications
Type QTT Surface
Points 18,223
Width 377.021633
Height 632.005095
Scale 3.097000
Heading N\A
Area 174,782.989813
Density 0.104260
Extents
X Min 617,731.201844
X Max 618,108.223478
Y Min 437,618.876171
Y Max 438,250.881266
Z Min 5.040003
Z Max 21.005259
Z
Mean 12.908676
StdDev 3.887072
Intensity
Min 0
Max 255
Mean 190.350327
StdDev 71.540183
Alpha
Min N\A
Max N\A
Mean N\A
StdDev N\A
Height
5
8
11
14
17
Export Histogram
Help
Close

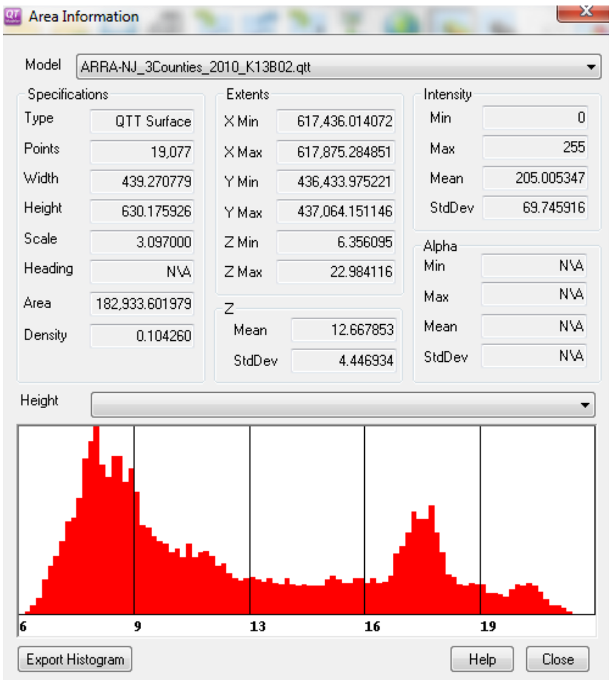


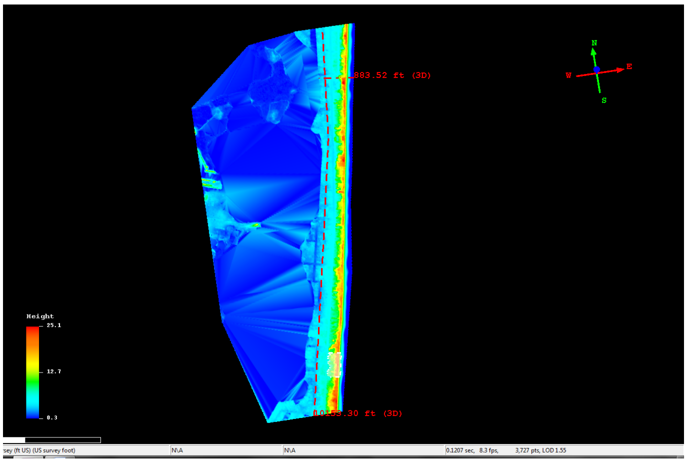

Volume Calculation
Configuration
Model 1
ARRA-NJ_3Counties_2010_K13B02.qtt
Model 2
REFERENCE PLANE
Comparison
Signed Delta Volume
Reference
0.0
Result
Calculate
2,040,717.179209
Close
Help

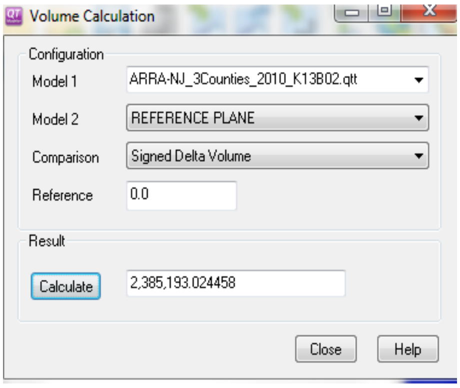

Area Information
Model
ARRA-NJ_3Counties_2010_K13B02.qtt
Specifications
Type
QTT Surface
Points
18,837
Width
424.458059
Height
627.221252
Scale
3.097000
Heading
N\A
Area
180,726.302356
Density
0.104260
Extents
X Min
617,570.692566
X Max
617,995.150625
Y Min
437,017.689822
Y Max
437,644.911074
Z Min
5.990006
Z Max
22.874955
Z
Mean
11.295064
StdDev
3.904388
Intensity
Min
0
Max
255
Mean
205.914636
StdDev
66.339330
Alpha
Min
N\A
Max
N\A
Mean
N\A
StdDev
N\A
Height
5
9
12
16
19
Export Histogram
Help
Close

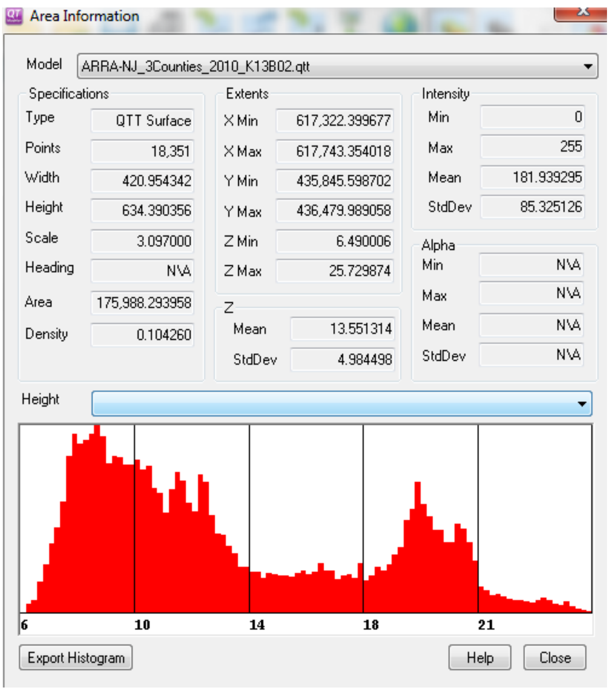


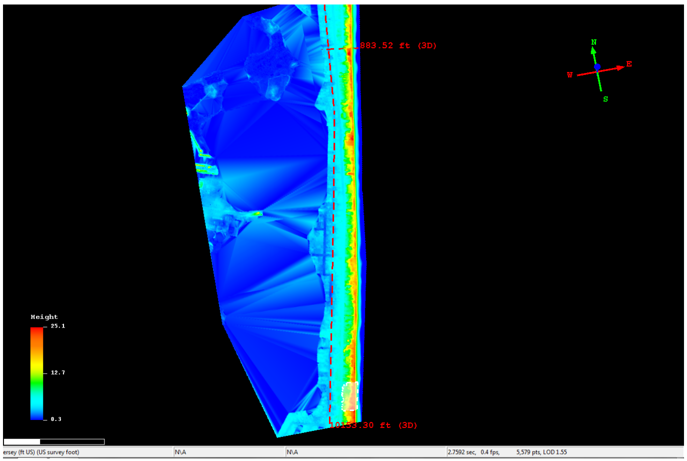

Volume Calculation
Configuration
Model 1
ARRA-NJ_3Counties_2010_K13B02.qtt
Model 2
REFERENCE PLANE
Comparison
Signed Delta Volume
Reference
0.0
Result
Calculate
2,317,904.096477
Close
Help

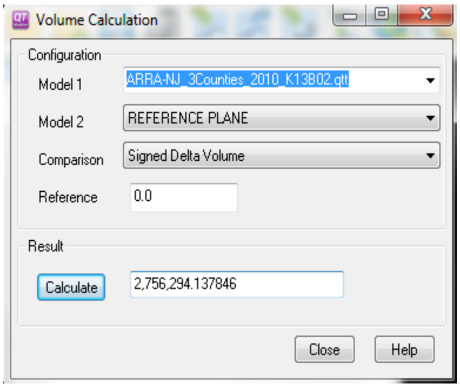

Area Information
Model
ARRA-NJ_3Counties_2010_K13B02.qtt
Specifications
Type
QTT Surface
Points
19,077
Width
439.270779
Height
630.175926
Scale
3.097000
Heading
N\A
Area
182,933.601979
Density
0.104260
Extents
X Min
617,436.014072
X Max
617,875.284851
Y Min
436,433.975221
Y Max
437,064.151146
Z Min
6.356095
Z Max
22.984116
Z
Mean
12.667853
StdDev
4.446934
Intensity
Min
0
Max
255
Mean
205.005347
StdDev
69.745916
Alpha
Min
N\A
Max
N\A
Mean
N\A
StdDev
N\A
Height
6
9
13
16
19
Export Histogram
Help
Close

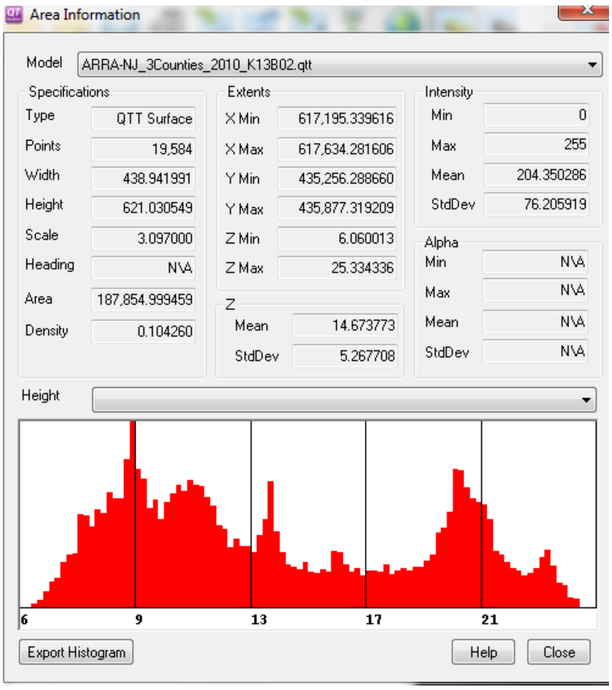

Height


Volume Calculation
Configuration
Model 1
ARRA-NJ_3Counties_2010_K13B02.qtt
Model 2
REFERENCE PLANE
Comparison
Signed Delta Volume
Reference
0.0
Result
Calculate
2,385,193.024458
Close
Help


Area Information
Model
ARRA-NJ_3Counties_2010_K13B02.qtt
Specifications
Type QTT Surface
Points 18,351
Width 420.954342
Height 634.390356
Scale 3.097000
Heading N\A
Area 175,988.293958
Density 0.104260
Extents
X Min 617,322.399677
X Max 617,743.354018
Y Min 435,845.598702
Y Max 436,479.989058
Z Min 6.490006
Z Max 25.729874
Z
Mean 13.551314
StdDev 4.984498
Intensity
Min 0
Max 255
Mean 181.939295
StdDev 85.325126
Alpha
Min N\A
Max N\A
Mean N\A
StdDev N\A
Height
6
10
14
18
21
Export Histogram
Help
Close




Volume Calculation
Configuration
Model 1
ARRA-NJ_3Counties_2010_K13B02.qtt
Model 2
REFERENCE PLANE
Comparison
Signed Delta Volume
Reference
0.0
Result
Calculate
2,756,294.137846
Close
Help


Area Information
Model
ARRA-NJ_3Counties_2010_K13B02.qtt
Specifications
Type
QTT Surface
Points
19,584
Width
438.941991
Height
621.030549
Scale
3.097000
Heading
N\A
Area
187,854.999459
Density
0.104260
Extents
X Min
617,195.339616
X Max
617,634.281606
Y Min
435,256.288660
Y Max
435,877.319209
Z Min
6.060013
Z Max
25.334336
Z
Mean
14.673773
StdDev
5.267708
Intensity
Min
0
Max
255
Mean
204.350286
StdDev
76.205919
Alpha
Min
N\A
Max
N\A
Mean
N\A
StdDev
N\A
Height
6
9
13
17
21
Export Histogram
Help
Close