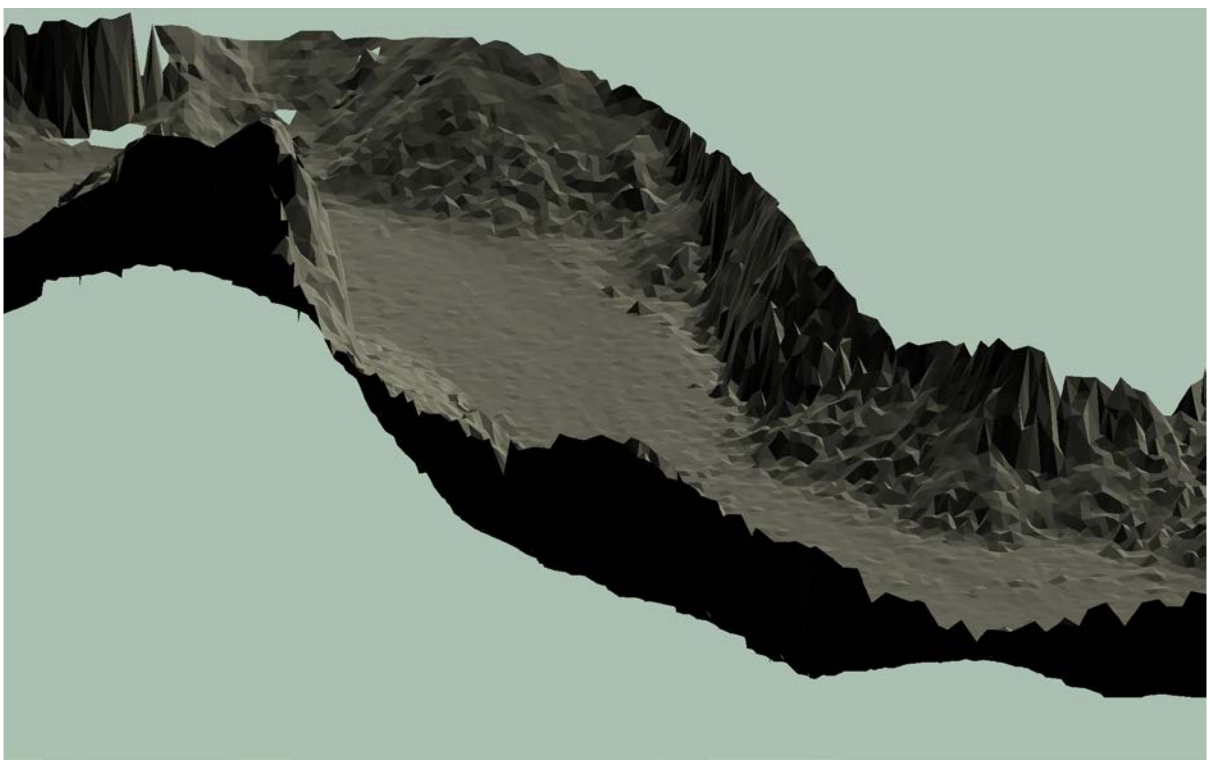
RECLAMATION

Managing Water in the West

Reconnaissance Technique for Reservoir Surveys



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14. ABSTRACT
The Bureau of Reclamation (Reclamation) Sedimentation and River Hydraulics Group (Sedimentation Group) of the Technical Service Center (TSC) has evaluated sedimentation on numerous reservoirs requiring extensive data collection and resources to complete. A complete hydrographic survey provides accurate reservoir topography, capacity, and sediment accumulation; however, survey cost of larger reservoirs has prohibited data collection. The limited budgets have affected survey frequency for updating reservoir information, resulting in limited knowledge of our nation's reservoir systems. "Reconnaissance Techniques" utilize streamline collection procedures, with the latest equipment and analysis technology, producing a quality product in a timely and cost-effective matter. Reconnaissance techniques survey the reservoir areas where majority of the sediment is known to accumulate. The technique requires use of digital original reservoir topography to guide the survey vessel to the sediment areas and for computing the updated reservoir information. The reconnaissance techniques were applied to surveys of Lake Mead and Lake Powell and could possible be used on other large reservoirs such as Yellowtail Reservoir and Lake Roosevelt to compute present capacity and sediment inflow rates in a more timely and cost-effective matter.

Using state of the art collection equipment and field reconnaissance techniques can greatly reduce collection and analysis costs, but still produce accurate and quality results. Presented are procedural techniques that were applied to the 2001 Lake Mead and 2004 Lake Powell surveys conducted by the Sedimentation Group. Presented reconnaissance techniques illustrate how to update area and capacity results on reservoirs, like Lake Mead and Lake Powell, more frequently and timely, but less costly.

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Reconnaissance Techniques for Reservoir Surveys

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Mission Statements

The mission of the Department of the Interior is to protect and provide access to our Nation's natural and cultural heritage and honor our trust responsibilities to Indian Tribes and our commitments to island communities.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner.

Acknowledgments

Reclamation's Sedimentation Group of the TSC prepared and published this report. The Sedimentation Group acknowledges Mr. Jim Kinney, Office of Program and Policy Services in the Water and Environmental Resources Office, for his recognition of sediment issues and their affect on current and future operations of Reclamation's structures and consequential environmental issues. Ronald Ferrari of the TSC was the main author with input from Tim Randle (Group Manager) and Kent Collins of the Sedimentation Group. As listed in the references, there was a great amount of information obtained from others. The greatest knowledge and development of the collection and analysis techniques came from previous members of the Sedimentation Group. There were numerous, with the following providing the most influence on this author: Mr. James O. Blanton, Mr. Joe M. Lara, Mr. Ernest L. Pemberton, and Mr. Robert I. Strand. Joseph Lyons of the TSC conducted the first peer review.

Reclamation Report

This report was produced by the Bureau of Reclamation's Sedimentation and River Hydraulics Group (Mail Code D-8540), PO Box 25007, Denver, Colorado 80225-0007. **http://www.usbr.gov/pmts/sediment/**

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Table of Contents

Page

Index of Figures

Page

Reconnaissance Technique For Reservoir Surveys

Abstract

Reclamation's Sedimentation Group has evaluated sedimentation on numerous reservoirs requiring extensive data collection and resources to complete. A complete hydrographic survey provides accurate reservoir topography, capacity, and sediment accumulation; however, survey cost of larger reservoirs has prohibited data collection. The limited budgets have affected survey frequency for updating reservoir information, resulting in limited knowledge of our nation's reservoir systems. "Reconnaissance Techniques" utilize streamline collection procedures, with the latest equipment and analysis technology, producing a quality product in a timely and cost-effective matter. Reconnaissance techniques survey the reservoir areas where majority of the sediment is known to accumulate. The technique requires use of digital original reservoir topography to guide the survey vessel to the sediment areas and for computing the updated reservoir information. The reconnaissance techniques were applied to surveys of Lake Mead and Lake Powell and could possible be used on other large reservoirs such as Yellowtail Reservoir and Lake Roosevelt to compute present capacity and sediment inflow rates in a more timely and cost-effective matter.

Using state of the art collection equipment and field reconnaissance techniques can greatly reduce collection and analysis costs, but still produce accurate and quality results. Presented are procedural techniques that were applied to the 2001 Lake Mead and 2004 Lake Powell surveys conducted by the Sedimentation Group. Presented reconnaissance techniques illustrate how to updated area and capacity results on reservoirs, like Lake Mead and Lake Powell, more frequently and timely, but less costly.

In 2001, the Sedimentation Group conducted the first know extensive multibeam survey of Lake Mead and the first multibeam survey by the Sedimentation Group. The reconnaissance technique was used during collection of the data that occurred over a three week period. The final analysis was not completed by the proposed reconnaissance techniques. Presented is a summary of the collection mythology and the field results.

In 2004, Reclamation's Sedimentation Group conducted multibeam surveys on Lake Powell. In 2005 the Sedimentation Group participated in a Lake Powell survey conducted by the University of New Brunswick as a cooperative study with the National Park Service (Clark Hughes, 2005). The surveys used state of the art collection instrumentation with field reconnaissance techniques that

significantly reduced the collection time and cost compared to a full reservoir survey. Presented are procedural collection and analysis techniques for the Lake Powell surveys. Preliminary analysis on a portion of the lake showed how reconnaissance techniques could be used to accurately update the area and capacities tables of Lake Powell from these partial survey data sets.

The size of Lake Powell (Colorado River Arm nearly 180 miles) with numerous tributaries means complete above and below water data collection would be very costly. Reconnaissance techniques utilize streamline collection procedures, with the latest equipment and analysis technology, producing a quality product in a timely and costly matter. Reconnaissance techniques survey the areas of the reservoir where majority of the sediment accumulates. The technique uses digital original reservoir topography to guide the survey vessel to the known sediment areas and for computing the updated reservoir information. The surveys used a multibeam system with global positioning system (GPS) that provided detailed results that could be used to develop an updated area and capacity table using a similar approach as the 1986 Lake Powell survey (Ferrari, 1988). The 2004 and 2005 multibeam surveys of a large portion of Lake Powell were completed in weeks compared to months during the 1986 collection. The surveys biggest limitation was Lake Powell being drawn down 130 feet due to draught conditions. The presented techniques illustrate how Lake Powell's area – capacity can be accuracy updated with streamline collection and analysis methods.

Introduction

This report presents methodology used by Reclamation's Sedimentation Group to measure reservoir topography for monitoring sediment deposition. The Sedimentation Group has monitored reservoir sediment over the last century with closure of several dam structures in the early 1900s. The monitoring methodology has varied between reconnaissance to detailed field collection and analysis. This report presents collection and analysis techniques, using modern instrumentation and analysis tools, with the goal to accurately update reservoir sedimentation information in a timely and cost-effective matter.

Reclamation's ability to manage current and future reservoir sediments will be determined by knowledge of the problem and available options. A sediment management plan must address the social, environmental, and technical options with a goal of avoiding legal and political pressures in making important decisions. A sediment management plan must consider different alternatives such as ignoring sediment allowing accumulating onsite for future generations to deal with, keeping it out of the reservoir with better upstream management practices, removing it from the reservoir, and flushing it downstream where it could be beneficial. The management plans are difficult to develop with our present limited knowledge of the problem and hazards associated with the reservoir sediments. Aside from gaining a better understanding of the loss of reservoir capacity due to sediment accumulation, an understanding of possible contaminants within the sediment is needed. The current knowledge of possible contaminants in both the deposits and within the mobilized sediments due to dredging, erosion, and flushing are minimal. The 2004 Angostura Reservoir Sedimentation survey addressed several of these issues and the results showed the continued success of a previous watershed management program to increase drainage vegetation to reduce erosion. The 2004 study also included sediment sampling that analyzed existing chemical composition for a future database (Ferrari, 2005).

Reclamation conducts reservoir surveys for the purpose of updating the area and capacity relationship and computing annual sediment inflow to project useful operation of their existing facilities. Reclamation has over 400 storage facilities, but only about 30 percent have had resurveys conducted since initial filling. Of these resurveys, about 30 percent have had multiple surveys for monitoring high sediment inflow rates. The majority of the high sediment rate sites are located in the southwestern United States and includes Theodore Roosevelt Reservoir in Arizona with 8 resurveys, Elephant Butte Reservoir in New Mexico with 11 resurveys, and Lake Mead in Arizona with 3 resurveys. There are Reclamation reservoirs in the state of Wyoming with high sediment yields that have had several resurveys, such as Buffalo Bill Reservoir with 3 resurveys and Guernsey Reservoir with 11 resurveys. All of these reservoirs are located in drainage basins with high sediment yields[1] requiring multiple resurveys for effectively monitoring reservoir sedimentation rates and future impacts.

A complete hydrographic survey of the reservoir provides the most accurate data of the reservoir bottom, the sediment accumulation, and the present reservoir capacity. However, a complete reservoir survey can be expensive which may limit the possibility and frequency of reservoir surveys. This especially applies to large reservoirs. Evaluation of reservoir sediment deposition usually involves extensive field data collection requiring significant time and resources to complete. The survey technology has changed significantly over recent decades with the dramatic increase in speed of data acquiring and computer system processing. This has significantly reduced the field collection and analysis time while resulting in higher accuracy.

With the ever-shrinking budgets, the level of detail or possibility of reservoir monitoring studies has been affected. Using state of the art equipment for field

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[1] The definition of numerous terms, such as "sediment yield," hydraulic height, structural height, etc. may be found in manuals such as Reclamation's *Design of Small Dams, Guide for Preparation of Standing Operating Procedures for Dams and Reservoirs,* American Society for Civil Engineer's (ASCE) *Nomenclature for Hydraulics, and ASTM D19 on "Water" standards.*

reconnaissance and analysis can greatly reduce costs while still producing meaningful results. The reconnaissance techniques must be designed for the reservoirs surveyed with the main objective to survey the reservoir areas where the majority of the sediment has accumulated. This is accomplished by projecting the sediment deposition, from the collected data, or assuming the unsurveyed original portions of the reservoir have no change. The reconnaissance technique requires the use of digital original reservoir topography to guide the survey vessel where the sediments are known to accumulate. The digital topography is also used during data processing to generate updated contours and area and capacity values. The reconnaissance survey techniques summarized in this report are ideal for reservoirs such as Lake Mead and Lake Powell. These reservoirs are of a great size where present mapping techniques would be very costly for total mapping of the existing reservoir area. Both reservoirs have adequate detailed original reservoir topography information. Using the reconnaissance survey technique, the original topography can be adjusted for sediment accumulation by mapping only the portions of the reservoir where sediment has accumulated. The resulting maps would illustrate recent sediment accumulations and be less costly to produce than a complete mapping of the reservoirs.

The reconnaissance technique estimates the sediment volume for the underwater portions of the reservoir from a bathymetric survey. The general approach is to survey the areas of the reservoir where the majority of the sediment accumulates and use the data to estimate the sediment volume for the entire reservoir. Using engineering judgment, the sediment deposition in areas of the reservoir not covered by the survey vessel can be extrapolated from the collected data. Based on the survey of the hundreds of Reclamation reservoirs, it is known that most sediment inflow tends to deposit in the upper reservoir delta and along the alignment of the original river channel (thalweg) as it intrudes further downstream towards the dam. As the suspended sediments move downstream, it deposits in the deeper areas of the reservoir. For the Lake Powell 1986 survey, the range line survey found the sediment distributed laterally across the reservoir. Although a few of the Lake Powell range lines measured channel cuts through the deposited sediments, the majority of the range lines measured the sediment lying horizontally in the deeper original river channel geometry (Ferrari, 1988).

The purpose of this report is to summarize the field collection techniques and analysis methodology used for the 2001 Lake Mead and the 2004 Lake Powell partial surveys. The collected data and techniques can be used to complete updated area – capacity tables for these and other reservoirs with similar conditions. In 2001, the Sedimentation Group conducted the first known multibeam survey of Lake Mead and in 2004 conducted the first known multibeam survey on portions of Lake Powell. In 2005, the Sedimentation Group participated on a Lake Powell multibeam survey that covered a larger portion of the submerged deposited sediments. The University of New Brunswick in cooperation with the National Park Service (Clarke Hughes, 2005) conducted the study. Using reconnaissance analysis techniques, data from these surveys can be used to develop updated area and capacity tables for Lake Powell and Lake Mead.

Purpose of Reservoir Surveys

Reservoirs come in all shapes and sizes and are designed for purposes such as retention for flood control, debris/sediment storage, irrigation and municipal water supply, power production, recreation, navigation, conservation, and water-quality control. The reservoir size, shape, and operation affect the location and nature of the sediment depositions (figure 1). Reservoir sedimentation is an ongoing natural depositional process that can remain invisible for a significant portion of the life of a reservoir. However, lack of visual evidence does not reduce the potential impacts of reservoir sedimentation on functional operations of a reservoir (Lin, 1997). As sediment deposition depletes reservoir storage volume, periodic reallocation of available storage at various pool levels may be necessary to satisfy operational requirements of water users.

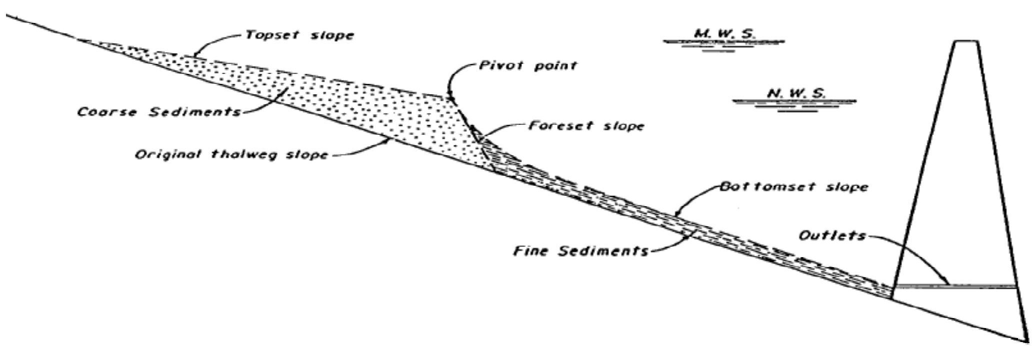

Figure 1 - Profile of reservoir delta formation.

As rivers and streams enter a reservoir, the flow depth increases and the velocity decreases causing a loss in the sediment transport capacity of the inflow. The loss of sediment transport capacity and the damming effect of the reservoir may cause deposition of sediment in the stream channels above the reservoir water surface and in the upper reservoir area. The sediment deposition process in reservoirs generally follows the same basic pattern, with coarser sediments settling first in the upper reservoir area as the river inflow velocities decrease, forming a delta. Deposition continues from upstream to downstream direction, with the sediment gradation becoming finer as the deposition progresses in the downstream direction towards the dam until the inflowing sediment is deposited throughout the length of the reservoir. Some of the inflowing fine sediments (silts and clays) typically stay in suspension and may discharge through the dam outlets and spillways. As sediments deposit near the dam outlets, they eventually will be discharged downstream as releases are made from the dam.

In the United States, reservoir sedimentation seldom receives attention until the reservoir capacity has been significantly reduced, or the reservoir operation and surrounding area is affected. The delta formation can cause local problems before sediment deposition significantly reduces reservoir capacity or causes operational problems at the dam. Some local problems that have been attributed to sediment deltas are increased elevation of the flood stage and groundwater table, silting of pumping and intake structures, and blockage of navigation passages. Once at the dam, the released sediments may have downstream impacts on river fisheries and municipal water systems.

The primary objective of a reservoir survey is to measure the current area and capacity. The main cause of storage capacity change is sediment deposition or erosion. Typical results from a reservoir survey and analysis include the measured sediment deposition since dam closure and previous surveys, the sediment yield from the contributing drainage, and the future storage-depletion trends. Survey results can also include location of deposited sediment (lateral and longitudinal distribution), sediment density, reservoir trap efficiency, and evaluation of project operation.

The Sedimentation Group typically computes reservoir sediment accumulation by comparing the measured original capacity, prior to inundation, to the updated measured capacity. This method calculates a long-term sediment deposition value used for future sediment projections. Making comparisons to the original survey, rather than previous surveys, prevents errors that might exist in previous resurvey results from being included in the analysis. The calculations typically rely on accurate original reservoir topography available for many of Reclamation's reservoirs, but this must be evaluated on a case-by-case basis. Modifications to the analysis and study objectives must be made for cases where accurate original reservoir topography is not available. This was the case for the 1995 Theodore Roosevelt (Roosevelt) Reservoir survey (Lyons-Lest, 1996) and the 2002 Deadwood Reservoir survey (Ferrari, 2003).

The Roosevelt and Deadwood Reservoir resurveys measured better detail then the original survey data. The 1995 Roosevelt survey was the eighth survey since dam closure in 1909, but the first survey to use aerial photography that provided more detail of the upper reservoir elevations than the original 1909 survey using land-surveying techniques and the previous resurveys using the range line method. Comparing the detailed 1995 survey results with previous mapping information was not a means for computing sediment accumulation due to the accuracy differences between the surveys. The previous resurveys of Roosevelt Reservoir were valid for computing sediment inflow since they utilized a rangeline collection method that monitored the same range line location over the years. The changes at these locations were compared to the original topography for estimating the sediment deposition. The detailed 1995 Roosevelt Reservoir survey will be used as the basis for future comparisons. The same was true of the 2002 Deadwood Reservoir resurvey. The detailed aerial and multibeam data from the 2002 survey could not be compared to the less detailed original data for computing sediment accumulation.

Additional objectives of Reclamation’s reservoir survey studies are to determine current reservoir topography, estimate the reservoir’s economic life, and resolve storage capacity conflicts. The resulting study information is beneficial for describing existing conditions for a specific reservoir, monitoring upstream land management practices, evaluating current operation of a reservoir, and planning future reservoirs. The results from the study can provide insight for such operational objectives as sluicing sediment deposits to increase reservoir volume and possibly enhancing the downstream river environment, establishing bench marks for forecasting future reservoir depletion rates, revising intake or outlet design, assessing water quality control methods, and designing recreation facilities, structures, and operational schedules.

Reservoir sediment accumulation and distribution can be theoretically approximated. However, an accurate reservoir survey is the best means for monitoring current reservoir sedimentation and for projecting future sediment inflow and deposition. The most accurate data requires measuring the complete reservoir area, or as much of the sediment delta as possible. As seen on figure 1, the majority of the delta may form in the upper reaches of the reservoir, but, eventually, the inflowing sediments can deposit throughout the reservoir. Full coverage requires both above and below water measurements that significantly increase field collection time and cost. The presented reconnaissance method measures only the underwater sediment portion of the reservoir at a significantly reduced effort and uses the best available above water data to complete the mapping. The main goal is to obtain up to date valid information that might not otherwise be collected due to time and budgets. The summarized techniques were applied to Lake Mead and Lake Powell. Ideally, it would be best to survey these reservoirs when they are as full as possible, but due to their sizes, that could take decades. Due to concerns on sediment inflow on these and other large reservoirs, that may be too long to wait to address the sediment issues.

Frequency and Schedule of Surveys

The schedule and frequency of conducting reservoir surveys should depend on the estimated rate of reservoir sediment accumulation, along with the current operation and maintenance plan. However, the current need to address site-specific problems, along with available funding, usually determines survey schedules. The frequency of resurveys may depend on the estimated rate of sediment accumulation in the reservoir. For example, some have used a projected percent of storage reduction between surveys or a 5- to 10-year interval. For Reclamation reservoir surveys, the decision on if and when a survey is conducted, is usually made by the responsible operations office. Influential factors in the decision include occurrence of a large flood, severe drawdown of the reservoir, planned construction of an upstream dam, loss of recreational area due to sediment encroachment, change in erosion characteristics of a basin due to land use or fires, raising of the dam, or changes to the reservoir operations. For Elephant Butte Reservoir in New Mexico, the frequency of surveys is set by a compact agreement between the states and federal government, using a projected 5-percent loss of capacity (Collins and Ferrari, 1999). The responsible office and available funding usually determines the method of collection. For example, the decision on whether or not an aerial survey for the above water portion of the data collection is conducted is usually based on cost and amount of shoreline erosion. The status of the reservoir (high pool or drought) is also considered. The Sedimentation Group works with the responsible field office to obtain the best study results with best means of collection within the allowable budget.

The schedule of the survey may be determined by methods of collection, weather, and reservoir operations. If aerial data are collected, it is recommended that collection take place when the reservoir is as low as possible and prior to the bathymetric survey. In most cases, this is in the fall, winter, or early spring and allows better coverage due to less vegetation. The bathymetric survey should be scheduled when the reservoir is as full or with as much aerial coverage overlap as possible. This allows complete mapping of the reservoir and speeds up the underwater collection if the aerial collection covered the shallow water and underwater hazard areas. Due to cost, some Reclamation surveys are restricted to underwater collection and use existing above water maps to complete the analysis. For these types of surveys, all attempts are made to schedule the survey when the reservoir is as full as possible requiring some survey delays during low runoff years. For some reservoir surveys, a limited amount of above water data is collected to complete the analyses. The collected data is usually in the upper tributaries where the exposed sediment delta has formed (Ferrari, 1996b and 2005).

Currently (2006), available equipment allows for year-round data collection and has significantly reduced field collection time. Advances in equipment technology and data collection techniques have also reduced the staff size and the amount of preliminary fieldwork that was previously required. Presently, collection systems are more compact and require less field staff for setup and operation resulting in reduced cost of downtime due to extreme weather conditions. However, each project contains unique conditions that must be considered when determining the timing, survey equipment, and frequency of the reservoir resurveys.

Means of determining frequency of reservoir surveys include measured sediment rates from previous reservoir surveys and sediment stream records. In the United

States, high operational costs have reduced the number of gauging stations that measure sediment inflow, requiring records from similar reservoirs, gauges, and drainages to be used. Observations of sediment deposition during a reservoir drawdown may also be used; however, as illustrated in figure 1, these observations may give a false impression of the severity of the problem if the exposed sediment delta is the only major deposition. In general, larger reservoirs require less frequent resurveys. More frequent surveys are usually required for reservoirs operating under conditions of greater risk such as for flood control, water supply storage, or are located in urban areas.

An additional factor in the survey schedule is the inflow of unconsolidated material that may create a soft reservoir bottom and erroneous echo sounder depths. The use of low frequency sounders, along with depth verification, may provide quality assurance of the depth measurements. However, these additional verifications add time to the collection and concerns about the accuracy. The lower frequency echo sounders can penetrate the soft layer and provide depths of the harder bottom, but these depths could be somewhat subjective to what is the true bottom. It would be best to avoid such conditions, but for some reservoirs, these soft bottom reservoir conditions always exist. For soft bottom reservoir surveys, echo sounder depths should be confirmed by manual measurement, despite the extra cost, but they are somewhat subjective to individual judgment and are difficult in deeper reservoirs. The soft bottom fluff conditions appeared to be a factor during the December 2004 and May 2005 Lake Powell surveys (Clarke Hughes, 2005). In 2005, a multibeam survey was conducted from May 12-21, 2005, on the entire length of Lake Powell. During low and high frequency depth collection on the upper San Juan reach, the high frequency readings were, at times, several meters shallower then the low frequency readings, indicating the soft fluff bottom of the reservoir from the river's inflowing sediments.

Methodology

Reclamation's Sedimentation Group of the TSC continuously upgrades their technical procedures to reflect the latest data collection technology. The following is a brief summary of hydrographic survey techniques utilized by Reclamation and others. This summary will provide a better understand of the reconnaissance procedures used for the 2001 survey of Lake Mead and the 2004 and 2005 surveys of Lake Powell.

Reservoir and River Survey Techniques

Survey techniques have evolved around the development of equipment and analysis systems. Prior to computerized data collection and analysis systems, the **range-line method** was viewed as the only practical method for collection due to its relatively low field and analysis costs (Blanton, 1982). The range-line method was used most often on medium to large reservoirs such as Lake Mead (Lara and Sanders, 1970) and Lake Powell (Ferrari, 1988). The collection and analysis consists of determining sediment depths along predetermined range-lines that usually were established prior to inundation. Analysis required detailed and accurate original reservoir topography. Various mathematical procedures were developed to produce the revised reservoir contour areas at incremental elevations for the surveyed range-lines. The range-line method is still a valid means of conducting survey studies for certain reservoir conditions or if more modern collection and analysis systems are not available. For the 1986 Lake Powell Survey, the range-line method was used due to deep, greater than five hundred feet at the dam, vertical wall conditions and good original topographic maps. It now is possible to completely map Lake Powell using GPS, multibeam system, and aerial collection, but the range-line method should still be considered for collection and analysis. For Lake Powell, a 2004 October and December multibeam survey on a portion of reservoir covered many of the range lines surveyed in 1986. The multibeam surveys covered in days what took weeks to cover during the 1986 survey. This report presents the results from this survey and a modified range-line method to generate updated area–capacity tables.

The contour method has become the preferred method for data collection and analysis with the development of electronic collection and analysis systems. It requires large amounts of collected data, something that present systems can easily handle. The contour method results in more accurate reservoir topography and computed volumes than the range-line method, but can take more time for field data collection. This method revolves around computer and software packages that provided a means of organizing and interpreting large data sets. Contour development and analysis may be quicker than the range line method, offsetting the extra field collection time. For the contour method, the hydrographic survey data is usually collected in an x, y, z coordinate data format conforming to a recognized coordinate system such as Universal Transverse Mercator (UTM), latitude/longitude, state plane, or other systems that represent the earth's 3-dimensional features on a flat surface.

The most accurate contour method is the survey of both the above and below water portions of the reservoir area. The ideal contour map is developed by photogrammetry (aerial) when the reservoir is empty exposing all areas to be measured, but this condition seldom occurs, making a combination of aerial and bathymetric surveys necessary. To reduce the time and cost associated with underwater data collection, aerial data should be collected when the reservoir is as empty as possible and the bathymetric survey conducted when the reservoir is as full as possible providing maximum overlap of the two data sets. Surveying the underwater portion after the aerial survey with a large overlap reduces the time and cost since the survey boat does not have to maneuver in shallow water portions already mapped by the aerial survey.

Due to cost of aerial data collection, some contour reservoir resurveys do not include an updated survey of the area above the existing reservoir water surface. For these surveys, the bathymetric survey should be scheduled when the reservoir is as full as possible. The above-water area may be measured using original or most recent contour map of the reservoir area. In this case, it is assumed no change has occurred since the above water area was last mapped. Some Reclamation surveys have used U.S Geological Survey (USGS) quadrangle (quad) maps for the above-water areas since it was the best data available. It must be noted that an assumption of no change can cause computation errors for reservoirs with significant shoreline erosion or where the majority of the sediment settles in the shallow upper end not mapped by the bathymetric survey. Extensive shoreline erosion on Tiber Reservoir in Montana had a significant impact on the final reservoir computations since the above water collection only entailed a developed contour from the reservoir water surface at the time of aerial collection (Ferrari, 2005).

Recent improvements in conventional survey equipment (GPS technology for example) allow accurate measurement of point data and provide a cost-effective method for smaller reservoirs. A combination contour and range-line method may also be used where the range-line method is used to measure the areas of exposed sediment deposition as was done for the 1994 Boysen Reservoir Sedimentation Survey (Ferrari, 1996). This method does not accurately measure the surface area of the above water areas where significant reservoir changes have occurred due to bank erosion, but is a viable alternative for measuring exposed sediment deltas in the upper reaches of the reservoir.

Shoreline Erosion

The 2002 Tiber Reservoir underwater survey witnessed extensive shoreline erosion throughout the reservoir area. During collection, the GPS positions were found at times to be outside the digitized USGS quad contour location, indicating that the boat was on solid ground. These USGS quad contours were developed from aerial photography taken in the 1960s. At times, the position of the boat was found tens of feet outside their boundary. In addition, a major windstorm occurred during the 2002 survey, and the crew witnessed vertical sections of the shoreline collapsing into the reservoir area for days afterwards. Even with the shore erosion, the survey vessel was, at times, able to hug the vertical banks in deep water where previous collapses into the reservoir had occurred. It appears that over time, the collapsed material washed further into the reservoir by wave action similar to shore ocean waves. This is possible because the shoreline material dissipated in the water and consisted of little to no rock or large cobble material. Figures 2 through 5 documents these shoreline conditions at Tiber reservoir.

The photographs show different stages of the shoreline erosion along with the extent of occurrence. If the erosion were just below the reservoir high water mark, the total volume of the reservoir would not be greatly affected and what occurred in the upper reservoir elevations resulted in a gain in surface area and volume. This volume gain in the upper reservoir area offsets the loss of surface area and volume in the lower elevations of the reservoir due to the eroded shore material depositing at the lower elevations. The photographs show the large amount of the eroded material above the reservoir area, meaning that a portion of the loss of the original total reservoir volume is due to the shoreline erosion, along with the incoming river sediments. The only means to accurately measure the extent of the shoreline erosion would be by an aerial and full bathymetric survey. Reconnaissance surveying techniques cannot be used in reservoirs with these types of conditions to obtain accurate results.

Figure 2 - Eroded material depositing forming a shelf (photo by S. Nuanes).

Figure 3 - Large areas of erosion above the reservoir maximum water surface, (photo by S. Nuanes).

Figure 4 - Recent eroded material that has not moved further into reservoir (photo by S. Nuanes).

Figure 5 - Eroded bank material depositing below the water line (photo by S. Nuanes).

Data Density and Line Spacing

The extent of data collection is determined by the project needs, reservoir conditions, cost of collection and analysis, and capability and limitations of the collection system. Typically, the GPS horizontal positions can be updated once per second, a single beam electronic depth sounder can provide continuous output of 20 or more depths per second, and a multibeam underwater collection system has the capability of several hundreds of thousands of points per minute. The advancement in the computer collection systems allows all of these data to be stored, but it is up to the study manager to determine what system and collection interval is necessary and practical. During collection, the most advanced available system should be used and the maximum amount of data should be stored. Filtering of the data that may be necessary for final computations should be conducted during data post-processing.

For single beam collection systems, survey line spacing must be selected to provide the needed density for the study results. The study manager must understand the goals of the study and must determine the data density to meet the goals while staying within budget. The range-line method assumes uniformity of the terrain between the survey lines, which is a valid assumption unless an abrupt change occurs. The problem is knowing if and where abrupt changes occur and spacing the lines to best represent the bottom conditions. The survey crew needs to monitor the survey line during collection for possible changes and examine existing topography maps that may warrant a modification of the line spacing during field collection. Typically, about 5 percent of the project study area is covered by the single beam collection method, which means care must be taken to collect adequate data to ensure accurate topography development.

The Sedimentation Group's single beam collection method typically beings with a 300-foot spacing and adjusts in the field to meet the study objectives. For smaller reservoirs and to show more bottom details, the data collections have been adjusted to 100- to 200-foot spacing. For some of the larger reservoirs, with flat bottom conditions with little or no detail, and when collection time and budget is limited, the spacing has been adjusted to 500, 600, and at times 2,000-feet. The upper delta of Canyon Ferry Reservoir in Montana was fairly flat with little to no channel detail in the deposited sediment. Those conditions permitted the collection crew to increase the profile spacing, allowing data collection during favorable weather conditions and reducing field collection time while maintaining the quality of the product (Ferrari, 1998). For the Salton Sea survey in California, the range-line spacing was adjusted to 2,000 feet due to the limited budget for data collection and the relatively flat unchanging bottom conditions (Ferrari, 1998). The Canyon Ferry and Salton Sea surveys were conducted on large water masses with assumed uniformity of terrain between surveyed range-lines justifying such large spacing. Parallel surveyed range-lines and perpendicular survey lines confirmed the uniform bottom assumption for these large water surveys.

The use of a multibeam collection system provides the capability of full bottom coverage of the underwater reservoir areas, but it requires more time for collection and analysis than many budgets will allow. The multiple-transducer and multibeam collection systems can provide 100-percent coverage that removes the unknowns between the survey line spaces, but the costs and operation of such systems are more difficult to justify. It is up to the study leaders to determine the extent of collection to meet the study goals within the budget. For the 2001 Lake Mead study, the collection was limited to the original river channel areas where the majority of the sediment deposition was projected to occur. Only about 30 percent of Lake Mead was covered by the multibeam survey, but the 20 million data points mapped the majority of the submerged, deposited sediment that could be collected by the survey vessel. This allowed the field collection to accomplish in 3 weeks and within budget, while obtaining the needed detail to meet the study needs.

Cost of Conducting a Reservoir Survey

Survey productivity has increased by a factor of 75 times since the 1960s and 10 times since 1990s (USCOE, 2004). The productivity increases are mainly related to electronic and computer development. Planning a survey is usually controlled by budget that determines detail and method of collection, analyses methods, and who will be conducting the study. Before the use of electronic positioning systems, the collections were conducted using visual or manual distance tag lines. The manual method had significant setup time to establish range-line locations and required large crew sizes using two to three vessels and crews of five to eight people to conduct the survey. Depending on conditions, the crews were able to collect data from one to five range lines per day. The computer microwave system development reduced the crew size during collection, but it still required a significant amount of time prior to the underwater collection to locate and establish control around the reservoir and river study areas. The field crew size during the underwater collection was usually around five, but three was a possibility for smaller jobs. Collection of sediment range-line data increased from 5 to 10 range lines a day, but the major benefit was the possibility of detailed mapping of the reservoir bottom. The development of GPS hydrographic collection systems significantly reduced the time and cost of a survey, increased the field collection productivity, and significantly reduced the staff days of conducting the overall study. The greatest cost reduction occurs because the detailed control network required prior to the underwater survey is significantly reduced.

The Sedimentation Group conducts the majority of their surveys using sonic depth recording equipment interfaced with a real-time kinematic (RTK) GPS that gives continuous sounding positions throughout the underwater portion of the reservoir covered by the survey vessel. The RTK GPS system allows control to be established in hours, rather than days or weeks, with conventional land surveys. The hydrographic crew size is usually two, compared to the previous three to five crewmembers. This result from using GPS and field computers allows the automated collection and storage of the massive amount of data. For multibeam systems, the initial cost is significant, meaning workload and budgets should be sufficient to support the cost and necessary personnel for operation. The major benefit of this system is full bottom coverage with greater detail and reduced uncertainty in the results. For many studies, the mobilization and demobilization costs can exceed the actual survey cost. For small survey jobs, the Sedimentation Group attempts to schedule more than one survey per trip to reduce this cost. An experienced collection crew can significantly reduce the cost, since less time is needed for planning, preparing, and training, which allows the work to be conducted more efficiently and safely.

Hydrographic Collection Equipment and Techniques

Hydrographic survey equipment has transformed dramatically throughout history, with the greatest changes occurring over the last decade. The latest major change in horizontal positioning is the use of GPS that is more accurate and less costly to operate than past survey methods. GPS has been rapidly adapted to hydrographic collection systems. The most recent significant development in depth soundings are multibeam systems that allow massive amounts of data to be collected. The multibeam system provides the option of complete coverage of the underwater areas, thus, removing the unknowns of previously unmapped underwater areas.

GPS Technology

GPS is a very versatile instrument for measuring horizontal positions, but is not ideal for all reservoir and river situations. Past horizontal positioning equipment and techniques are still viable where site conditions may prohibit the use of GPS. Such systems include marked tag-lines stretched across the range-line, electronic distance meters that measure distances from a known point to the survey boat as it proceeds along the range-line, range-azimuth positioning that involves the intersection of an angular and distance observation, and range-range positioning where survey vessel distances are measured from two or more shore stations. These still-viable methods are detailed described in Blanton (1982) and Corps (2004).

GPS collection techniques can vary depending on cost, need, and availability. Absolute positioning normally involves a single GPS receiver and at one time was not accurate enough for use in hydrographic positioning. Previously, a large error source in GPS collection was caused by false signal projection that was implemented to discourage use of the satellite system as a guidance tool by hostile forces. When active, the errors were up to 100 meters horizontally. This practice was eliminated by Presidentional order in May of 2000, but absolute positioning errors are still around ± 8 meters and do not satisfy the majority of hydrographic surveying requirements. The reconnaissance techniques used on Lake Mead and Lake Powell, at times, utilized absolute positioning along with other GPS collection methods. This did not adversely affect the results due to flat bottom conditions of the sediment deposition.

A method of collection to resolve or cancel the inherent errors of GPS is called differential GPS (DGPS). Differential surveying is the positioning of one point in reference to another with the basic principal being that errors calculated by GPS receiver at a known point or datum would have common errors with other GPS receivers in the general area. DGPS determines the position of one receiver in reference to another and is a method of increasing position accuracies by eliminating or minimizing the uncertainties. Differential positioning is not concerned with the absolute position of each unit, but with the relative difference between the positions of the two units that simultaneously observe the same satellites.

The method includes setting one receiver over a known geographical benchmark programmed with the known coordinates. This receiver, known as the master or reference unit remains over the known benchmark, monitors the movement of the satellites, and calculates its apparent geographical position by direct reception from the satellites. The inherent errors in the satellite position are determined relative to the master receiver's programmed position, and the error corrections or differences are applied to the mobile GPS receiver on the survey vessel. The attainable accuracies using differential survey techniques are usually dependent on the grade or cost of the GPS receivers with the common horizontal accuracies being submeter. High-end survey grade receivers can obtain subcentimeter accuracies and are necessary for monitoring water surface level movement.

Real-time DGPS is the current standard for hydrographic positioning. Real-time DGPS is where a master receiver is stationed over a known datum where it computes, formats, and transmits correction information through a data link to the mobile GPS receiver on the survey vessel. There are some community base stations maintained by United States federal, state and local government offices that transmit correction information that can be utilized by any manufacture's mobile receiver. There are also commercial services that offer real-time correction information that is transmitted by such means as geostationary satellites and local radio station towers. The weakness with all real-time collection systems is the communication link between the master and mobile GPS receivers. Surveying on open water removes many of the obstacles, but communication problems can occur with all systems when surveying in areas with obstructions such as mountains, cliffs, vegetation and structures along the shoreline. When these situations occur, the flexibility of the hydrographic survey crew being able to move the master receiver to new locations makes it more viable, but at times more costly.

RTK GPS in hydrographic surveying provides the highest precision of GPS positioning. The major benefit of RTK versus DGPS is that precise heights can also be measured in real-time. This is a major benefit for surveys in tidal and river conditions. The basic outputs from an RTK receiver are precise three-dimensional coordinates with accuracies in order of two centimeters horizontally and three centimeters vertically. RTK GPS employs at least two receivers that track the same satellites simultaneously just like with DGPS. To obtain these accuracies the base station must be near the survey vessel.

Horizontal and Vertical Control

The basic horizontal control for many Reclamation projects varies from region to region and from project to project. There were many project datums located and developed with conventional survey equipment on local horizontal and vertical coordinate systems. Some projects were tied to National Geodetic System (NGS) or USGS monuments, but they have not been referenced or adjusted with the current national networks. Many Reclamation projects are tied to the national state plane coordinate system in North American Datum of 1927 (NAD27), and some projects cover several zones of the state plane coordinate system. Care must be taken to ensure the collected data and results conform to the requested datum system for the study.

It is recommended that all new surveys conform to the national network and that all study results clearly state on all maps and reports the horizontal and vertical datums used, along with the year the datum was established. For positions reported in state plane coordinates, the units of feet or meters should be stated with the state plane zone and year, such as NAD27 or North American Datum of 1983 (NAD83). The UTM coordinate system is also an acceptable measuring projection that should be clearly labeled with proper zones and years.

Differential GPS collection systems are used for horizontal control for the majority of the hydrographic collection. The horizontal datum used for GPS is the World Geodetic System of 1984 (WGS84) that is essentially equivalent to NAD83. It is suggested that all new surveys be conducted and reported in NAD83 or WGS84, but NAD27 is also an acceptable horizontal datum for a project study. Even if the results are to be reported in NAD27 or a local datum it is recommended that all GPS data be collected in WGS84 or NAD83 then converted to NAD27 during postprocessing. Collecting the data in WGS84 or NAD83 preserves the data in a raw format that can easily be used and imported into Geographic Information Systems (GIS) systems without worrying about datum conversion errors generated by the field crew and collection software.

The vertical controls for Reclamation projects cause more problems and confusion than the horizontal controls. This is mainly due to most Reclamation vertical datums being established during project design and construction and have been operating with this datum since initial operation. There are some projects where Reclamation, USGS, Bureau of Land Management, state, water district, project, and NGS datums were established resulting in different vertical elevations for the same point. The final results from the reservoir survey should clearly state the datum used and if possible reference it to permanent project features such as top of dam, spillway crest, and outlet elevations as a means of clarifying datum differences. Many recent studies have established new survey control with the hope of clarifying multiple vertical datums. However, some surveys failed because previous resurveys were not tied to any permanent reference points. Survey grade GPS, when used properly, will bring in the most accurate horizontal and vertical positions, but care must be taken to tie new control to previously established control, such as brass caps, sediment range-line monuments, water surface gauge monuments, or top of the dam, spillway, and outlet works. There are some Reclamation projects that have operated for nearly 100 years with a local vertical datum and all drawings and records for these projects were developed with these datums. Making any vertical adjustments would be a great expense if it results in all past records needing adjusting. It could also become a safety issue during reservoir operation if not all are aware of the vertical adjustment.

Depths Measurements

Over the last 50 years, the majority of all hydrographic surveys have been conducted using some form of acoustic depth sounder that provides a digital record. Manually operated sounding lines and poles may be considered outdated, but they are still a viable means of depth measurements in reservoirs with thick vegetation and shallow depths. These manual measurements can also be used as confirmation of electronic depth soundings. Faulty or questionable readings from depth sounders may be caused by noise from vertical walls and structures or from silty bottoms containing "fluff" or light suspended material. Manual collection methods can be used to confirm the "fluff" type conditions and possibly determine the type of material on reservoir bottoms. Brief summaries of manual collection techniques can be obtained from other publications (Corps, 2004 and ASTM, 2005).

The electronic method using sonic (echo) soundings has been the norm in hydrographic collection systems for recording the bottoms of small and large reservoirs for several decades. The echo sounders have the capability of recording continuous profiles of the reservoir bottom, providing an analog bottom profile chart, and digital computer records. The computer system software matches these depths with other digital information such as horizontal positioning and heave components. The basic components are the recorder, transmitting and receiving transducer, and power supply. With careful calibration and correct collection techniques, a high degree of bottom profile accuracy can be obtained and recorded.

Calibrations of the echo sounder are critical in assuring high-quality depth measurements by the hydrographic survey system. The largest and most critical correction results from the variability of the sound velocity in water due to temperature changes, but other factors such as water density, salinity, turbidity, and depth also affect sound velocity. Most reservoirs exhibit large variations in temperature with depth meaning the velocity of the sound wave will not be constant for the distance from the depth sounder's transducer to the bottom depth and back. The effect of the variation can be significant with a temperature change of 10^{o}F changing the velocity around 70 ft/s or changing the depth measurement 0.8 feet per 50 feet of depth. For reservoirs such as Lake Mead and Lake Powell, the summer surface temperatures can be in the high 70s while the bottom depths are in the 40-degree range causing a significant change in the sound velocity through the vertical zones.

For most single beam, shallow water, echo sounding work, an average velocity of sound is usually assumed. Bar-check calibration determines the actual depth at the study area, and the sounder is adjusted to measure the correct depth. If the study is conducted in areas with known large variations in velocity by depth or location, the sounder should be set to measure the average or deeper depths that will be encountered during that time over the area being surveyed. For these types of conditions, frequent calibrations are needed. The sound velocity can be determined by a bar check calibration or measured directly using a velocity probe. The velocity probe can measure the sound velocity at every foot of depth, and an average value can be computed from these measurements. Current hydrographic software allows the depth incremented velocity measurements to be recorded, stored, and used during postprocessing to adjust the sounder measurements to actual depths. The method of using a velocity probe for measuring depth-related sound velocities is more critical for multibeam systems when correcting the field readings, mainly for the outer beam depth adjustments.

An echo sounder's transducer has many frequency options and should be selected to meet the study needs. The Sedimentation Group surveys are usually conducted using a 200 kilohertz (kHz) high-frequency echo sounder and also has a low-frequency 24-kHz option. In general, the higher frequency transducers of 100-kHz and greater provide more precise and detailed bottom depth measurements due to the frequency characteristics and narrow beam width. The major disadvantage of higher frequency transducers is that they tend to reflect off first signal change that may provide false readings of the actual depth for such conditions as suspended sediments (fluff) and bottom vegetation. The lower frequency transducers of less than 40-kHz are less subject to attenuation and are capable of greater depth measurements, since they can penetrate the suspended sediment or fluff type conditions. However, the lower-frequency transducers have a larger beam width that may provide readings that are distorted due to smoothing of irregular bottom features and side slopes. An experience operator is needed along with some manual readings to assist in making a distinction between the fluff and actual bottom readings.

In 2001, the Sedimentation and River Hydraulics Group began utilizing an integrated multibeam hydrographic survey system. The system consists of a single transducer mounted on the center bow or forward portion of the boat. From the single transducer a fan array of narrow beams generate a detailed cross section of bottom geometry as the survey vessel passes over the areas to be mapped. The system transmits 80 separate 1-1/2 degree slant beams resulting in a 120-degree swath from the transducer. The 200 kHz high-resolution multibeam echosounder system measures the relative water depth across the wide swath perpendicular to the vessel's track. Figure 6 illuminates the swath of the sea floor that is 3.5 times the water depth below the transducer.

The Sedimentation Group's multibeam system is composed of several instruments that are all in constant communication with a central on-board notebook computer. The components include the RTK GPS for positioning; a motion reference unit to measures the heave, pitch, and roll of the survey vessel; a gyrocompass to measures the yaw or vessel attitude; and a velocity meter to measure the speed of sound in the reservoir water column. With proper calibration, the data processing software utilizes all the incoming information to provide an accurate detailed x, y, z data set of the lake bottom.

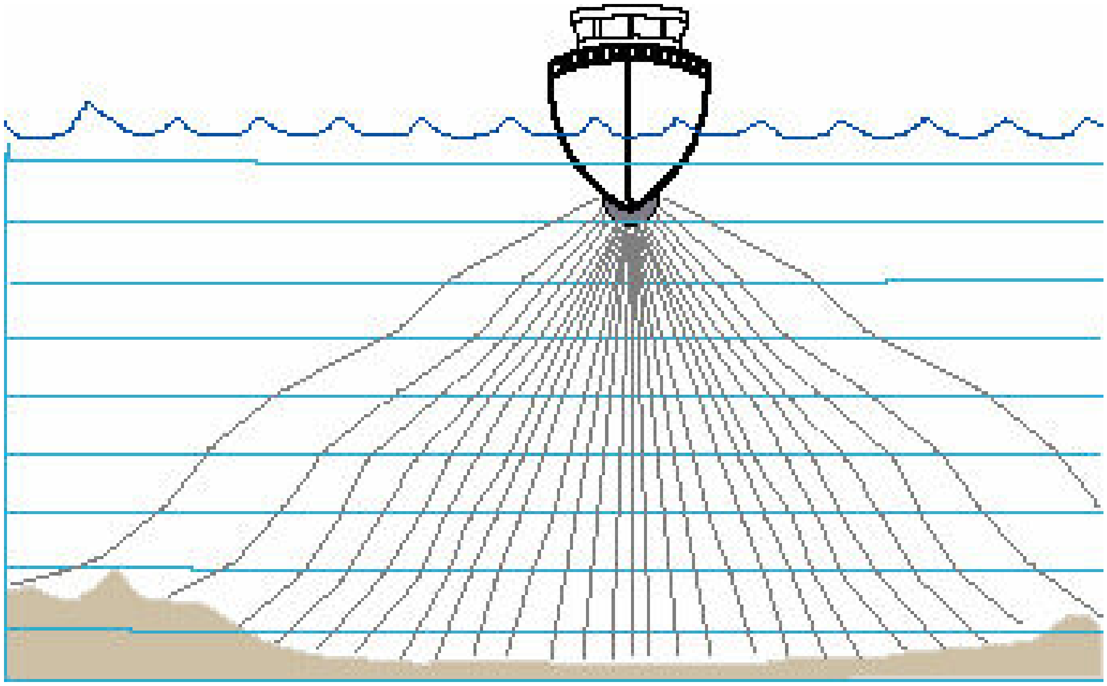

Figure 6 - Multibeam collection system.

The system was first used to survey the sediment deposition of Lake Mead from the dam to the upper shallow water areas of the reservoir. The 2001 final product included cross sections every 5 meters for the underwater reservoir areas covered by the survey vessel. The detailed collection of all the underwater portion of the Lake Mead sediment deposition was completed in three weeks with a two person crew compared to the 6 months and six person crew it took to collect 407 cross sections for the 1986 Lake Powell sedimentation survey using a single beam collection system.

Each transducer acts as separate acoustic-distance measuring units like a single beam vertical mount system, except the multibeams are at a given angle with respect to the mounted single vertical transducer. Computations determine the depth of each beam from the slant-distance signal adjusted with the velocity profile data. Multibeam vessels can survey in rougher water and offer greater coverage, depending on the water depths. With a fan of 120 degrees, the bottom sweep width is around 100 feet in 30 feet of water and around 350 feet in 100 feet of water. It must be noted that for navigation type surveys it is recommended that there is a 50 percent overlap of the survey sweeps for quality control. Most Reclamation surveys are not performed for navigation purposes so the fan overlap can be reduced. The overlap should be enough to assure the outer beams of the two sweeps are collecting high quality data.

Field calibration of multibeam systems is more critical and complicated than what is required for single beam systems. Periodic precise calibration is essential to assure the multibeam positions and elevations are accurate. The horizontal positioning accuracy is dependent upon the ability of the system to compensate for pointing errors caused by vessel roll, pitch, and yaw where a small degree of roll can cause large errors in the outer beams. For high accuracy surveys, restrictions are typically placed on the use of the outer beam data. The manufacturer's suggestions and experience should be used to determine the use of these outer beams. Velocity profile data is very critical to collect for all beam measurements, but mainly for correction of the outer beams. Velocity profile readings should be taken at minimum once per day and more often when the survey vessel relocates to different portions of the study area.

Side scan sonar is a high-resolution tool that provides a map on both sides of a survey vessel's path. The system does not provide absolute elevations of objects; however, it will provide relative elevations of the surrounding topography. The map images can be recorded as an analog image paper chart or a digital data image that allows mosaics to be produced and merged with other data sets such as multibeam data. The quality of sonar data is often a function of the height of the towfish above the bottom. Multibeam systems have the capability of providing a side scan image, but the quality is not as good as the towed side scan systems.

Airborne Light Detection and Ranging (LiDAR) hydrographic surveying method is a means for collecting above and below water data. The Sedimentation Group and other agencies have successfully used LiDAR to conduct shallow water river surveys (Hilldale, 2005). The primary constraint of LiDAR is water clarity. LiDAR has been successful at collecting bottom data through as much as 60-meter depths of clear water. In less clear waters, LiDAR data collection has been successful at depths of 2 to 3 times the visible depth.

RESERVOIR AREA AND CAPACITY

Topography Development

Since the late 1980s, the majority of the reservoir studies conducted by the Sedimentation Group produced new reservoir topography and updated reservoir area and capacity tables from the newly developed topography. The range line method has been used for a few studies. For the 1999 Elephant Butte Reservoir survey, the underwater data was used to developed new reservoir topography, but the analysis used the range line method to compute the updated reservoir information to conform to previous analysis methods (Collins and Ferrari, 2000). There are numerous software packages for the topographic development. The Sedimentation Group uses several with ARC/INFO GIS) software the main one for reservoir studies. Contours for the reservoir, using the underwater data set, uses the triangular irregular network (TIN) surface-modeling package within ARC/INFO. A TIN is a set of adjacent non-overlapping triangles computed from irregularly spaced points with x,y coordinates and z values. TIN was designed to deal with continuous data such as elevations. The TIN software uses a method known as Delaunay's criteria for triangulation where triangles are formed among all data points within the polygon clip. The method requires that a circle drawn through the three nodes of a triangle will contain no other point, meaning that sample points are connected to their nearest neighbors to form triangles using all collected data. This method preserves all collected survey points. Elevation contours are then interpolated along the triangle elements. The reservoir surface areas by elevation increments are developed from the TIN. The linear interpolation option of the ARC/INFO TINCONTOUR command is used to interpolate the reservoir contours from the TIN. The TIN method is discussed in detail in the ARC/INFO *Users Documentation,* (ESRI, 1992).

Development of the Contour Areas and Reservoir Volume

The contour surface areas for the reservoir studied are usually computed at 1-foot increments for the elevation range studied. The ARC/INFO VOLUME command computes areas at user-specified elevations directly from the TIN and takes into consideration all regions of equal elevation. For studies that have both above and below water data, this usually completes the information for computing the final area and capacity tables. For studies with no undated reservoir information, engineering judgment is required to best determine the full updated reservoir capacity.

The Sedimentation Group computes the storage-elevation relationships, based on the measured TIN generated surface areas, using the area and capacity computer program ACAP85 (Bureau of Reclamation, 1985). The surface area information, as described above, is used as the control parameters for computing the updated reservoir capacity. If the study has no above-water data, then usually the original surface areas above a certain elevation are used to complete the area and capacity tables. Due to lack of updated above-water data, the study must assume no change since original computations.

The ACAP85 program can compute an area and capacity at elevation increments 0.01- to 1.0-foot by linear interpolation between the given contour surface areas. The program begins by testing the initial capacity equation over successive intervals to ensure that the equation fits within an allowable error limit. The capacity equation is then used over the full range of intervals fitting within this allowable error limit. For the first interval at which the initial allowable error limit is exceeded, a new capacity equation (integrated from a basic area curve over that interval) is utilized until it exceeds the error limit. Thus, the capacity curve is defined by a series of curves, each fitting a certain region of data. Differentiating the capacity equations, which are of second order polynomial form, the final area equations are derived:

$$y = a_1 + a_2x + a_3x^2$$

where: y = capacity
x = elevation above a reference base
a_1 = intercept
a_2 and a_3 = coefficients

Results of the new ACAP85 reservoir area and capacity computations are compared to the original surface areas and recomputed ACAP85 original capacities for estimating sediment deposition. For most studies, a separate set of area and capacity tables is published for the 0.01, 0.1 and 1-foot elevation increments. A description of the computations and coefficients output from the ACAP85 program is included with these tables.

Lake Mead 2001 Reconnaissance Survey

Reclamation's Sedimentation Group surveyed Lake Mead Reservoir in the spring of 2001 to develop a present storage-elevation relationship (area and capacity tables). This was the first multibeam survey conducted by the Sedimentation Group and the first known extensive multibeam survey of Lake Mead. During a planning meeting in July of 2000, it was proposed to survey Lake Mead using reconnaissance techniques utilizing a multibeam collection system. Due to the size of the reservoir and limited budget, the survey collection was limited to the areas of known sediment accumulation. Previous surveys of Lake Mead (1948 and 1963-64) and the 1986 survey of Lake Powell measured the sediment accumulation in the deeper portions of these reservoirs along the original river channel alignment. The 2001 multibeam survey of Lake Mead was focus on areas of the reservoir with known sediment deposition. During field collection, judgments where made as to the boundary of the existing sediments and the multibeam sweeps extended beyond this area.

The Lake Powell 1986 range line survey found the sediment distributed laterally across the reservoir. Although a few of the Lake Powell range lines measured channel cuts through the deposited sediments, the majority measured the sediment lying horizontally in the deeper original river channel geometry (Ferrari, 1988). Between 1999 and 2002 extensive sidescan sonar imagery, seismic-reflection profiles, and bottom sampling was conducted on Lake Mead by the United States Geological Survey from Woods Hole, Massachusetts and the Lake Mead/Mojave Research Institute out of the University of Nevada. There are numerous Lake Mead publications summarizing the method of collection and results of this research. These studies found the post-impoundment sediments mainly covering the floors of the former streambeds of Lake Mead. The remainder of the mapped reservoir bottom was rock outcrops with no major change due to sediment accumulation (Twichell, 1999). The analysis of the reservoir indicated that a large volume of sediment carried by the Colorado River has accumulated in Lake Mead since impoundment in 1935. The analysis of the seismic-reflective found the sediment was not uniformly distributed, but concentrated in the deepest parts of the lake covering the floors of the valleys cut by the Colorado River and the other tributary streams that originally flowed through the Lake Mead area (Twichell, 2003).

The LC Regional Office contracted with the Sedimentation Group to conduct the 2001 collection and processing of the multibeam data. The major objective of the field collection was to map the areas of sediment accumulation since closure of Hoover Dam in February of 1935. The Lake Mead underwater survey was conducted over 22 days in April and May of 2001. The LC Regional Office provided assistance during a large portion of the collection and conducted the GIS analysis of the x,y,z data sets provided by the Sedimentation Group. In the fall of 2001, a limited aerial LiDAR survey was conducted in the Grand Bay and Pierce Basin area of the upper reservoir. Due to low reservoir conditions and 9/11, the Sedimentation Group did not survey the upper reservoir area above Pierce Basin beyond the area mapped by the LiDAR survey. Previous Lake Mead sediment surveys indicated a large portion of this reservoir area was lost due to sediment deposition, but the upper elevation zones are still available for water storage. The upper zone, above around elevation 1,180 feet[2], is 40 miles of reservoir volume that should be accounted for. As named, lower Granite Gorge is narrow compared to the rest of the reservoir, but still has available capacity. Data for this area of the Colorado River were obtained by cross sections collected between 1999 through 2001 by a contractor studying the effect of the reservoir on bird nesting areas. The cross sections were tied to the reservoir water surface that varied between reservoir elevation 1,178 and 1,194.

The Sedimentation Group's underwater survey used multibeam sonic depth recording equipment interfaced with GPS to obtain continuous sounding positions throughout the underwater portions of the reservoir covered by the survey vessel. The reservoir topography was determined by importing digital images of the contour lines from the USGS quad maps of the reservoir area. The new topographic map of Lake Mead Reservoir was developed from the combined 2001 underwater measured topography and the USGS quad contours.

Prior to the underwater collection, a RTK GPS control survey was conducted to establish a temporary horizontal and vertical control point near the Lake Mead Marina. This control point, with the RTK GPS system, was used for the survey of the lower portion of the reservoir that included Boulder Basin and Las Vegas Bay. The horizontal control was established in the UTM coordinates zone 11 in the can

[2] All elevation levels in this report are shown in feet unless otherwise noted. All elevations are based on the project or dam's construction datum unless otherwise noted.

NAD83. The RTK GPS control was conducted with the base set on the NGS datum point located downstream of the dam. A temporary control point was established on the Overton Arm of the reservoir near Echo Bay Marina, but due to time limitation and need for highly accurate data, it was decided to use a military issued GPS unit with horizontal accuracy of ± 4 meters. All elevations were reference to the reservoir water surface gauge that is tied to the Hoover Dam construction datum.

The 2001 survey utilized a high-resolution multibeam mapping system for collecting x,y,z data of the Lake Mead bottom from depths of 3 meters in the upper portions of the lake to greater than 140 meters near Hoover Dam. The system consisted of a single transducer that was mounted on the center bow or forward portion of the boat (figures 7 and 8). From the single transducer a fan array of narrow beams generated a detailed cross section of bottom geometry as the survey vessel passed over the areas to be mapped. The system transmits 80 separate 1-1/2 degree slant beams resulting in a 120-degree swath from the transducer (figure 6).

Figure 7 - Sedimentation group's multibeam vessel.

Figure 8 - Multibeam transducer with angle mount.

The areas covered included the underwater river channels of Las Vegas and Overton arms and the Colorado River channel from the dam to just downstream of Pierce Ferry. Since the survey was limited to the deeper areas of the reservoir with sediment deposition, the time of collection was significantly reduced. For example, mapping the full extent of Las Vegas Wash would have taken many days to complete, but since this study was mapping just the areas of sediment accumulation, the multibeam system mapped this area in only one day. A 2-person crew that consisted of personnel from Reclamation's Denver and Boulder City offices operated the boat and system. For the deeper portions of the reservoir, the procedure included running parallel survey lines whose alignment were longitudinal with the original river channel alignment. The distance between the parallel survey lines was depth dependent and was set to provide overlap of the data sweeps. Enough parallel survey lines were run to ensure that complete mapping of the deposited sediments would be obtained. As the survey vessels mapped the shallow water areas in the upper reaches of the reservoir, the overlapping of the data sweeps was abandoned due to the time it would have taken to ensure full coverage. Here the sediments were found to be lying flat and it was determined that the areas missed could be projected during final analysis.

The multibeam survey found for the majority of the reservoir area the sediment lying very flat like a pancake. With this being the case, the collection speed could have been greater and the amount of overlap of the collection profiles could have been reduced without affecting the quality of the data collection and final analysis. However, since this was the first multibeam collection by the

Sedimentation Group, an extensive overlap of the profiles was maintained and the speed of collection was usually kept around seven miles per hour or less. During data processing it was found that one multibeam profile happen to map an area of the Overton Arm of Lake Mead where a B29 military aircraft had crashed in 1948. A private diving team conducted research and sidescan collection to pinpoint the location of the B29 that was found to have settled on a ridge just above the original Overton River channel. (B29, 2002). The plane was found in around 300-feet of water. Pictures from dive teams very clearly showed images of the plane and instrument interior with little to no silt material. Figure 9 is an unfiltered image from one profile of the multibeam collection system revealing the general outline of the plane.

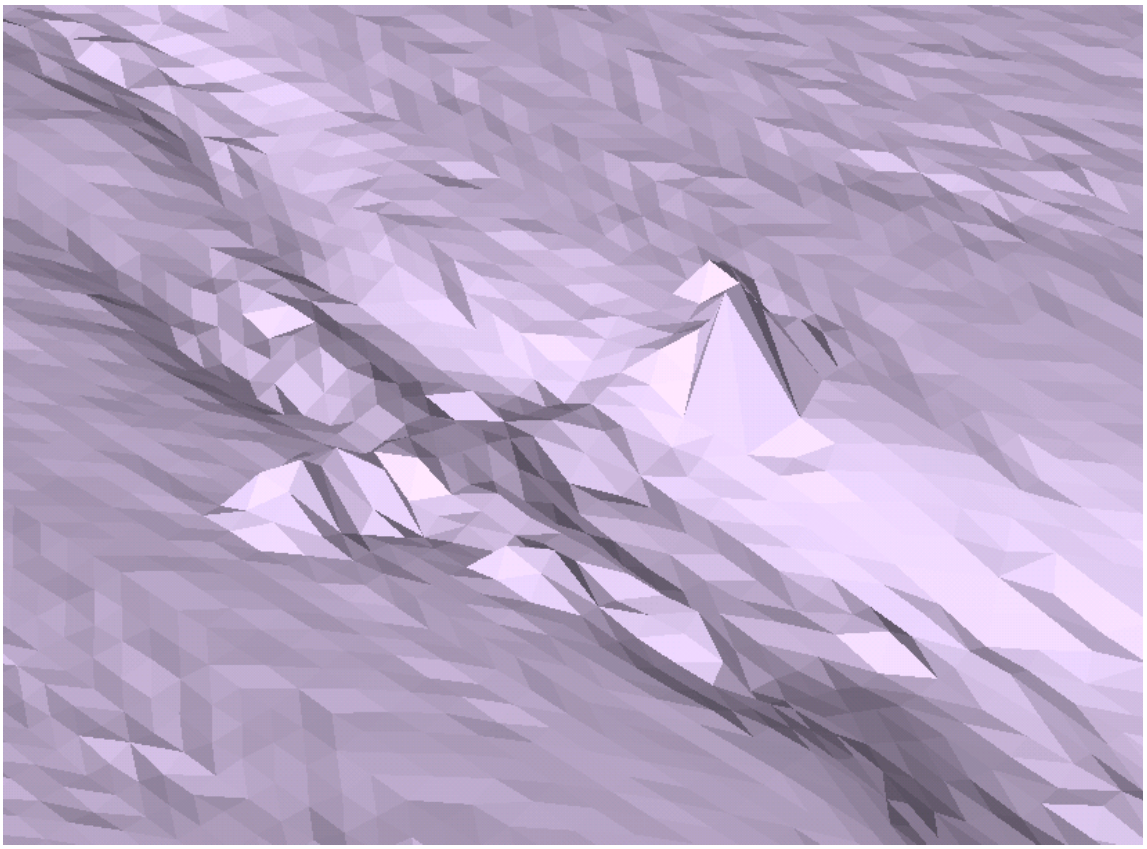

Figure 9 - B29 multibeam image from Lake Mead.

Reconnaissance Procedures for Lake Mead Bathymetric Analysis

The first part of the analysis included processing the collected multibeam raw profile files of the reservoir bottom. This included applying all necessary correction information such as vessel location along with the roll, pitch, and yaw effects. Other corrections included applying the sound velocity and converting all depth data points to elevations. All elevations were tied to the measured water surface elevation at the time of collection. Filtering of data was completed due to the massive amount of information that was collected by the multibeam system. This was accomplished by filtering the data into 5-meter grids or cells and saving one sounding each. Quality control and assurance of the data set was accomplished by conducting field calibration as required by the multibeam system. The final data included 53 files of x,y,z data sets of over 20 million points covering about 30 percent of the underwater portion of Lake Mead.

Generating 1935 surfaces

The analysis required the generation of the 1935 (original) surface topography into digital data files. These digital images were used during the collection to assure the vessel was collecting within the original river channel area and beyond. The 2001 collected x,y,z data was overlayed on the original digital surfaces and provided the 2001 surface images. Comparison of the original surface and the 2001 surface provided the quantity and location of sediment that has deposited in Lake Mead since the closure of Hoover Dam in February of 1935. The 2001 data were cut into the 1935 data with the assumption there has been no change since 1935.

The Lower Colorado Regional Office (LC Regional Office) in Boulder City Nevada completed the GIS analysis of Lake Mead producing digital images of the original and 2001 reservoir topography along with the resulting sediment accumulation and reservoir volume for the areas studied. The original topography of Lake Mead was developed from aerial photography flown prior to the closure of Hoover Dam. The results were 10-foot contours at a scale of one-inch equals one thousand feet on map sheets labeled one through fifty-two. Previously these map sheets were scan by the USGS to develop 10-meter Lake Mead underwater digital elevation model (DEM).

The Lake Mead contour map was divided into individual sheet as identified in the 1963-64 Lake Mead Survey (Lara – Sanders, 1970). The purpose for the individual sheets was for comparison purposes with the previous study results that were conducted in 1948 and 1963-64. The original surface areas and resulting capacity of Lake Mead along with the updated area and capacity from the 1948 and 1963-64 surveys were determined from these individual data sheets. Previously the 10-foot contours for each topographic sheet were planimetered to generate the original surface areas and resulting capacity. The results from the 1948 and 1963-64 studies were determined by measuring the changes from the original computations. For the 2001 LC Regional Office analysis, the original reservoir area above Pierce Basin was assumed filled with sediment and had no volume capacity. The 1948, 1963 and the 2001 survey results found that the majority of this area was silted in but as seen on the longitudinal profile there are over 40 miles of original reservoir from elevation 1,180 and above with no sediment accumulation.

Using clip and TIN processes within ARCINFO, contour coverage for each individual sheet was generated for the original data set. From the developed TIN, surface areas for each individual map sheet were generated in ten-foot increments to match the original elevation contour interval. The resulting surface areas were imported into a database to generate the original surface area and resulting capacity values for the portion of the reservoir studied. These values were compared to the 2001 generated values for computing loss of storage due to sediment accumulation.

Note that the generated 10-foot incremental surface area values from the 2001 study for the individual maps did not match the original surface area values listed in the 1963-64 report. For computing the 2001 loss due to sediment accumulation, this is not a major issue since these computed coverages were developed by comparing original and 2001 results using the same method for processing the data. However, for generating updated capacity of Lake Mead this issue needs further study, mainly when operating the reservoir during flood routing. There are many reasons for the different values, with the main reason being the different methods for surface area computations. The original surface areas of the 10-foot contours for the individual maps were determined by planmetering and a computer processing produced the 2001 surface area results. The 1963-64 Lake Mead report indicated that for portions of the reservoir the planimetering process was an average of a minimum of three runs. The 2001 process generated TINs of the individual maps. These TINs were developed from 10-meter DEMs that were developed by the USGS from scan images of the original 10-foot contour maps. Some of these differences can be attributed to the fact the planimeter data was of better detail (10-foot contours) than the 10-meter DEMs. Further verification of either method is needed, but when it comes to sediment computations, both methods should result in similar values.

The Sedimentation Group had proposed to determine the 2001 area and capacity tables by measuring the changes on the individual maps due to sediment accumulation, but above this area of change assume no original surface area changes. As part of this process, the available cross section data for the reservoir area above Pierce Basin would also be included. Even though the majority of this area is lost due to siltation, there are 40 miles of surface area in the upper contours that should be included in the final area and capacity computations. The final 2001 computations of the individual map data of Lake Mead was provided to the Sedimentation Group in September of 2002 and due to time limitation and minimum budget, these computations were not completed. The reconnaissance technique method of collection and analysis was applied to the 2004 Lake Powell data and described in more detail in that section. This method should not result in any major change of the sediment inflow since dam closure when compared to the LC Regional Office approach, but would provide a complete reservoir volume for all reaches of the original reservoir. The only means to truly measure the current volume of the reservoir would be to have a combined above and below water detailed survey.

Summary of Lake Mead Analyses

Figures 10 and 11 are digital mapping results from the 2001 Lake Mead survey. The LC Regional Office GIS group developed the images from the 2001 multibeam data only that was collected by the Sedimentation Group. The x,y,z data set was generated from three profiles from Hoover Dam upstream on the Colorado River about one mile. The data set was filtered into 2-meter grids for computational purposes. The first image shows the cofferdam located just upstream from the dam face. The second image shows the base of two of the four intake towers that are located on the left bank looking towards the dam.

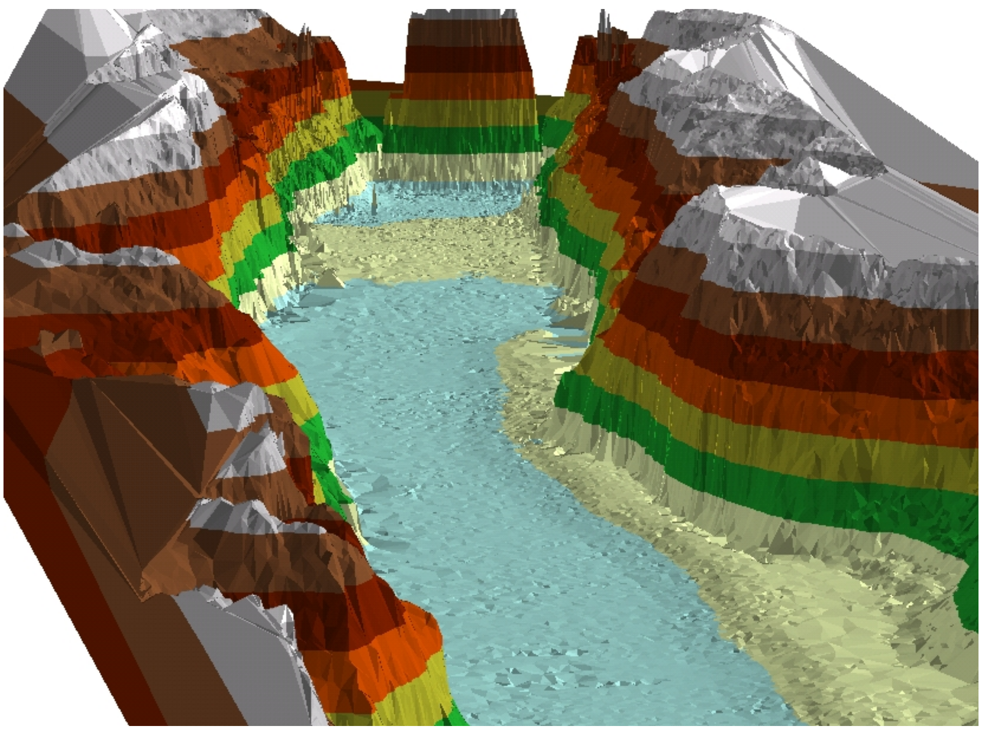

Figure 10 -Multibeam data of Colorado River upstream of Hoover Dam.

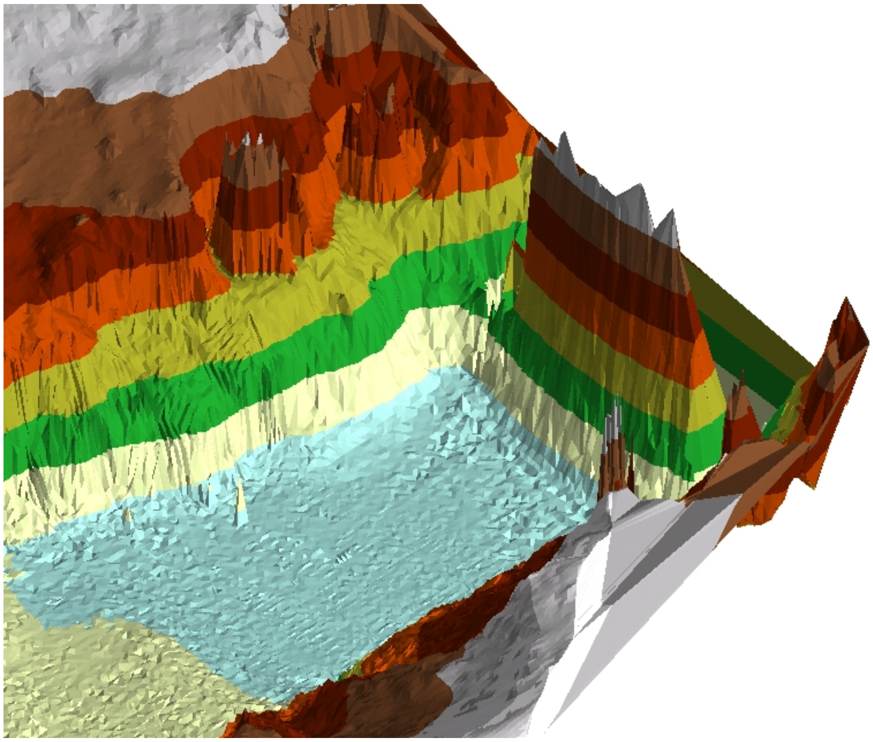

Figure 11 - Multibeam generated image of Hoover Dam and intake towers.

Figures 12 and 13 are longitudinal profiles computed for the 1935 (original) and 2001 data for Las Vegas Wash and the Overton basins of Lake Mead. Both plots show a minimal change due to sediment accumulation in the respective drainage basins that have occurred over the first 65 years of reservoir operation. These profiles show the classic build-up of the sediment delta in the upper reservoir area. The plots also show the build up of Colorado River sediment in the lower reservoir area at the confluence with the Colorado River.

The Lake Mead longitudinal profile (figure 14) shows the comparisons between the 1935, 1948, 1963 and 2001 survey results of the Colorado River. The 2001 profile of the Lower Granite Gorge above Pierce Basin was developed from cross section data from a LC Regional Office contractor studying the effect of the river and Lake Mead on bird nesting habitat. These cross sections were collected without a true vertical datum to compare to, but with some engineering assumptions these cross sections were able to be used to complete the thalweg profile from Pierce Ferry upstream, about 40 miles of the upper reservoir. The longitudinal plots show some interesting results. The 2001 bottom data was found to be lower then the 1948 and 1963 longitudinal profiles in the lower reservoir area. The 2001 bottom data results were compared with other information to support the 2001 bottom results. It is assumed that over time compaction of the previous accumulated bottom sediments has occurred resulting in the lower elevations. There are mathematical means to compute the compaction rate that occurs over

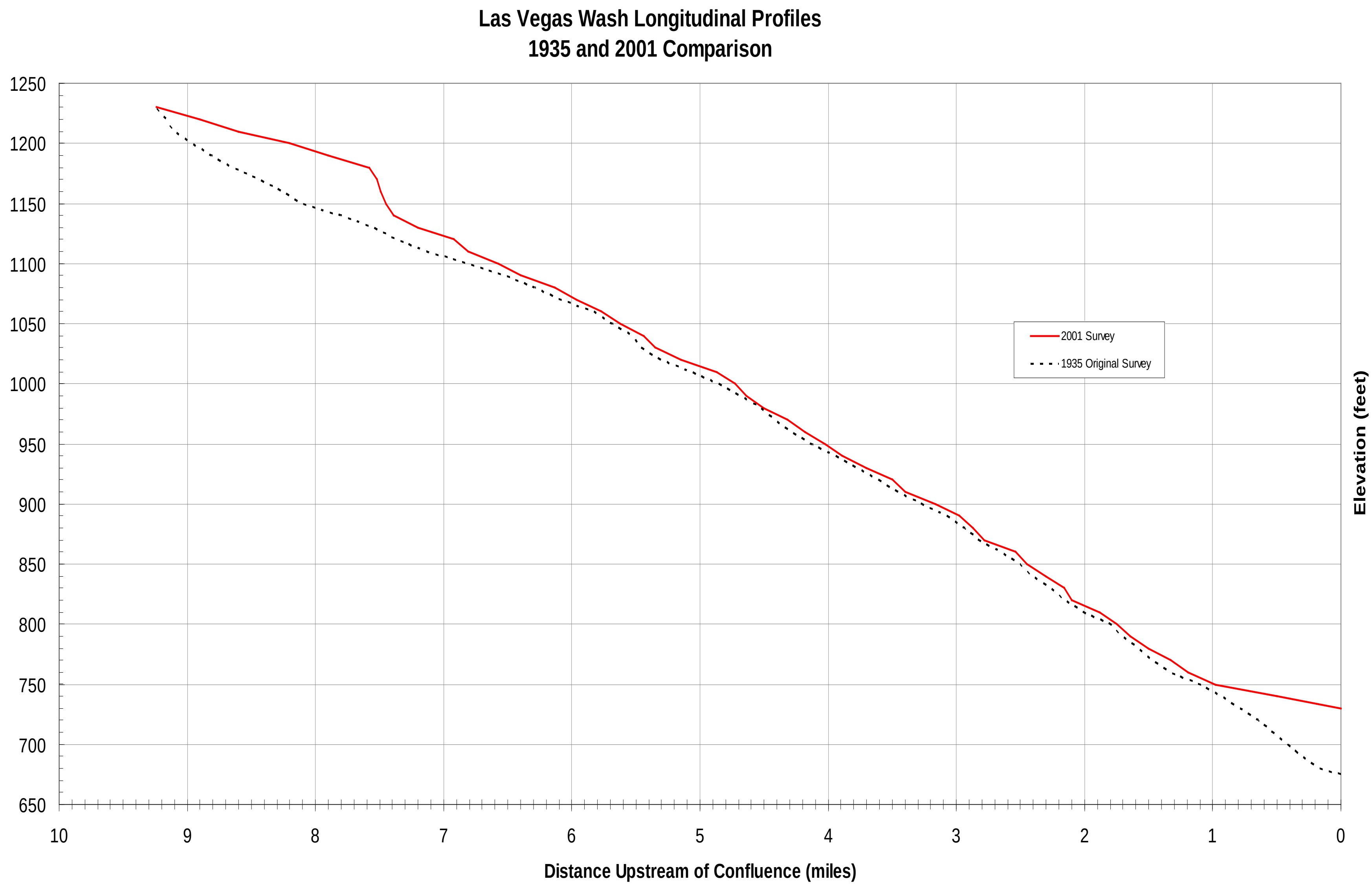

Figure 12 - Las Vegas Wash longitudinal profile.

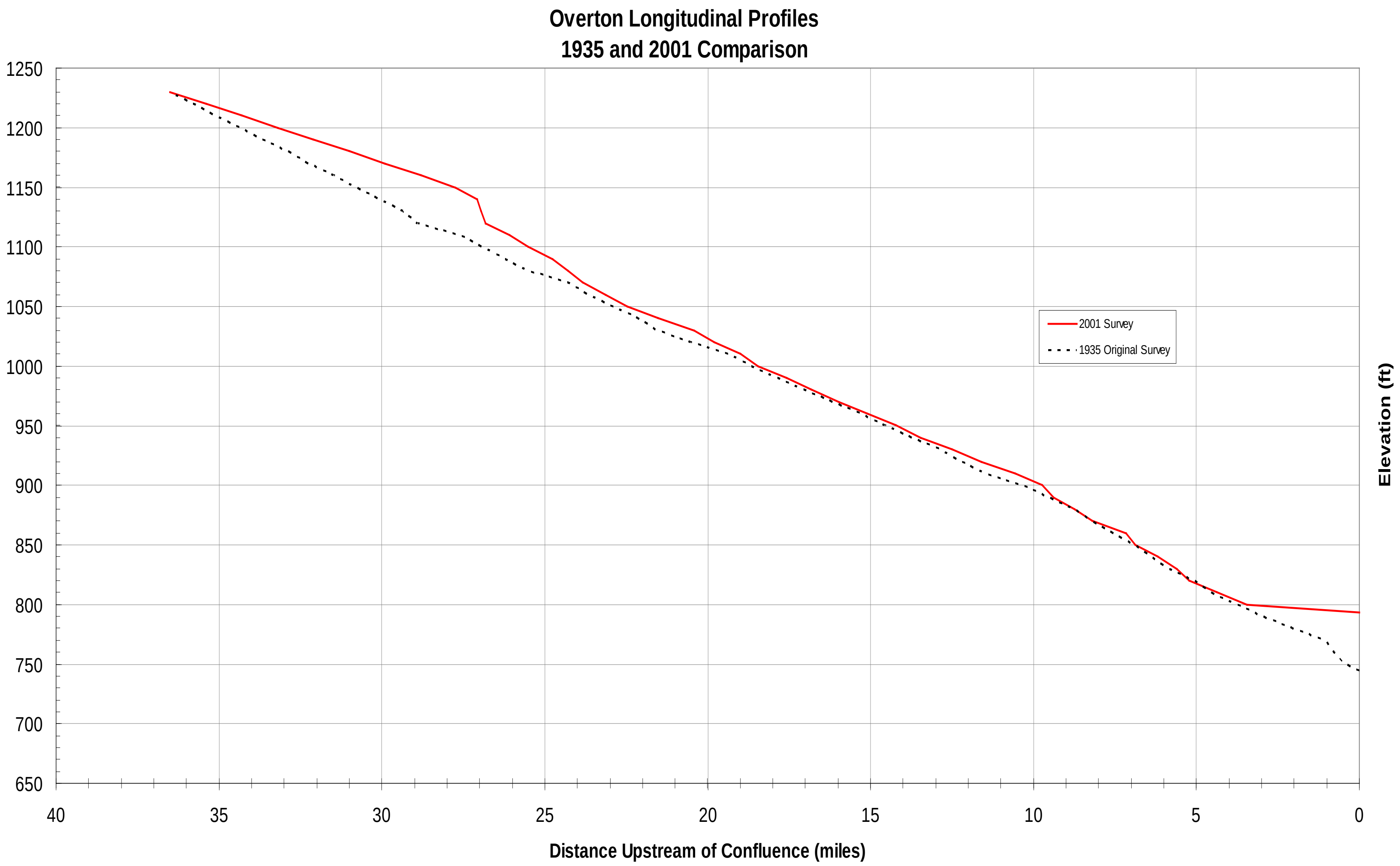

Figure 13 - Overton longitudinal profile.

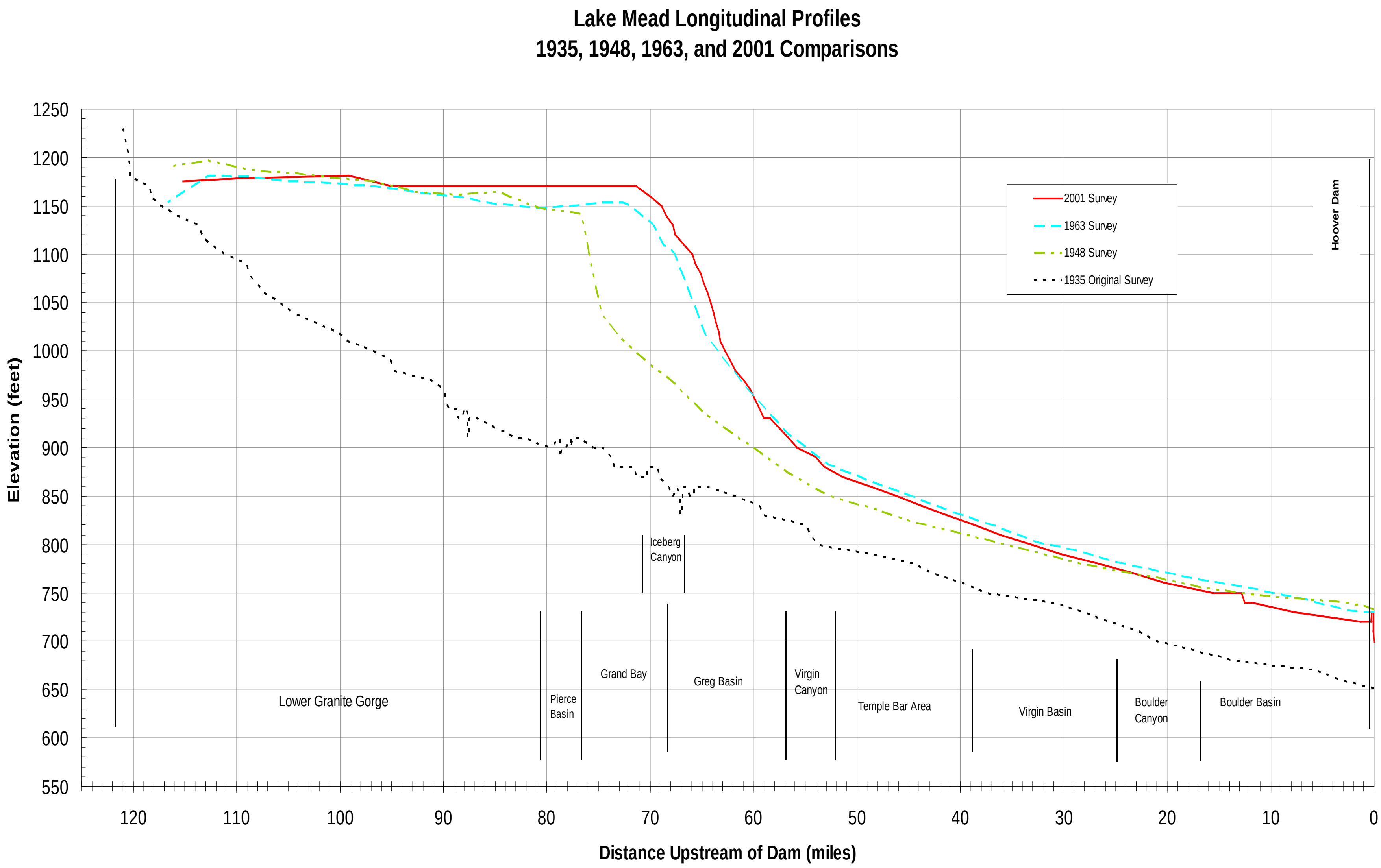

Figure 14 - Lake Mead -- Colorado River longitudinal profile.

time (Strand and Pemberton, 1982). In 2002, there were sediment samples collected on Lake Mead by the USGS, but no known density information was obtained from these samples to compare with previously collected bottom sediment samples.

Lake Powell Reconnaissance Survey

Glen Canyon Dam, which closed in March of 1963, forms Lake Powell Reservoir that is located in Arizona and Utah. Glen Canyon Dam is a concrete structure with a structural height of 710 feet. The top of active conservation storage is elevation 3,700 feet[3] and had an initial total storage of 27 million acre-feet. The reservoir extends around 180 miles from the dam upstream along the Colorado River and 80 miles up the San Juan River from its confluence with the Colorado River.

The first extensive survey of the lake was conducted by Reclamation in 1986 and the results are summarized in the report "1986 Lake Powell Survey" (Ferrari, 1988). The 1986 survey was conducted between April and September of 1986 using the range line method with an average crew size of six. A total of 407 range lines were surveyed throughout the reservoir. This included the 2 major tributaries, Colorado and San Juan Rivers, and over 20 other tributaries that were considered as possible sediment contributors. The analysis resulted in new area and capacity values and an estimate of sediment deposition since March of 1963. This was possible by using the original topography and projecting the change from the range lines surveyed. The original Lake Powell topography was developed from aerial photography that was flown in the late 1940's and 1950's. Ten-foot contour intervals are presented on over 300 hard copy maps. The surface areas of each 20-foot contour from elevation 3,140 through 3,700 and the 3,710 contour was determined by planimetering the contours on each map in the 1960s. The summation of these map surface areas was used to compute the original volume of Lake Powell. In the 1990s, the maps were scanned and processed into digital formats that were available for the 2004 field collection and analysis. Maps of the reservoir and range line location are located in Appendix IV.

In 2004, the Sedimentation Group conducted several multibeam surveys on Lake Powell. The size of Lake Powell (Colorado River Arm nearly 180 miles) and the numerous tributaries means an extensive above-water data collection is very costly. A reconnaissance type survey, using a multibeam system with GPS, could provide detailed results to develop an updated area and capacity table using a

[3] All elevation levels in this report are shown in feet unless otherwise noted. All elevations are based on the project or dam's construction datum unless otherwise noted.

similar approach as the 1986 study analysis. The 1986 survey was conducted over a six-month period, with an six-person crew, and resulted in 407 range lines located an average of a mile apart. A multibeam survey of the same area could be completed in less than month with a two or three person crew, and result in closely spaced cross sections. The Sedimentation Group's 2004 surveys in 2004 and the New Brunswick 2005 survey demonstrated this process (Clark Huges, 2005).

Summary of Lake Powell Vertical Wall Survey

A detailed vertical wall survey was conducted for the City of Page and Navajo Generating Power Plant on Lake Powell in October of 2004. This was the first known extensive multibeam survey conducted on Lake Powell. For the City of Page, the vertical wall on the left bank (east bank) of the dam was mapped for a proposed water intake structure. For the Navajo Generating Power Plant, the vertical wall below their existing intake structure was mapped. The proposed intake is located on the left bank (south bank) just upstream of the Antelope Marina. These surveys were accomplished by using the multibeam collection system and RTK GPS for positioning. Staff of the Sedimentation Group conducted the collection.

Prior to the collection, a RTK GPS control survey was conducted to provide base station control information. The NGS point "Wall" was used that is a 2nd order horizontal control point. The horizontal data was tied to NAD83 in Arizona's central coordinate system. For this and all studies of Lake Powell all elevations were tied to Lake Powell water surface gauge measurement that are reported to be NAVD29. During the collection, the recorded reservoir level was near elevation 3,570 that is 130 feet below normal pool elevation. The recorded reservoir water surface at the time of collection was used for the vertical control.

For the vertical wall survey the multibeam system was set with the transducer head tilted 30 degrees to the starboard side of the survey vessel, figure 15. In theory, is would allow collection from the water surface elevation and below. Multiple lines were collected running the boat upstream and downstream along the vertical wall alignment.

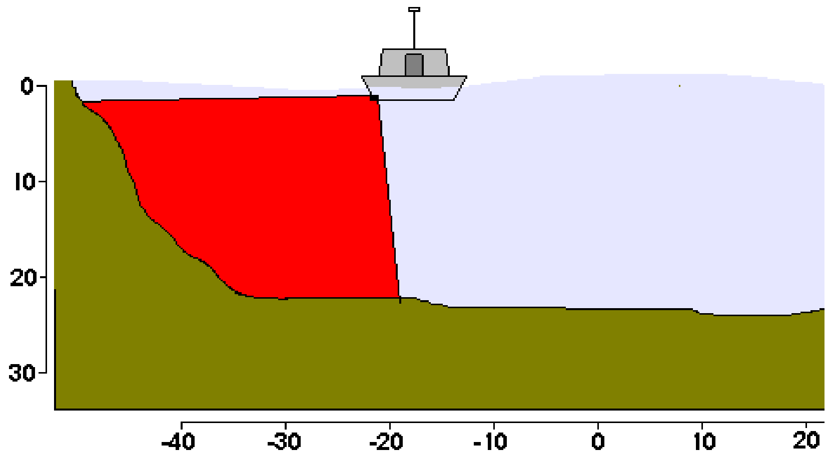

Figure 15 - View of mounting options with multibeam survey boat (HYPACK, INC.).

Vertical Wall Survey at Navajo Power Plant

The vertical wall survey of the Navajo Power Plant was conducted just upstream of the Antelope Marina on the south bank of the reservoir below the intake structure. Several lines where run parallel to the vertical wall alignment with the first line around 500-feet from the vertical wall and several parallel offsets were run closer to the walls at around a 50-foot spacing. The lines were run until they ran into the wall or until GPS control became an issue. To the surprise of the survey crew, data was collected with the survey vessel nearly touching the vertical wall without significantly losing the GPS signal (figure 16).

Figure 16 - Vertical wall area at Navajo Power plant.

During analysis, the multibeam data was found to have lots of noise in the data set due to pushing the system to the extremes by tilting and the depths the system was attempting to measure along the vertical wall. The goal was to develop a detail map of the vertical wall from the shallow water zone to the toe of the vertical wall that was around 390 feet tall. The vertical wall was mapped with the combined data, but the detail was not as good as hoped. The analysis found the deeper depths with less noise than the shallower zones of the vertical wall that were used to map the vertical wall alignment. It was recommended that divers and underwater cameras be used to verify the multibeam results. The following image (figure 17) was developed with the collection software. The TIN shows the materials that exist along the toe of the vertical wall throughout the study area.

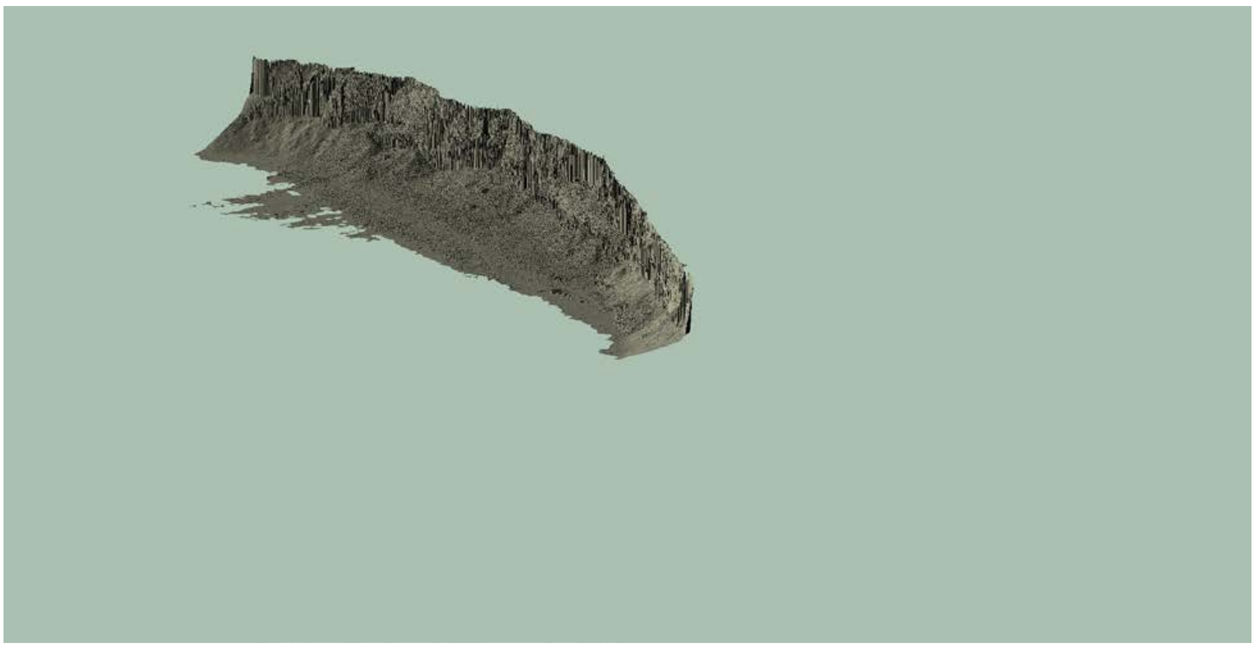

Figure 17 - Power plant site, solid TIN.

City of Page Proposed Water Intake Structure

There are three proposed intake structure sites on the East bank with one just upstream the spillway inlet and the other two near the log boom attachment point on the East vertical wall (figure 18). The multibeam system was set in the tilted position like the Navajo Power Plant site survey and several lines were surveyed parallel with the vertical wall alignment. As with the Navajo Power Plant site, the data sets were very busy. In addition, the GPS data was limited due to the surrounding topography and Glen Canyon Dam blocking of some of the satellite signals. Figure 19 and 20, indicate the developed images had holes in data set, but it was determined that the proposed intake locations were not in those locations. There are also holes in the data set near the right bank due to limited collection, but this area was not needed for this study. The multibeam profiles also covered a large portion of the cofferdam structure. From the developed image, one can see the cofferdam with what appears to be a channel dredged through it. There is no information that supports this area was dredged prior to closure of Glen Canyon Dam so the assumption is a channel was cut by the river as it overtopped the cofferdam.

The processing of the data sets revealed less detail than desired. It was generally concluded that a second set of data should be collected with the multibeam transducer head in its normal position. The final processed data sets were forwarded to both clients for their use along with the recommendation that further clarification was needed.

Figure 18 - City of Page site upstream of Glen Canyon Dam.

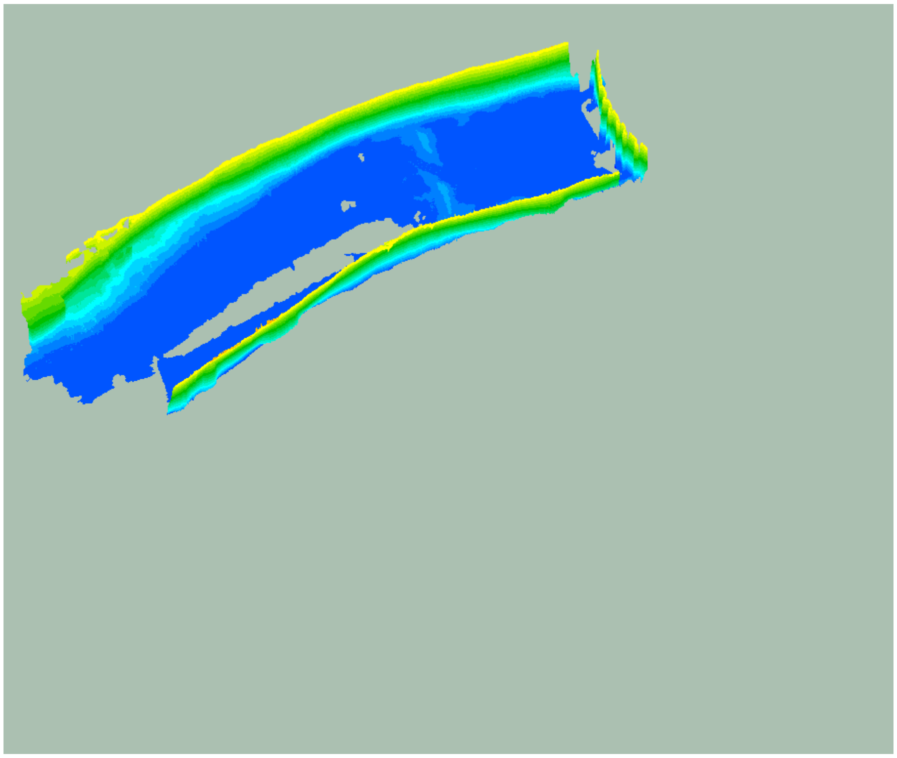

Figure 19 - View of left bank - cofferdam with cut.

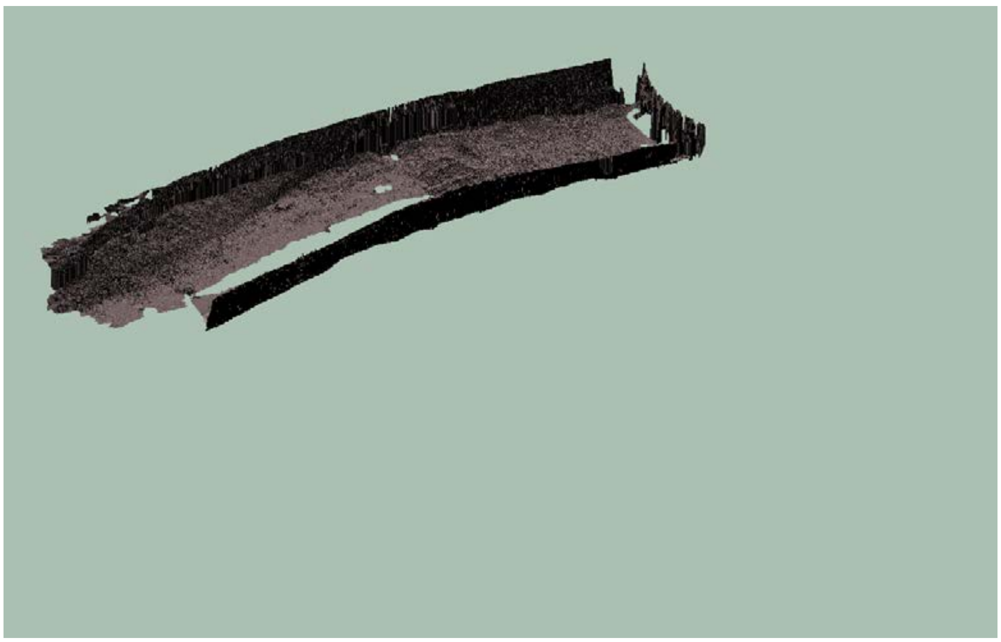

Figure 20 - Solid TIN of city of Page site.

Reconnaissance Techniques for Lake Powell

In December of 2004, the Grand Canyon Monitoring and Research Center (GCMRC) in cooperation with the Sedimentation Group conducted a ground truthing survey on the upper end of the San Juan River arm of Lake Powell. GCMRC contracted with the Corps of Engineers for collection of digital elevation data from an airborne LiDAR survey over the riverbed portions of two study areas. The Sedimentation Group has been involved in collection of river bathymetry in shallow water conditions in the Yakima, Washington area using airborne LiDAR (Hilldale, 2004). The first GCMRC study area was within the Colorado River corridor from Lees Ferry boat dock upstream about 2.5 miles. This reach is located downstream of Glen Canyon Dam and has very clear river flows. The second site was on the upper San Juan arm, starts 37 kilometers from its confluence with the Colorado River, and extends up the San Juan 33 kilometers, figure 21.

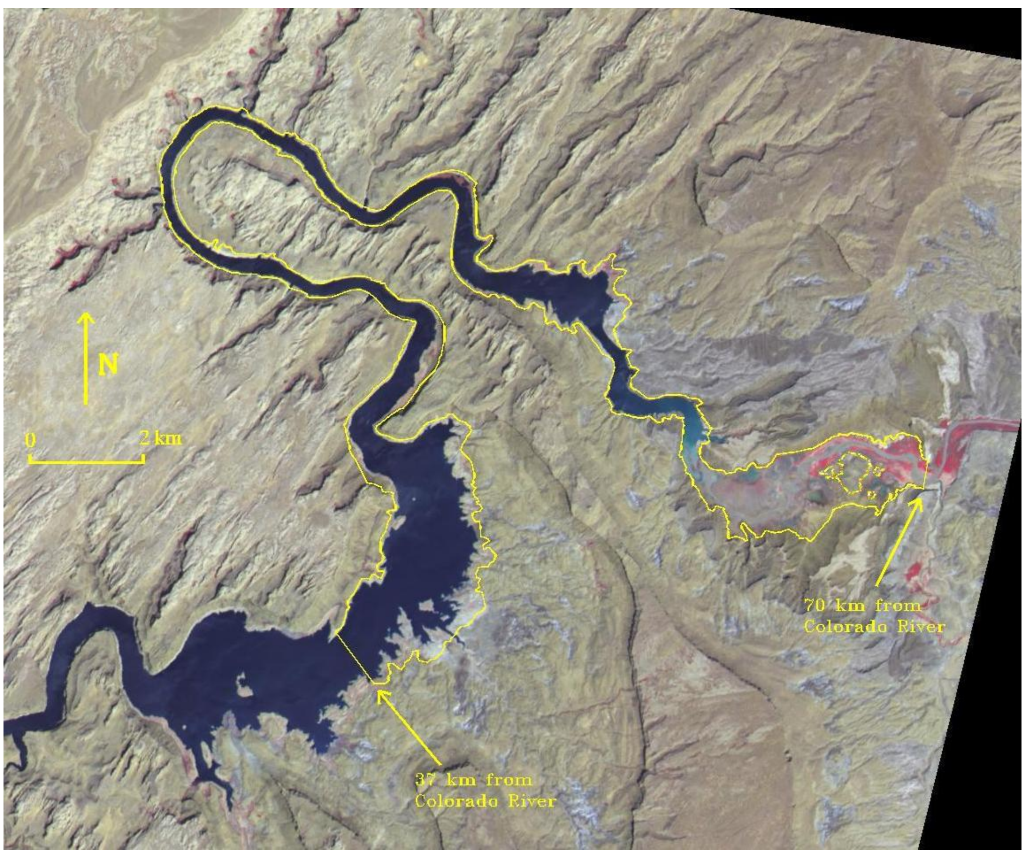

Figure 21 - San Juan River airborne LiDAR study reach.

The GCMRC needed the bathymetry of the San Juan River and land area to support sediment storage and movement studies. These data were to be used to model sediment response within the reservoir to Glen Canyon Dam's operations. Along with the LiDAR data, the system carries a digital camera with blue, green, and red wavelength bands. The gain on the green and blue wavelength bands were set to provide maximum water penetration. The Interagency Contract Agreement was to test this system for obtaining accurate bathymetry within the channel and water penetration imagery to identify channel target materials corresponding to the LiDAR bathymetry data. The survey was to coincide with numerous ground and air surveys that occurred, in late November of 2004, as part of an experimental release for downstream sediment and wildlife behavior.

The cooperative study was to utilize the Sedimentation's multibeam system and vessel to map the upper San Juan River arm for ground truthing the LiDAR survey. This survey was originally scheduled for late November to early December, but was delayed due to other priorities. Even though the original intent was to collect data for ground truthing, the water penetration of the LiDAR was limited in the upper San Juan River. During this time, storms in the San Juan River drainage area increased river flows and the suspend river sediments into Lake Powell. Since the data was needed for the ongoing studies, it was decided to proceed with the multibeam collection.

During October 2004, the multibeam system mapped the Colorado River thalweg from Glen Canyon Dam to just upstream of the Antelope Marina. This was the first known multibeam survey of this area and as shown previously the detail of the construction cofferdam upstream to the Antelope Marina was mapped. The multibeam system was able to map the flat lying sediment deposition from bank to bank with just two lines of collection. It was the general conclusion that this method of collection could map the same area of the 1986 collection in less than 30 days compared to the 6 months it took in1986. The 1986 survey covered 580 miles of the reservoir that included the total length of all the tributaries surveyed. The 1986 survey was conducted at near full reservoir, elevation 3,700. The 2004 survey near elevation 3,570 is 130 feet lower due to extended drought conditions. Multibeam survey results conducted at a low reservoir elevation could be projected upstream to update the area and capacity information if the water level was below 3,700 at the time of the survey. The results of the multibeam collection would be continuous data where the boat is able to travel compared to only the 407 discrete cross sections from 1986.

Although the main interest from the USGS was in the upper San Juan River reach the Sedimentation Group proposed to collect a continues profile of the original river thalweg alignment from Antelope Marina to the study area. Besides providing valuable data for monitoring change since 1986, driving slower saved on fuel that was a concern with this survey. The USGS arranged to have fuel cans left in the San Juan study area and were used for this survey. While waiting for the USGS personal arrival, a RTK GPS multibeam survey was conducted at the Navajo Canyon Power Plant site with the transducer head in the normal position. In addition, a reconnaissance survey was conducted on Navajo Canyon using absolute GPS for positioning.

Navajo Canyon Survey

There are ongoing studies on options for bypassing sediment from Lake Powell downstream into the Colorado River that flows through the Grand Canyon and eventually deposits into Lake Mead. One alternative was studying Navajo Canyon as a potentional sediment source. Navajo Canyon drainage, river confluence located a few miles upstream of Antelope Marina, was shown have a significant sediment source from the 1986 survey results. While waiting on the arrival of the USGS personal for the San Juan River survey, a reconnaissance multibeam survey was conducted on Navajo Canyon using the multibeam sounder and GPS. The GPS was in absolute solution meaning no correction or differential signal was obtained. With the steep narrow canyon situation, a differential correction would be very difficult to maintain throughout the canyon. In general, the boat was kept in the center thalweg, as it was maneuvered upstream and downstream of Navajo Canyon. This was maintained by using the digital map contours as a guide on the collection software. For the majority of the time the survey vessel plotted in the center of the original channel meaning good GPS geometry even with the narrow steep canyon conditions.

The result was a continues profile of the original river alignment with the December 2004 sediment deposition elevation levels. The limitation of the data was boat access because the reservoir was drawndown 130 feet and the very short days of sunlight in December. The canyon was surveyed in one day along with the profile from the confluence downstream to Antelope Marina.

Figures 22 and 23 are developed TIN images from the raw x,y,z points from the multibeam system, figure 22 and 23. The first image is the Navajo Canyon and Colorado River confluence. The details of the canyon wall and the very flat sediment laden bottom were captured from two profiles from the multibeam system. The second image is within Navajo Canyon and shows the detail of the canyon walls and the very flat sediment deposition within the original river bottom alignment.

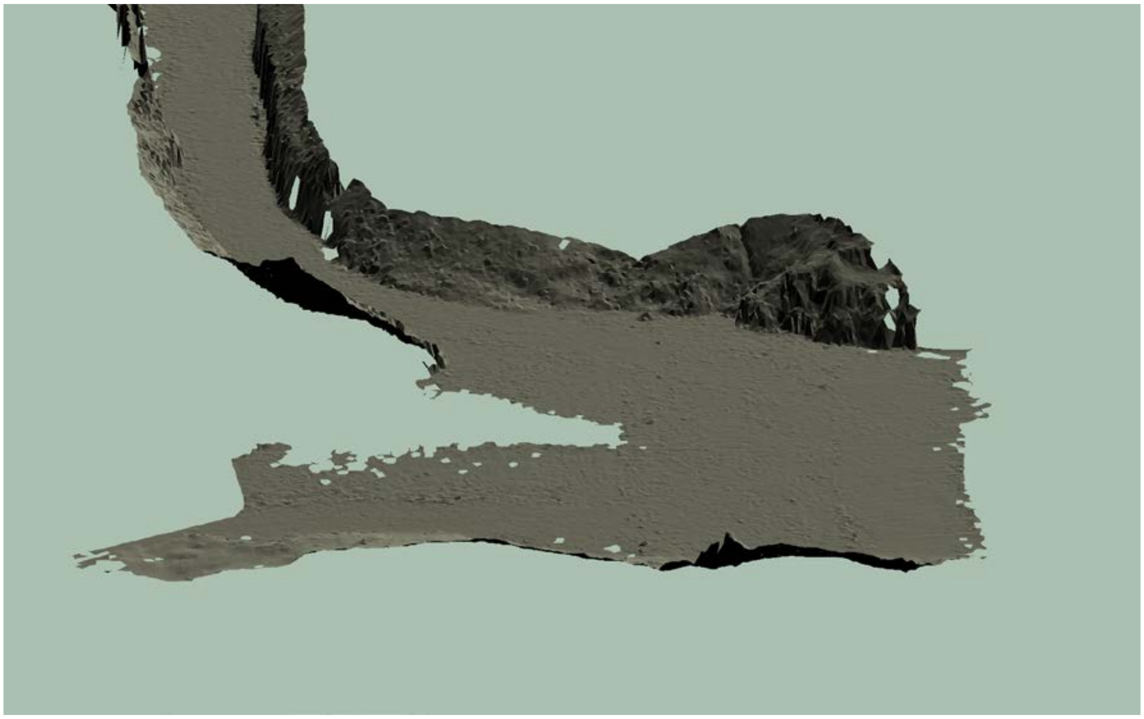

Figure 22 - Colorado River and Navajo Canyon confluence.

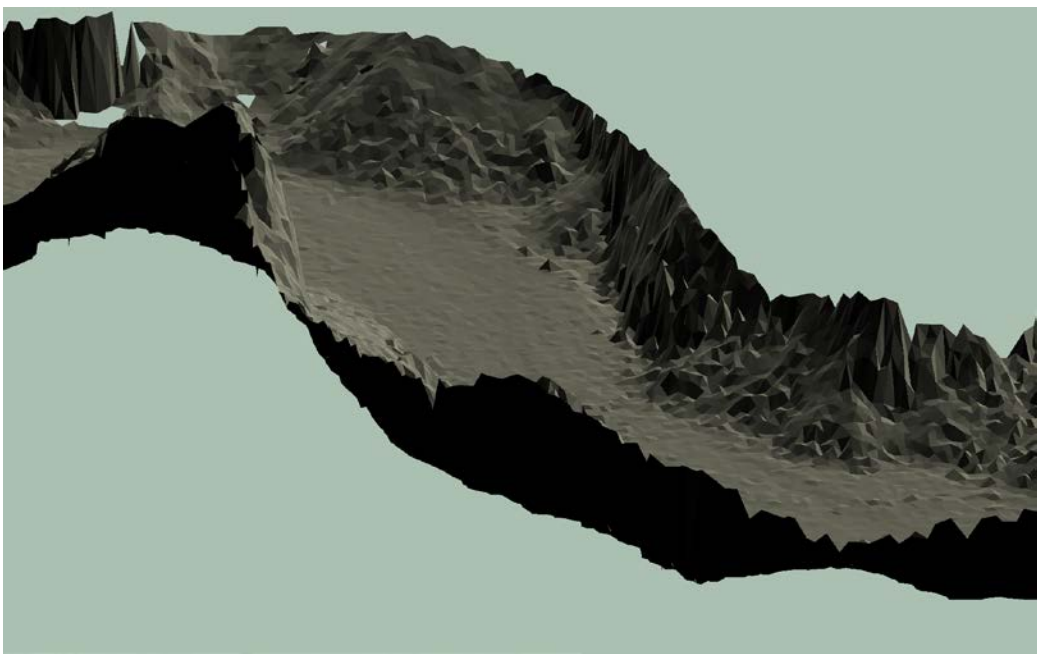

Figure 23 - Navajo Canyon TIN generated from multibeam data only.

Navajo Canyon Area Computations

The following is a summary of the analysis that was conducted using the Navajo Canyon original topography, 1986 cross section results, and the 2004 multibeam data. The original Lake Powell maps and the 1986 range lines located within the map boundaries that covered the Navajo Canyon reach of Lake Powell are listed below.

Map 557-414-335 (includes large main channel area) (RL110, RL421, RL422)
Map 557-414-336 (all Navajo canyon) (**No** RL423)
Map 557-414-342 (RL 424)
Map 557-414-343 (RL425) (**No** RL426)
Map 557-414-346 (RL 427)
Map 557-414-347 (**No** RL428)
Map 557-414-348 (RL429)
Map 557-414-349 (RL430)
Map 557-414-350 (RL431) (**No** RL432, RL433)
Map 557-414-351 (RL434, RL435)
Map 557-414-352
Map 557-414-353

The computations included Map 557-414-335 that covered the confluence of Navajo Canyon with a large portion of the Colorado River area included. Using ARC GIS tools, the Colorado River portion of this map could have been removed, but the proposed reconnaissance technique that was used for the 2004 Navajo Canyon reservoir portion looked at the changes map by map. Using ARC GIS, all the Navajo Canyon map contours could be merged or a grid (DEM) could be created and contours could be created, but this would result in new original surface areas and volumes. As was done for the 2001 Lake Mead analysis, the 2004 data points could be cut into the original contours or grid points and a new TIN and resulting surface areas and volumes could be computed. The difference between the original and 2004 TIN results would be the sediment deposition, but as was the case with the Lake Mead study, the recomputed original developed TIN surface area results would differ from the original published surface areas. The arguments could be this difference is due to an error in the original digitized surface areas, but there could be induced errors in scanning and processing of the 300 plus hard copy maps.

The Lake Powell maps were hand digitized in the late 1950s, reportly at 20-foot intervals and checked by digitizing a second and sometimes a third time. The hard copy Lake Powell maps were 1:4800 scale with 10-foot contour intervals. The San Juan maps were much older and the paper quality image was poor.

These map contour surface areas were also measured by planimetering the original contours.

Using ARC GIS tools, cross sections were cut through the original digital contours and the 2004 multibeam x,y,z data set. The plotted results from these cross sections are in Appendix I. The cross sections were cut on the same alignment as the 1986 Lake Powell cross section locations. The locations were estimated using copies of the marked maps from the 1986 field collection. The 1986 study's elevations were plotted using the average bottom elevation from the 1986 Lake Powell Survey report. (Ferrari, 1988). The results from the plots showed the distribution of the sediment within Navajo Canyon with the bottom sediments fairly flat and distributed laterally across the reservoir.

The average bottom results for the original, 1986, and 2004 surveys for each cross section location was plotted longitudinally from the confluence upstream about twenty five miles to the headwater of the reservoir. The longitudinal plots show the sediment deposition from around elevation 3,510 (range line 430) and below (figure 24). Of interest is the little change, since 1986, between elevation 3,410 and 3,510. 2004 data was not collected above elevation 3,510 due to low reservoir and short daylight during the day of collection, but for computing loss due to sediment deposition in 2004 it was assumed there has been no change since 1986. The longitudinal plot showed the sediment build up since the 1986 survey. Why there is little change since 1986 at range line 427, 429, and 430 is noted, but not addressed at this time.

For the Colorado River analysis, some interesting results were answered by cutting profiles in some of the 2004 data set along the original river alignment. This approach should be completed on all of the 2004 data to better confirm the range line plots and to look for vertical wall collapses that have affected some of the sediment deposition locations. The results of the Colorado River longitudinal profile further confirm the results of the Navajo Canyon plot where it appears the sediment deposition has pushed in the lower elevations in the Colorado River channel, elevation 3,220 and above, and have protruded downstream towards the dam. The Colorado River longitudinal profile for 1986 and 2004 shows this buildup of bottom sediment from the dam upstream to Navajo Canyon and then a gradual decrease upstream of Navajo Canyon (figure 25). This appears to indicate the Navajo Canyon sediment inflows are one of the bigger contributors of the sediment deposition from the confluence downstream towards the dam. It is assumed a portion of this sediment accumulation was deposited during construction when the waters were backup by the cofferdam, but the 2004 survey also shows build up since 1986.

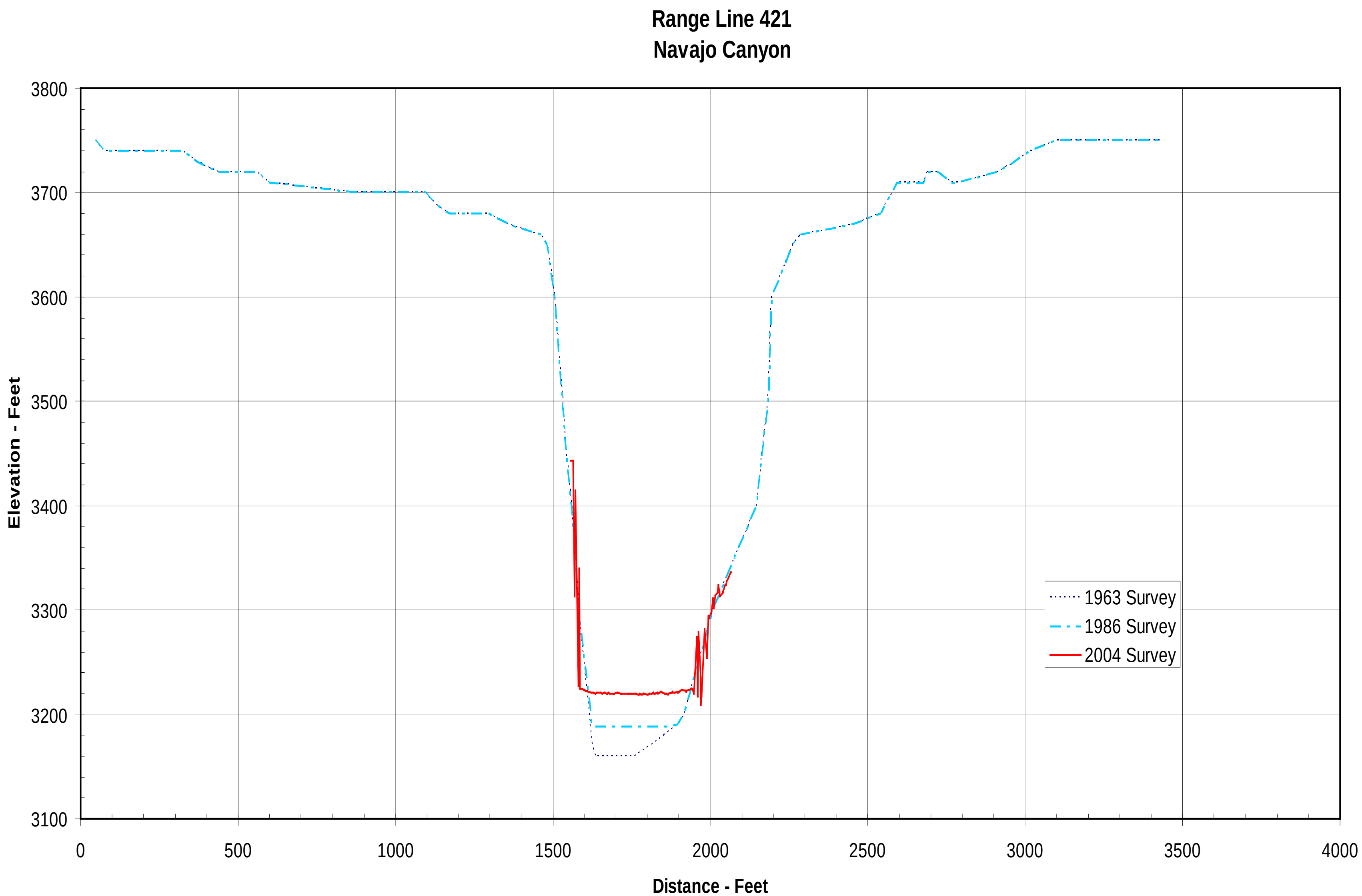

Figure 24 - Range line 422 from Navajo Canyon.

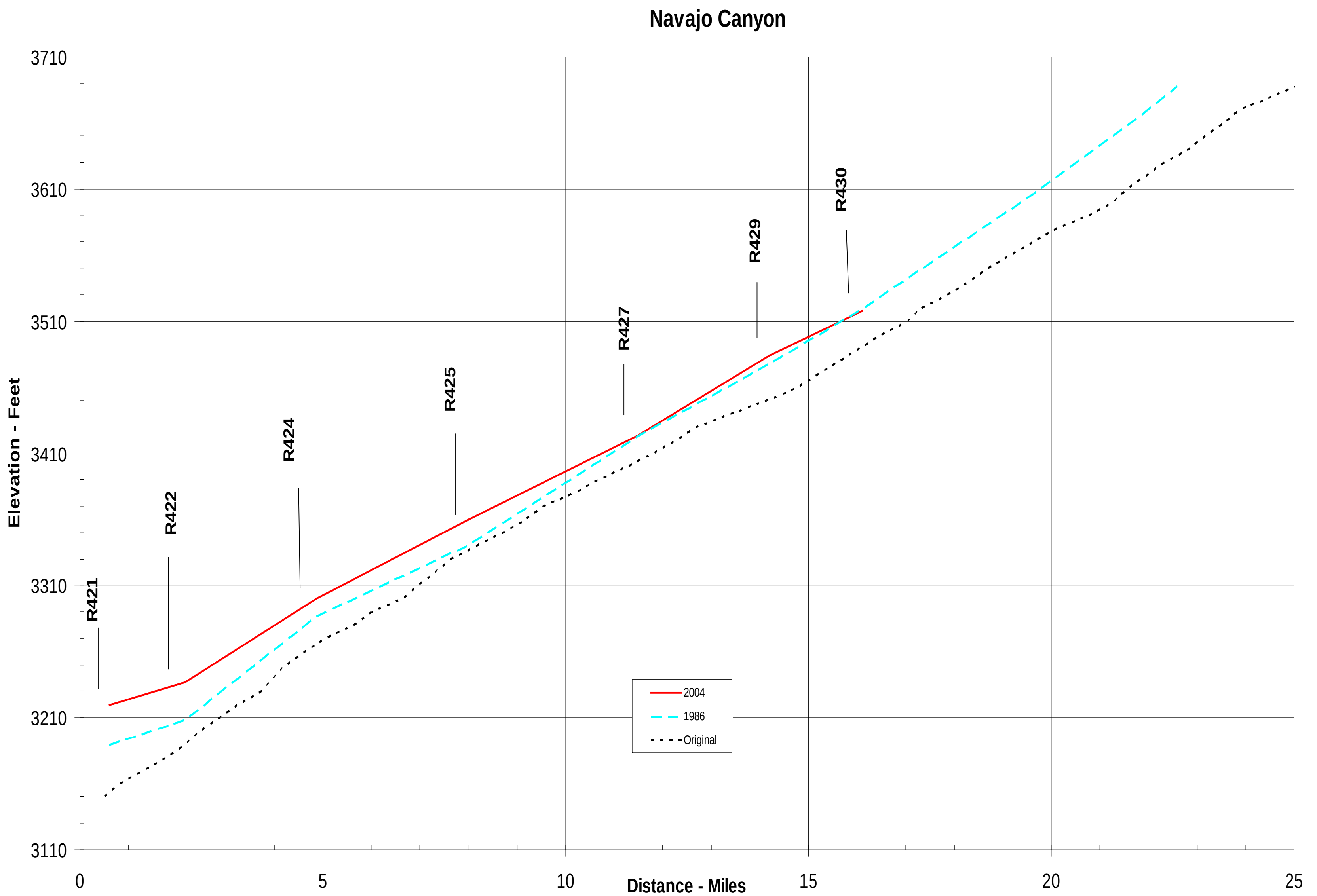

Figure 25 - Navajo Canyon longitudinal profile.

The question of how the inflowing Navajo Canyon sediments push so far downstream in the lower portions of the reservoir may be answered by studying the density currents. There are other issues to look at, such as the recent reservoir drawdown to elevation 3,570, and the steep narrow canyon walls causing higher velocity conditions pushing the sediment-laden water further downstream. The density current influence would be where one fluid flows over or under another fluid due to the density differences between the two fluids. In reservoirs, the density differences would cause warm water to flow as a surface current across the top of colder and denser water in the reservoir or the cooler inflowing turbid water plunging below the warmer reservoir surface water (figure 26) and travel across the top of the thermocline downstream (Morris and Fan). Further studies are needed to determine how the Navajo Canyon inflowing sediments push further downstream into the reservoir.

Figure 26 - Colorado River, upper Lake Powell, inflow interface.

For computing the sediment deposition in Navajo Canyon, the above listed maps that form the boundary around the canyon were used along with the cross section results to determine the 2004 surface areas at the 20-foot elevation increment for each map. As stated previously, the original surface areas for the 20-foot contour interval was digitized, listed on a spreadsheet by map, and the summation determined the total reservoir surface area by elevation. This approach was used for Navajo Canyon by summing the surface area by elevation for the maps that represented the Navajo Canyon study area. The cross section results were used to determine the 20-foot surface areas that were totally lost, by map, for the different elevation increments. ARC GIS mapping tools were used to develop a TIN and resulting contours from the 2004 multibeam bottom data. This information was used to locate the upper end of the 20-foot contours for each map. The resulting surface areas for the contours, affected by sediment deposition, were the final 2004 surface area for the map being studied. If the contour was not affected by sediment deposition, then the original surface area was used. This process was completed for the above listed maps and the summations of the surface areas, for the 20-foot contour interval, was the 2004 surface areas for Navajo Canyon. The 2004 final surface areas were the input information for computing the new capacity of the Navajo Canyon section of Lake Powell. Following are the results from the study, at elevation 3700, using all maps covering Navajo Canyon.

1963 capacity =	628,129 acre-feet
2004 capacity =	599,125 acre-feet
Total sediment	29,000 acre-feet

The results found that after 40 years of reservoir operation 29,000 acre-feet of sediment has deposited in Navajo Canyon study from the Colorado River confluence upstream. This computes to an average of 725 acre-feet of sediment per year. From the Navajo Canyon and Colorado River profiles, it appears a portion of the Navajo Canyon drainage sediments have deposited downstream of the mapped study area towards Glen Canyon Dam. The collection only went to around elevation 3,520 due to low reservoir conditions, but the upstream data still suggested sediment deposition. For this analysis, it was assumed no change of reservoir area lost, since the 1986 survey, for the area above range line 430 or elevation 3,520. It is assumed that with the low reservoir elevation, over 130 feet lower then 1986, that some of the accumulated sediment since 1986 has been eroded downstream. Nevertheless, even with the thalweg eroded; it is assumed that there would still be sediment deposition along the banks. In addition, the upper area is only a small portion of the total volume. Thus, if this assumption is not correct, the volume difference is not large.

Colorado River Analysis

The reconnaissance analysis for the Colorado River portion, from the dam to just upstream of the San Juan confluence, was conducted similar to the Navajo Canyon analysis. Using ARC GIS tools, cross sections were cut at the 1986 range line locations from range line 102 through range line 154. The cross section result of range line 102, located just upstream of Glen Canyon Dam, shows the sediment accumulation for 1986 and 2004 (figure 27). The results of the remaining cross sections are in appendix II. As with the Navajo Canyon cross sections, the plots show the distribution of the sediment fairly flat and distributed laterally across the reservoir. In viewing the cross sections one will see that for some the 2004 data only covers a portion of the reservoir bottom. Due to time constraints, only one multibeam profile was run from Navajo Canyon confluence to the Dangling Rope area, Range Line 112 through 134. Even though the whole bottom was not covered, this collection showed that for these area two collection profiles is adequate for full bottom mapping. This was further verified during the 2005 collection (Clarke Hughes, 2005). Ideally, one would like more profiles for verification, but due to the depths and flat bottom conditions, one or two profiles are more than adequate. This principle also applies to each of the tributaries to be surveyed. Since the boat must return to the confluence, two profiles can and should be collected, and due to the pattern of sediment deposition, the two profiles are more than adequate for bottom mapping of Lake Powell at this time in the deeper zones. More profiles maybe need in the upper shallow water reaches where the sediment deltas have formed.

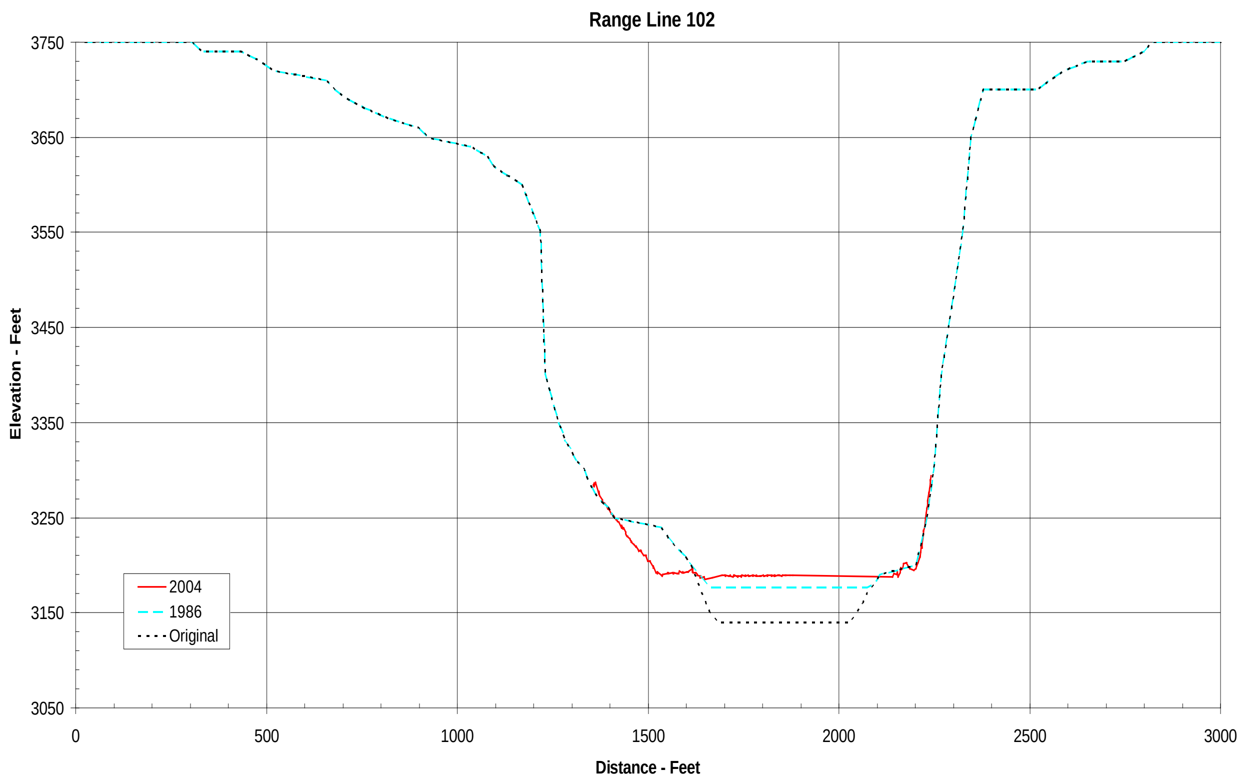

Figure 27 - Range line 102.

As noted previously, the Colorado River profile data was collected during several periods using different methods of positioning. During October 2004, a portion of the thalweg was collected using RTK GPS for positioning the boat (centimeter accuracy). During the December collection, the area from Antelope Marine to Dangling Rope Marina was collected using absolute positioning or no differential corrections to the rover satellite signal (accuracies of ± 8 meters or less). From Dangling Rope to the upper portion of the San Juan River a differential GPS method was utilized with submeter accuracy using a correction signal obtained from a commercial service that transmits the signal from a stationary satellite. From all indication during the collection, the commercial differential signal was obtain throughout the collection even in the steeper canyon wall conditions that exist throughout Lake Powell. The multibeam system made this possible as the survey vessel tended to stay more near the center of the reservoir channel with a clear view of the sky and satellites.

The Sedimentation Group's goal for all surveys is to collect the most accurate data possible within a reasonable budget. From the results of the Lake Powell and Lake Mead collections, it appears any of the GPS methods will adequately map the bottom sediments in the original river channel alignment. As long as the study is only looking at change to the original digital contours due the flat lying sediments absolute GPS position solutions can be adequate, but if full bottom mapping or more accurate location of features is needed then much higher GPS position solutions are necessary. It is recommended that the differential positioning method be used via commercial or governmental broadcast, but there will be areas these signals cannot be obtained. During the 2005 Clarke survey, the differential broadcast signal was lost at times and there were times absolute GPS solutions were not possible due to the steep vertical wall conditions blocking the differential and satellite signals. During the 2004 survey, the upper San Juan arm the view of the sky provided the necessary satellites. Since both the 2004 and 2005 surveys were mainly focused on the flat lying sediments in relation to the original digital contours, the areas missed due to lack of GPS positions can be interpolated.

The average Colorado River profile bottom results for the original, 1986, and 2004 surveys for each cross section location was plotted longitudinally from the dam upstream to over 180 river miles upstream to the headwaters of the reservoir (figure 28). This 2004 plot ends just upstream of the San Juan River confluence where data collection ended. The 1986 plot versus the original bottom illustrates the upstream sediment deposition that is very typical for this type of reservoir configuration and operation. The 2005 Clarke multibeam survey mapped to just below Hite Marina. The survey was limited to this area as the lake level was around 3,570. It is proposed to analyses the 2005 data similar to the process using the 2004 data to complete the longitudinal profile to elevation 3,570. Using results from previous studies, such as the 1963-64, and 2001 Lake Mead surveys, judgments can be made for extending the profile beyond the available 2005 data. From this, an updated volume could be computed for the Colorado River portion of the reservoir. The Colorado River longitudinal was plotted, figure 29, showing only the area from the dam upstream to Escalante River confluence. This provides a magnified view of the section of the Colorado River arm that was surveyed in 2004.

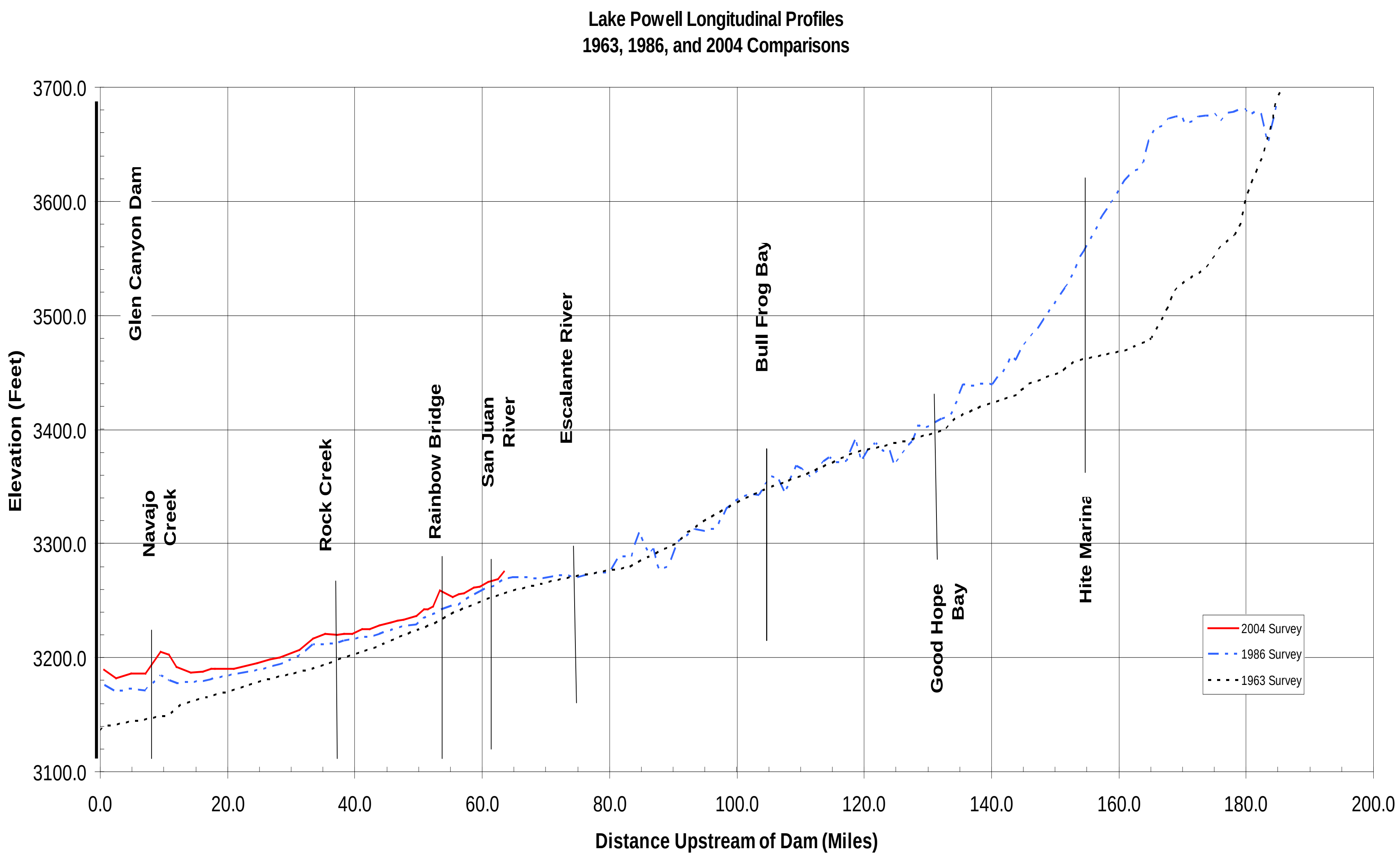

Figure 28 - Colorado River longitudinal profile, complete.

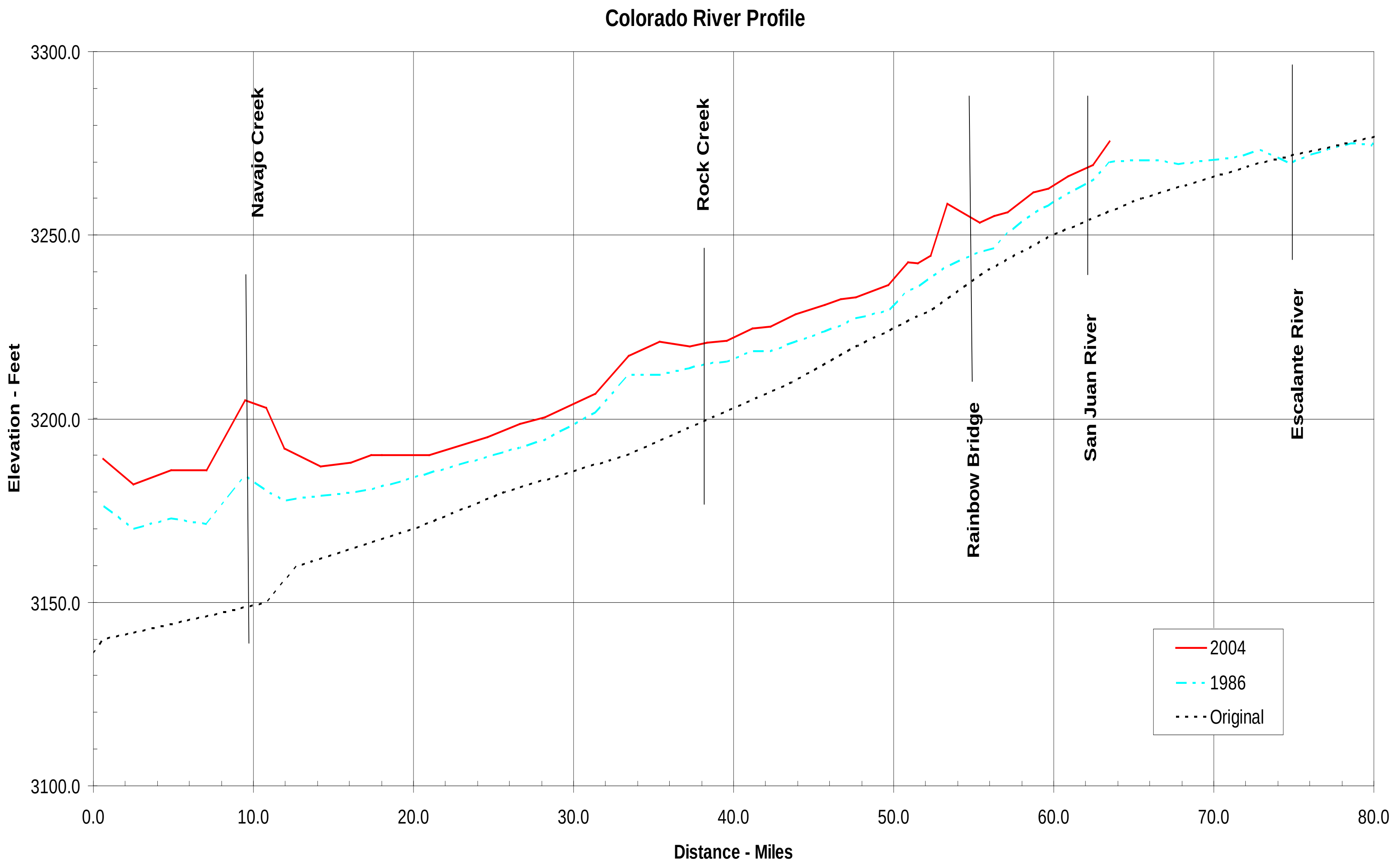

Figure 29 - Colorado River longitudinal profile, partial.

The Colorado River longitudinal plots show a similar pattern between the 1986 and 2004 thalweg plots that at times appear to be parallel to each other. Viewing the range line plots showed the measured sediments lying very flat from bank to bank while the longitudinal profile plot shows some peaks and valleys. A more detailed view of this could be obtained by cutting more cross sections or developing a routine to plot the average bottom of the thalweg upstream. Some of the peak and valleys of the longitudinal plotted profile can be explained by looking at the locations of the numerous tributaries and the results from the 1986 survey. At mile 10, the profile shows a major build up that gradually tapers off. The survey of Navajo Canyon in 1986 and 2004 showed that Navajo Canyon sediments have encroached in the lower elevation range all the way to the confluence. The next tributary upstream is Warm Springs and the 1986 study showed little to no sediment accumulation on the Warm Springs profile plot meaning little deposition at confluence is attributed to the Warm Springs drainage. Further analysis of the Colorado River Profile plot could be used to determine what tributaries should be surveyed in the future if a partial resurvey of Lake Powell is conducted due to time and limited budget. This information, combined with the 1986-plotted results, would provide enough data for identifying tributaries that provide sufficient sediment inflow that warrants monitoring.

The 2004 longitudinal profile shows a spike just downstream of Rainbow Bridge that was looked at further as part of this analysis. This spike elevation was from the 2004 data collected at range line 142 with average bottom elevations much higher than what would be predicted from the 1986 results. The 1986 longitudinal plot of Rainbow Bridge tributary showed some sediment accumulation but nothing to explain such a large build up at range line 142. Using ARC GIS tools, a cross section was cut through the 2004 multibeam data starting downstream of range line 142 alignments to just upstream (figure 30). The profile shows the buildup is localized and more than likely is due to material deposited from a possible vertical wall collapse. If the 1986 and 2004 range lines were the same alignment, it would suggest this collapse occurred since 1986. Over the years, this plug will cause the bottom sediments to build up behind it until they eventually push over the top and beyond. Future surveys could better confirm this theory by collecting more detailed information upstream and downstream of this location and up the different tributaries in the surrounding area. During the 2005 Clarke survey there where other areas noted where material plugs existed in the original river channel alignment. One area was in the Escalante River tributary. These plugs can be created by different means, such as tributary deposition (such as Navajo Canyon) vertical wall collapses, or preexisting restrictions that would have been locations of rapids prior to creation of Lake Powell.

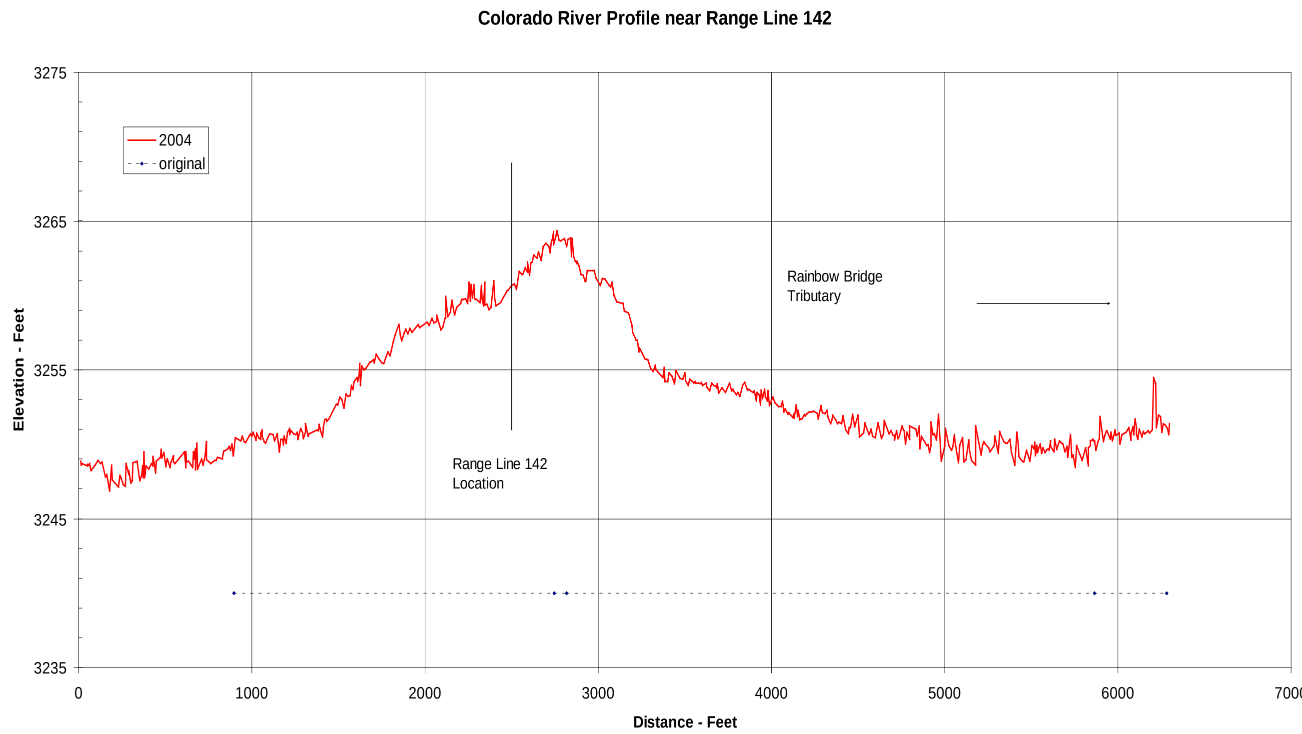

Figure 30 - Colorado River thalweg near range line 142.

San Juan River Analyses

The multibeam collection system was used to collect San Juan River bottom data from the confluence to the upper end of the reservoir that was accessible with the survey vessel. The commercially provided differential signal was utilized with good success throughout this area. Once in the shallow water conditions (less than 30 feet) the multibeam transducer head was tilted 30 degrees to the starboard side of the boat to allow more coverage in the shallow water conditions. There were some problems encountered working in the upper end that has been attributed to suspended sediments from the recent increased inflows from the San Juan River, but the cross sections in the very upper end more than likely are providing higher sediment elevations than actually exist. This also caused a major problem in attempting to obtain bathymetric data using the airborne LiDAR system where the visibility was less than ideal. For the multibeam collection, the problem appeared to be that with the settings on the high frequency multibeam system the depth hits were off the top of the fluff at times. This provided uneven hits and false readings of the actual bottom. Cross sections and longitudinal profiles were developed using the same techniques as Navajo Canyon and the Colorado River, but the cross sections in the very upper end more than likely are providing higher sediment elevation levels than actually exist . The resulting cross section plots are in Appendix III. Only San Juan longitudinal plots were developed due to time and budget limitations (figure 31 and 31).

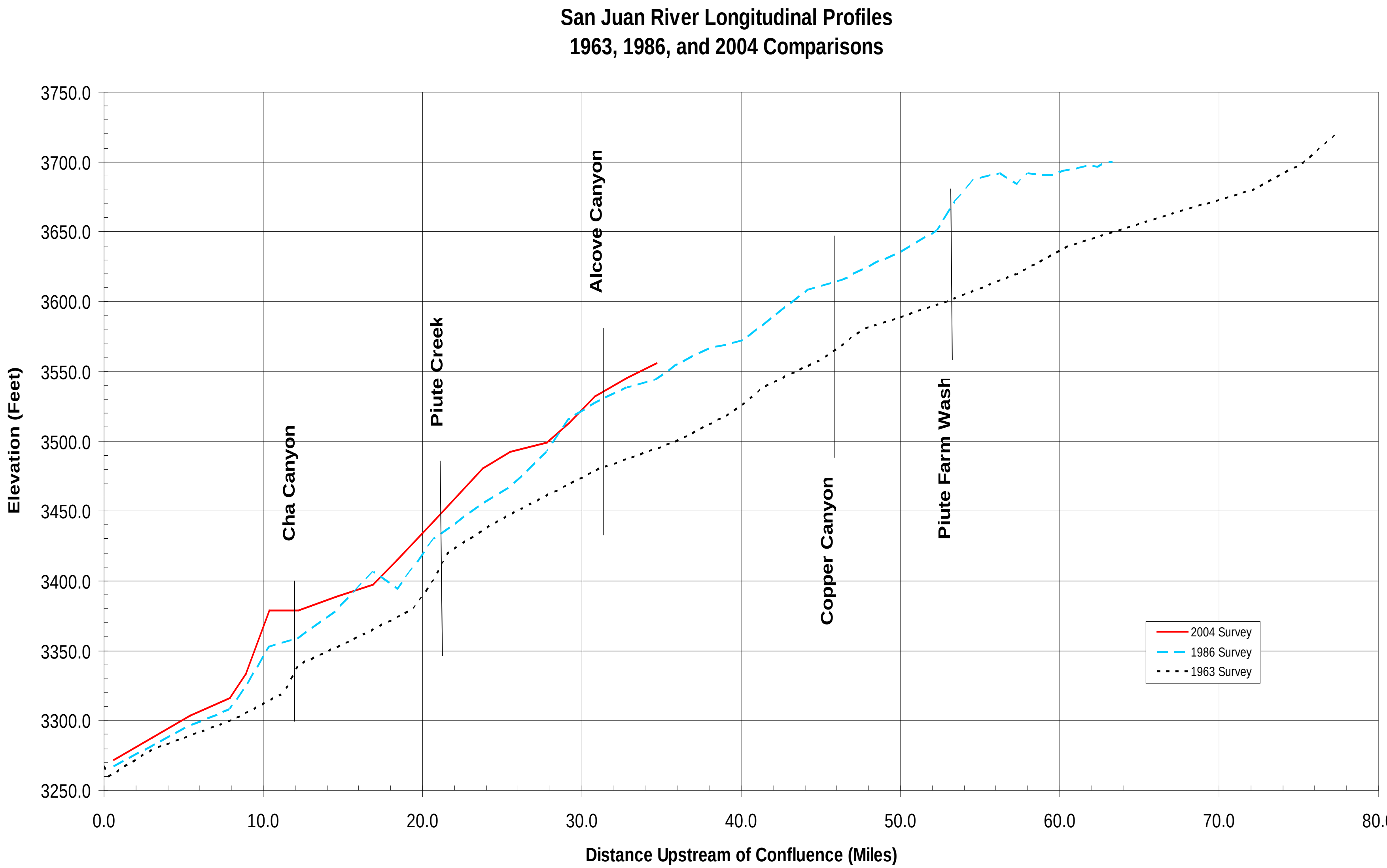

Figure 31 - San Juan River longitudinal profile, complete.

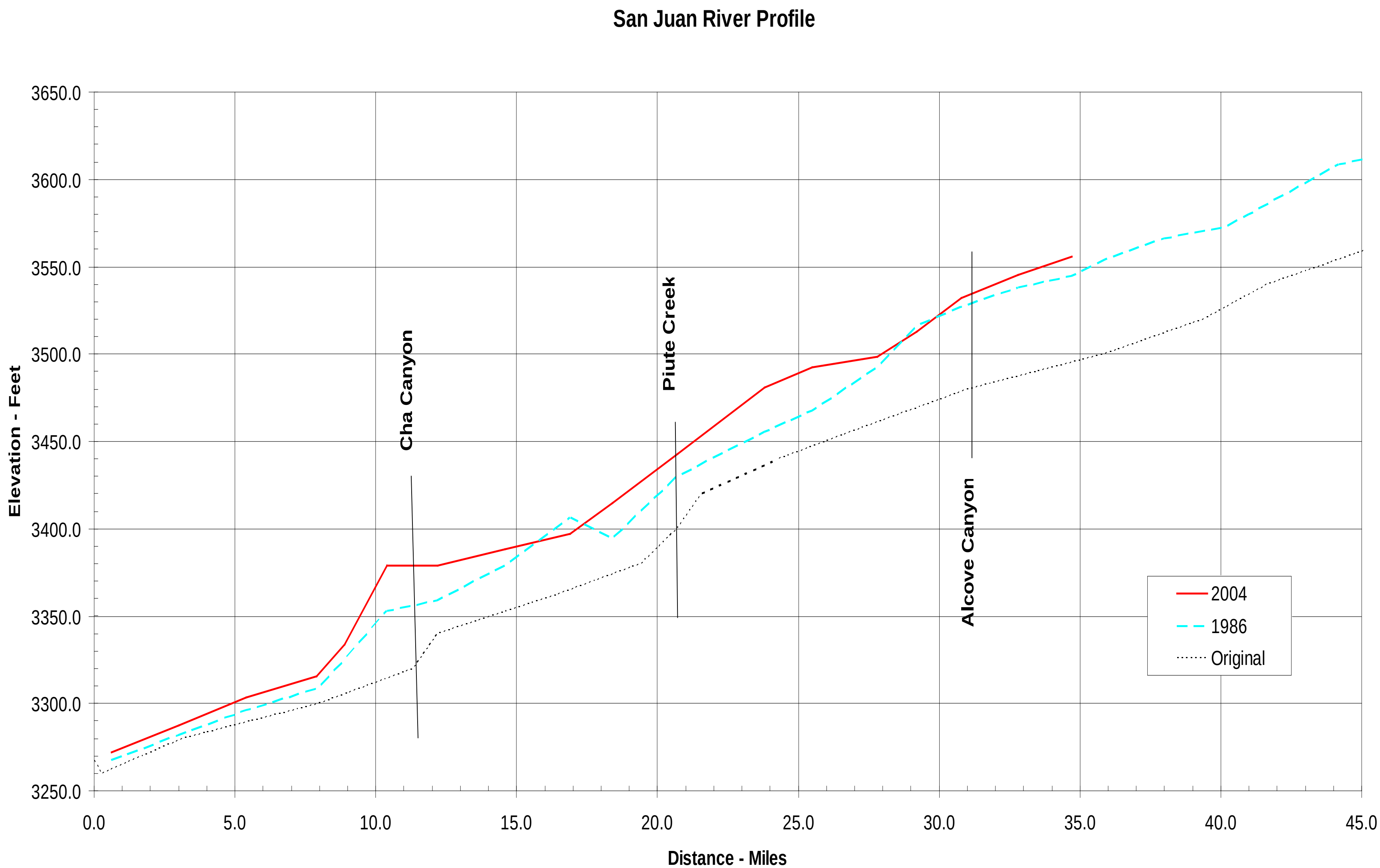

Figure 32 - San Juan River longitudinal profile, partial.

Summary and Conclusions

The Reclamation's Sedimentation Group has been involved with several collection efforts on Lake Powell since the 1986 sedimentation survey. This included the first known multibeam survey in October 2004 that started at Glen Canyon Dam and mapped upstream to the Colorado River confluence with the San Juan River and upstream to the upper reach of the San Juan. This data was evaluated for monitoring sediment accumulation for the portions of Lake Powell covered by the survey vessel in 2004 and is presented in this report as a method of collection and analysis for updating the area and capacity tables for Lake Powell.

This method, title "Reconnaissance Technique," utilizes the latest collection and analysis technology and applies streamline collection and analysis procedures to produce a quality product in a timely and cost-effective matter. The ever-evolving technology has drastically changed the method of collection and analysis for reservoir surveys. The high-speed computers, GPS, and multibeam depth sounders have dramatically reduced the time of collection while increasing the accuracy. Even with that, the ever-shrinking budgets for these types of studies makes for the need to adjust the full coverage capability of these technologies. Presented are partial survey methods that provide valid data for computing up to date accurate results concerning Reclamation's water resources. The presented reconnaissance techniques can be applied to Reclamation water bodies such as Lake Mead and Lake Powell, and possibly Yellowtail, Lake Roosevelt, and others to compute present capacity and sediment inflow rates in a timely and cost-effective matter.

The Reconnaissance Technique could be applied to the existing data from the 2001 Lake Mead survey and the 2004-2005 Lake Powell surveys. The approach was initiated for the 2001 Lake Mead data, but budget and time limitation ended the effort. Presented in this report is a start to end reconnaissance technique approach that was applied to the Navajo Canyon arm on Lake Powell resulting in updated area – capacity values and sediment yield rates. The 2004 data on Colorado River and San Juan River portions of Lake Powell was only processed to develop the cross sections and thalweg profiles. This data and resulting images could be used to update the area and capacity for the areas covered.

In May of 2005, the Sedimentation Group participated with the NPS and the New Brunswick University on a Lake Powell multibeam survey that collected a continues bottom profile from Glen Canyon Dam to the headwaters on the San Juan and Colorado River. Multibeam data was also collected on several of the tributaries such as the Escalante. Part of the reason for this collection effort is ongoing research into the density current effects on Lake Powell and other reservoirs. Over the years there have been several studies on Lake Powell, including some that included the Sedimentation Group as a participant. It is the recommendation of this author that Reclamation become more involved with these efforts including budgetary assistance and research participation. Water bodies such as Lake Mead and Lake Powell appeal to the public and research committee due to their size and world recognition. Reclamation involvement in a budgetary and participation effort with these research efforts allows exchanges of collection and analysis techniques along with data that would be more costly and less likely to be obtained by Reclamation alone. The knowledge and data gained as a participant are of great value on these reservoirs. In addition, the knowledge gained from these research efforts can be applied to the numerous Reclamation reservoirs being studied and monitored for sedimentation impacts.

New Brunswick University has been willing to share their collected data with Reclamation's Sedimentation Group once the raw data are processed. It is recommended that these data be analyzed using the presented Reconnaissance Techniques for updating the change in reservoir volume since Glen Canyon Dam closure and the 1986 survey. Since Lake Powell was so low, the data ends about elevation 3,570, but with assumptions, this information could be extrapolated for determining loss due to sediment and computing present reservoir capacity. The profiles up the San Juan and Colorado River reaches can also be used to determine what tributaries should be collected during future field collections. Ideally, the collection should be scheduled when the reservoir is nearly full, but that could take years to occur. There have been discussions of future research trips on Lake Powell and maybe those trips might occur as the reservoir begins to rise again. Besides obtaining information on the portions of the reservoir not covered due to low reservoir content, future surveys would provide data on the pivot point and slope of the upper delta that will provide a better understanding of what to expect in the future.

The Sedimentation Group is providing the Reconnaissance Techniques as a means of streamlining the collection and analysis process for hydrographic surveying. This is not a recommendation as the typical method of collection and analysis. Ideally, the best method would be to have full reservoir are coverage using both aerial and underwater technology, but budgets and limitations in the technologies affect this approach. The airborne LiDAR collection of bathymetry would be an idea means to collect data on Lake Powell if water clarity were not an issue and if detailed above water data are collected. In theory, if the LiDAR could collect data in the upper 30 to 100 feet of depth, a multibeam collection system could be used to fill in the rest of the reservoir area. During the 2004 and 2005 multibeam surveys, problems were encountered when the system was attempting to acquire data on both the vertical wall and deep-water flat bottom of Lake Powell. Changes in collection techniques and the system used might be able to resolve this issue, but since the main objectives of these surveys were of the sediment deposition in deep canyon areas, a great deal of time was not spent attempting to try different methods of collection.

It is anticipated that presently unknown issues will need to be resolved during the analysis process, but it is the general conclusion that the presented reconnaissance techniques for collection and analysis would provide valid results for monitoring the sediment inflow trends and computing present reservoir capacity.

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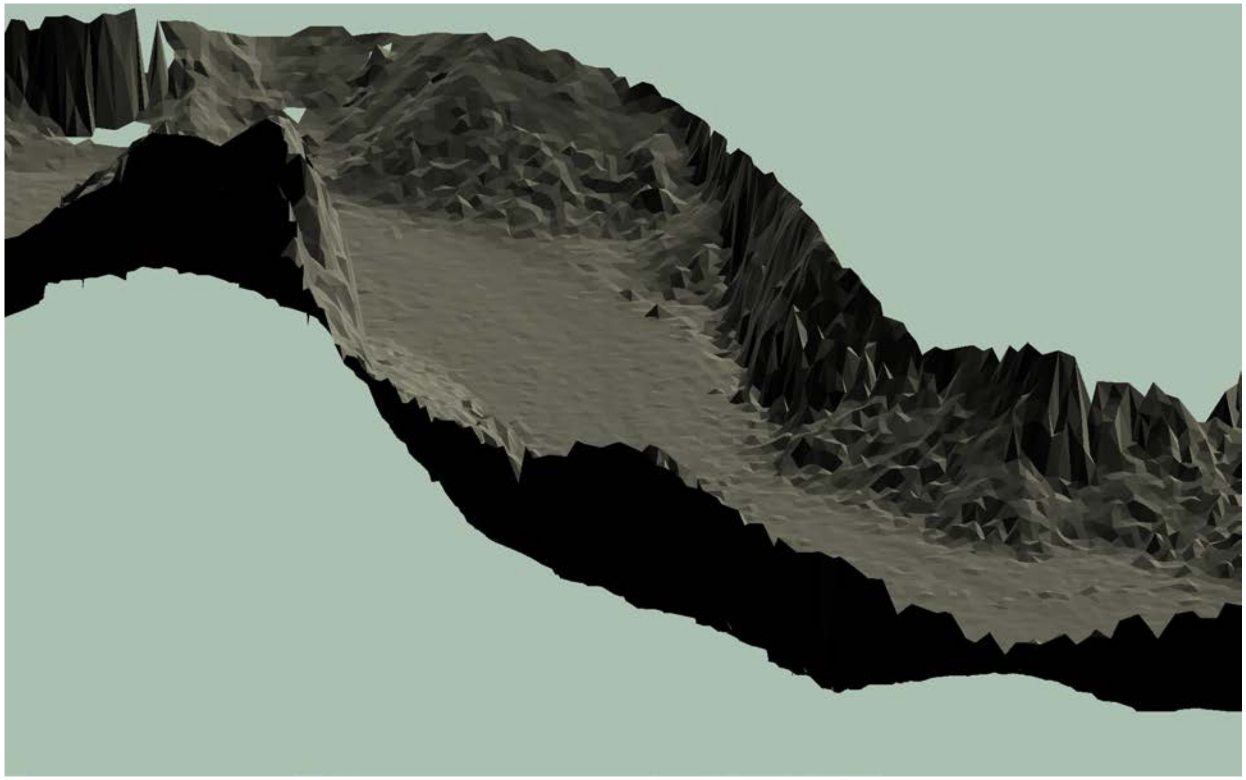
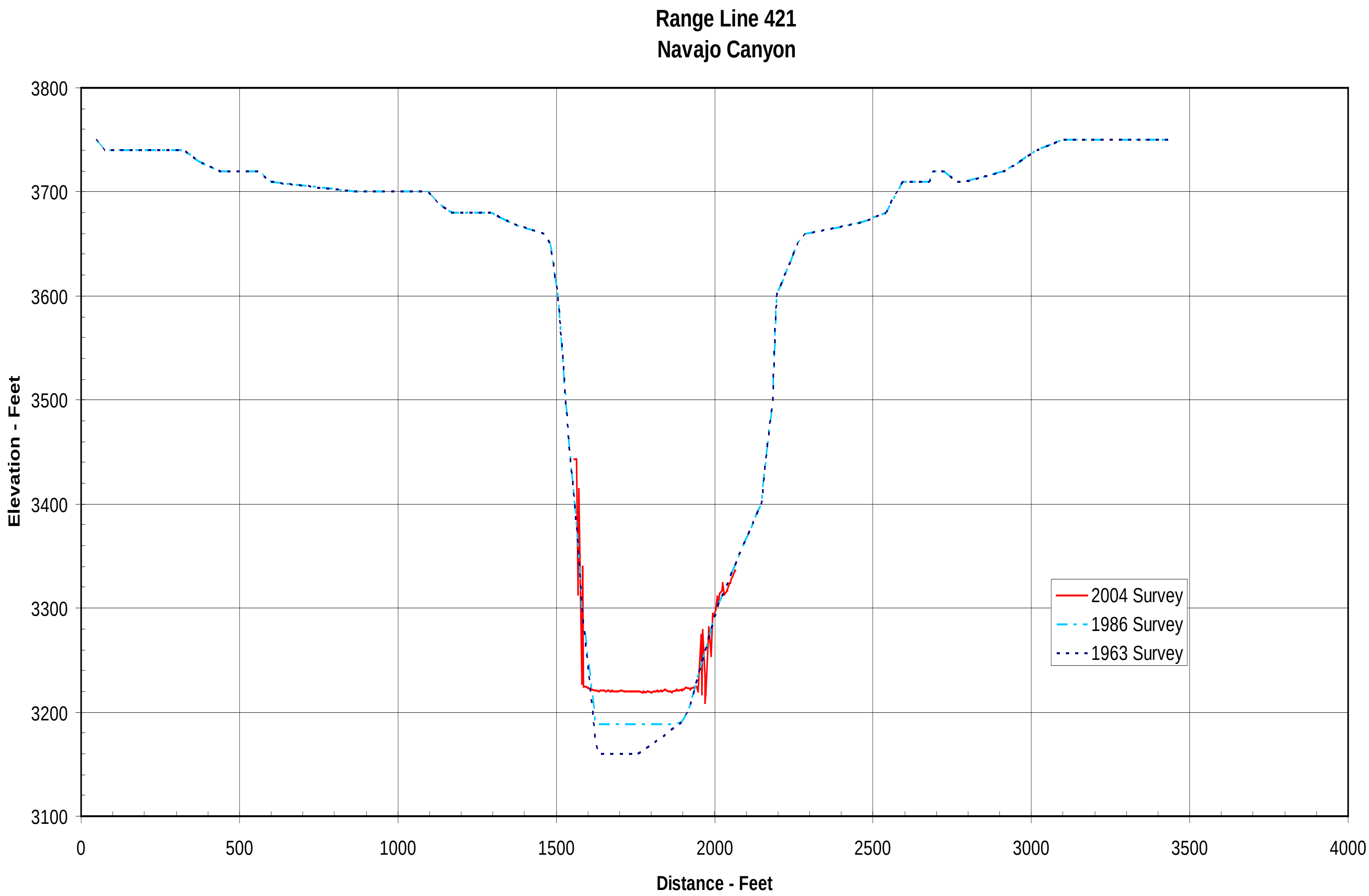


Appendix I --

Navajo Canyon Range Line Plots



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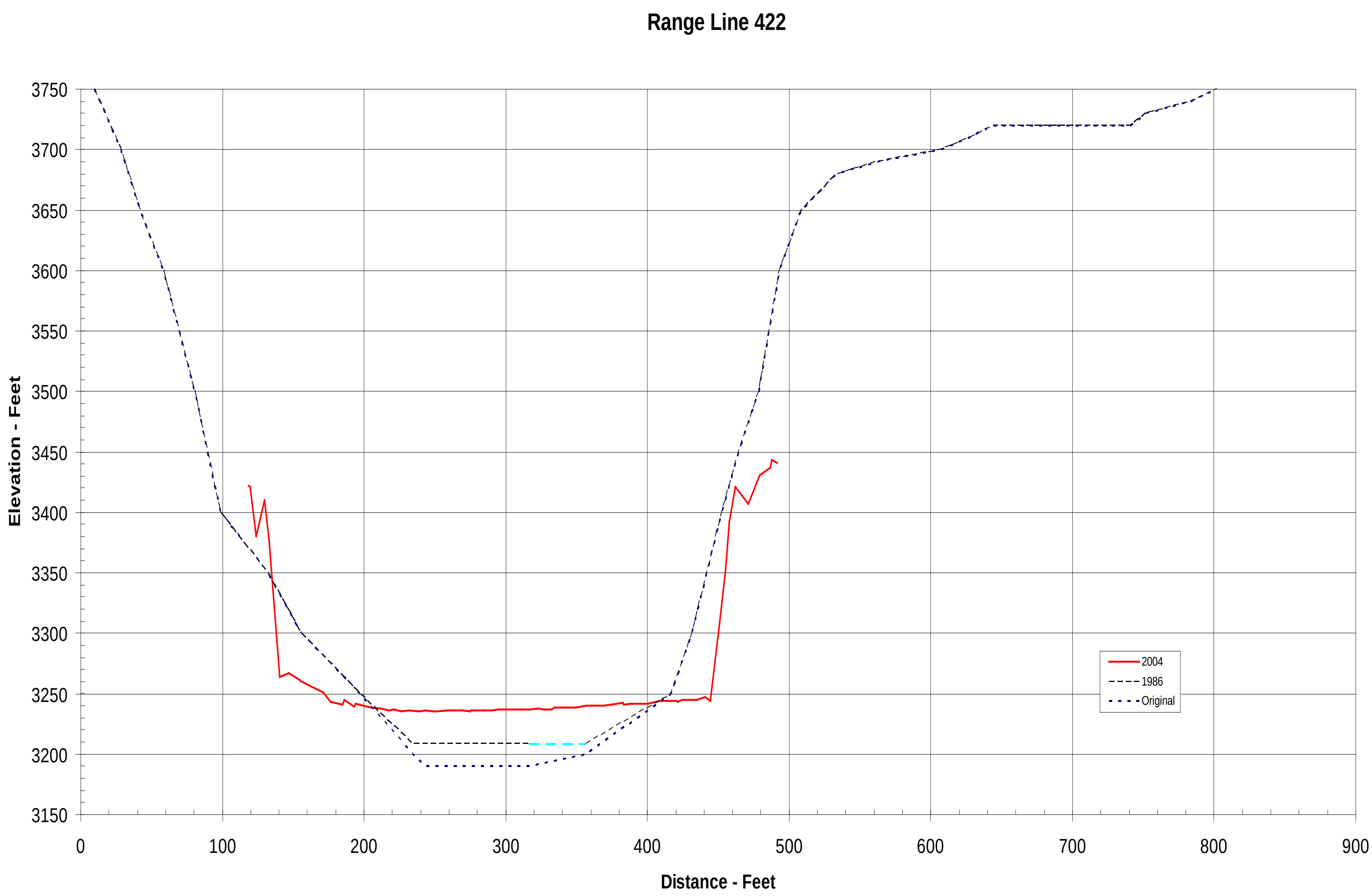
3500
4000
Distance - Feet
2004 Survey
1986 Survey
1963 Survey



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700
800
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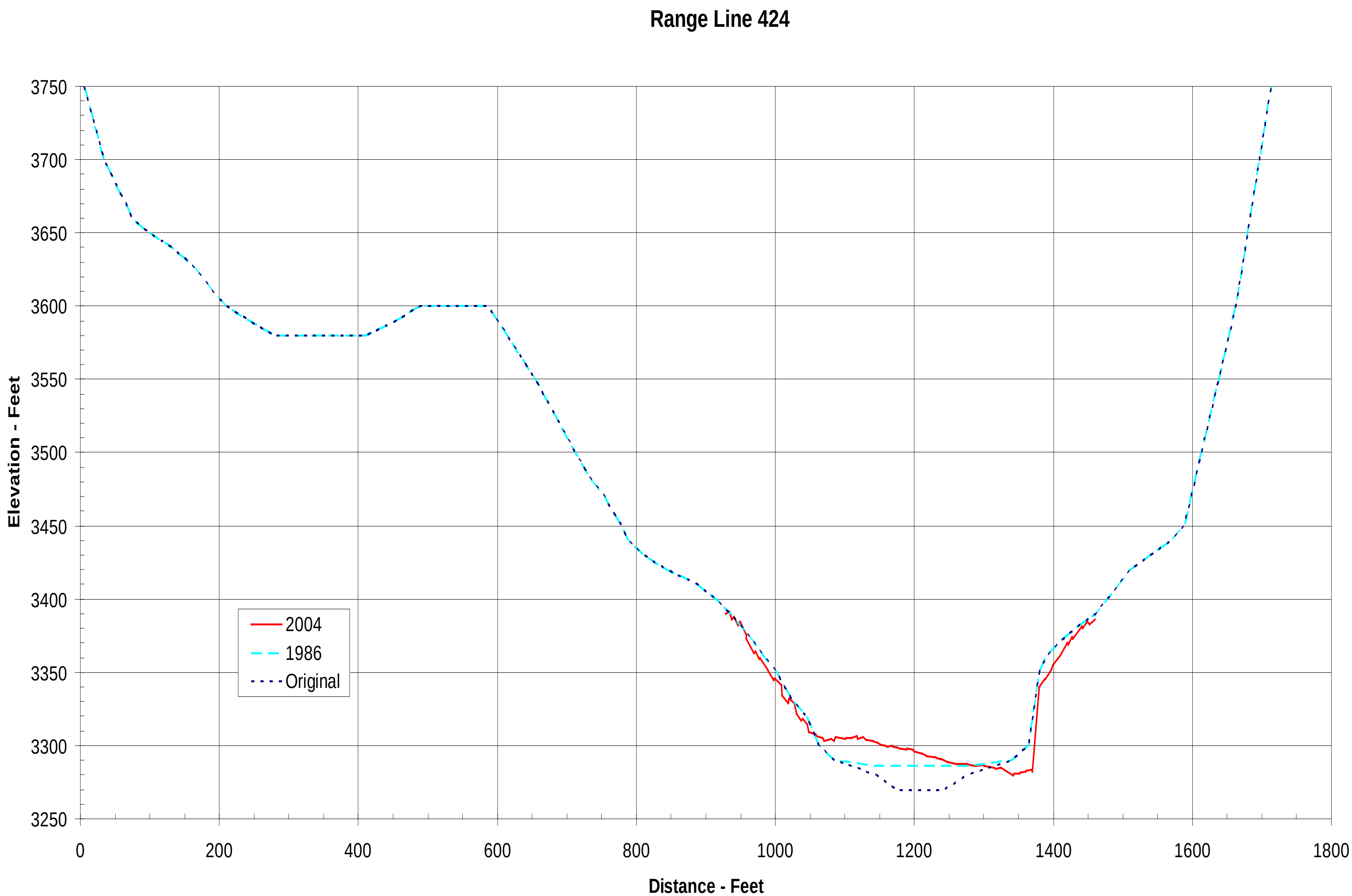
Distance - Feet
2004
1986
Original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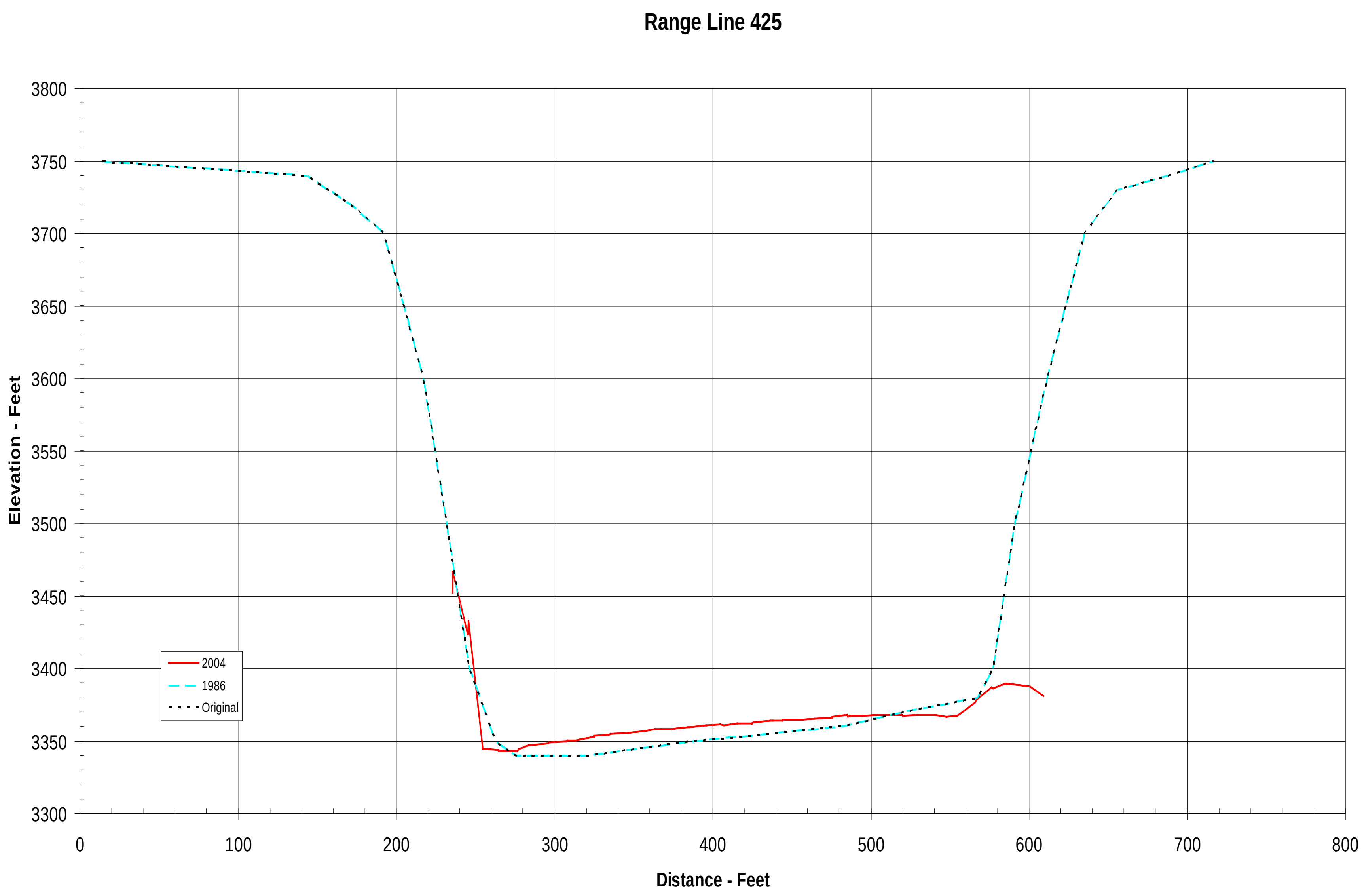
Distance - Feet
2004
1986
Original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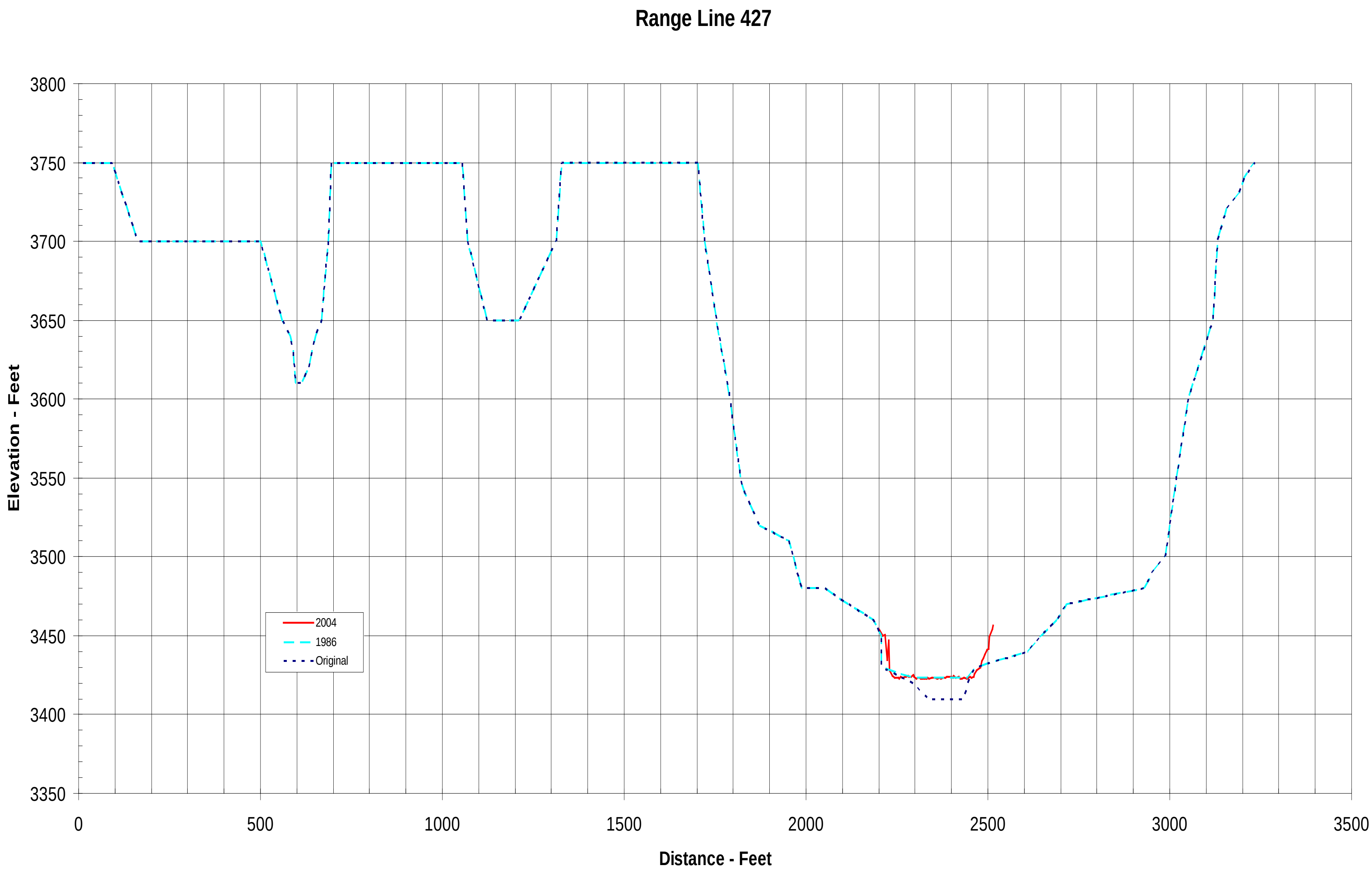

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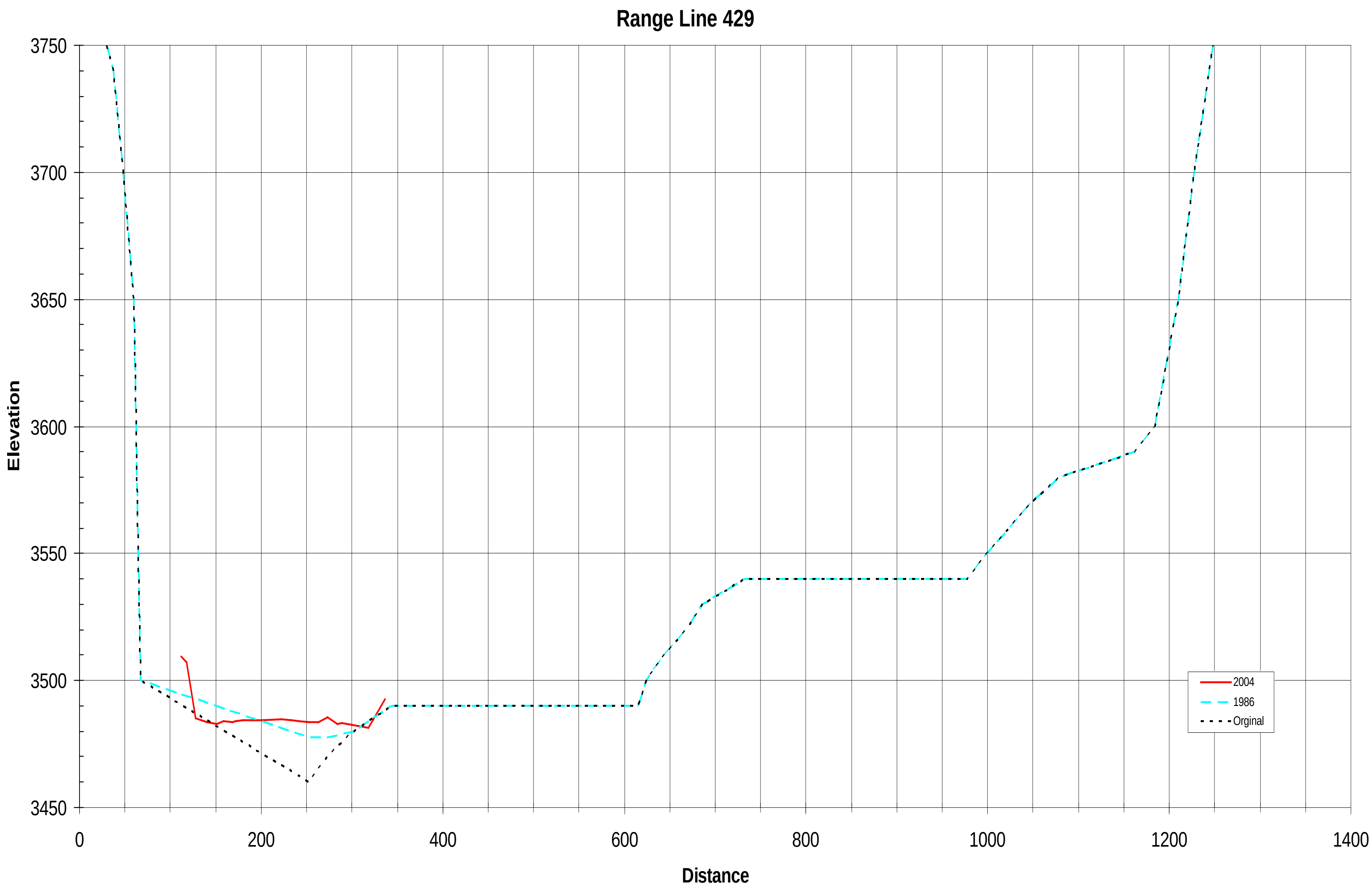
1986
Original



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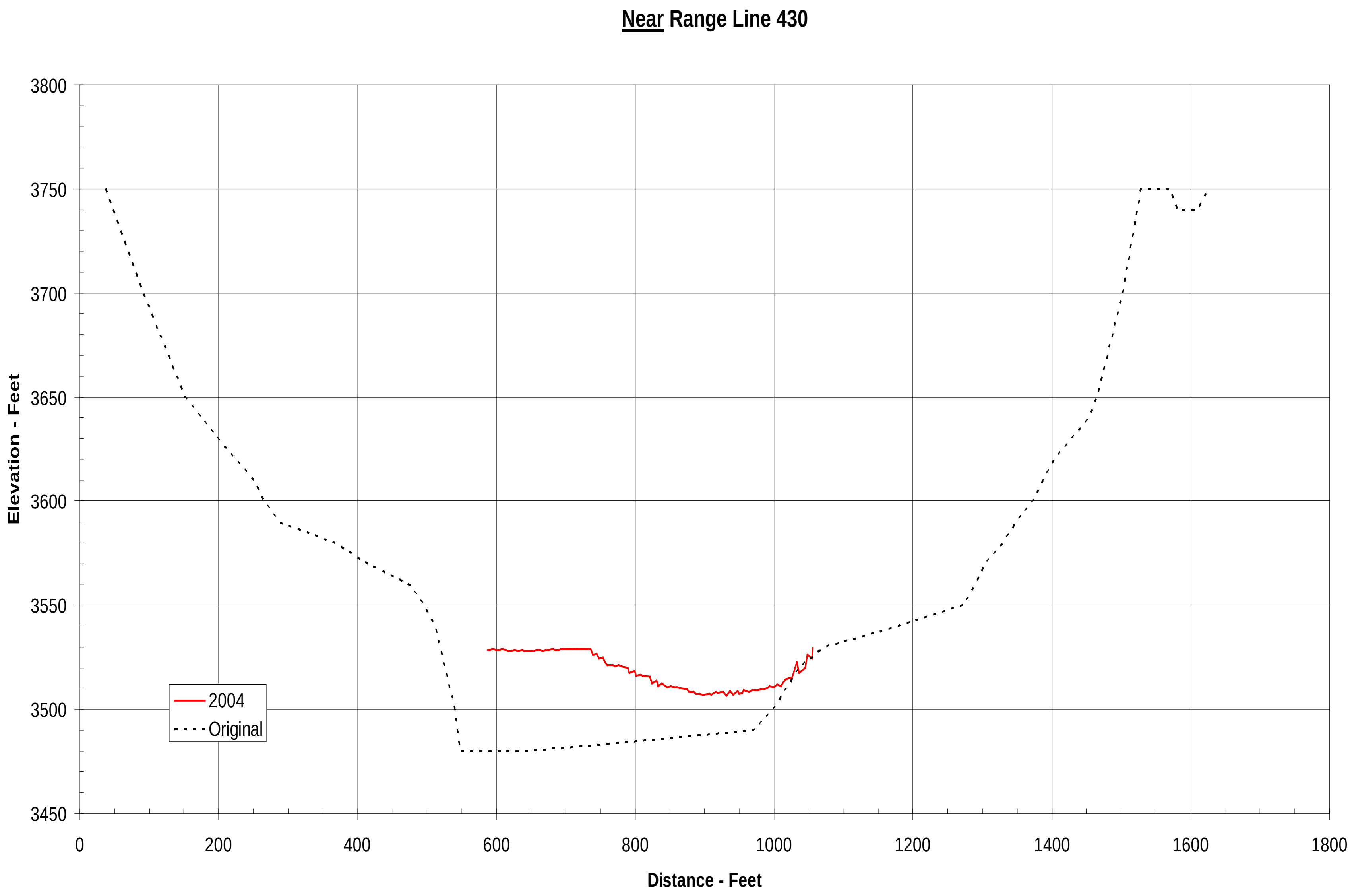
Distance
2004
1986
Orginal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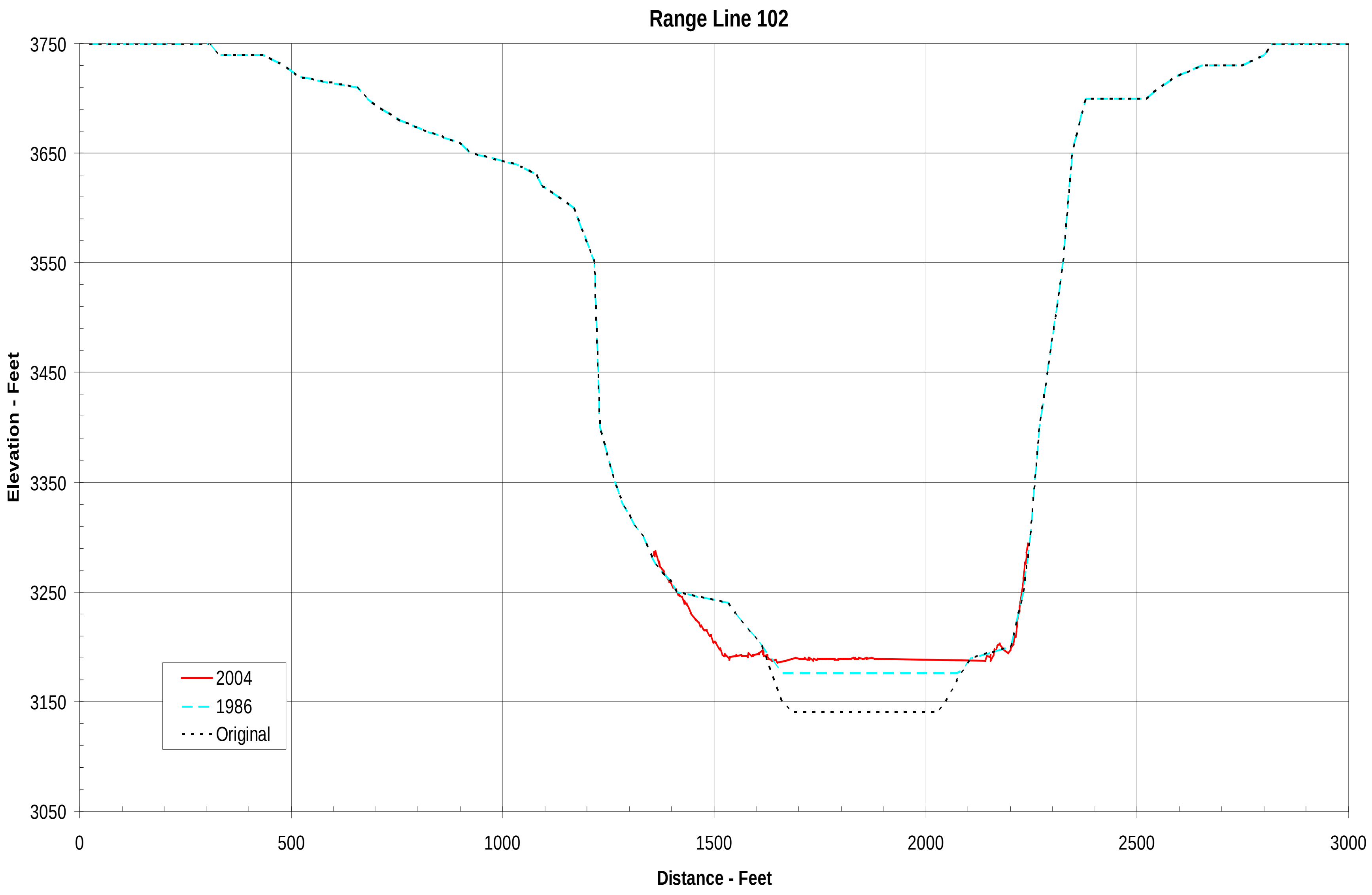
2004
Original

Appendix II --

Colorado River Range Line Plots



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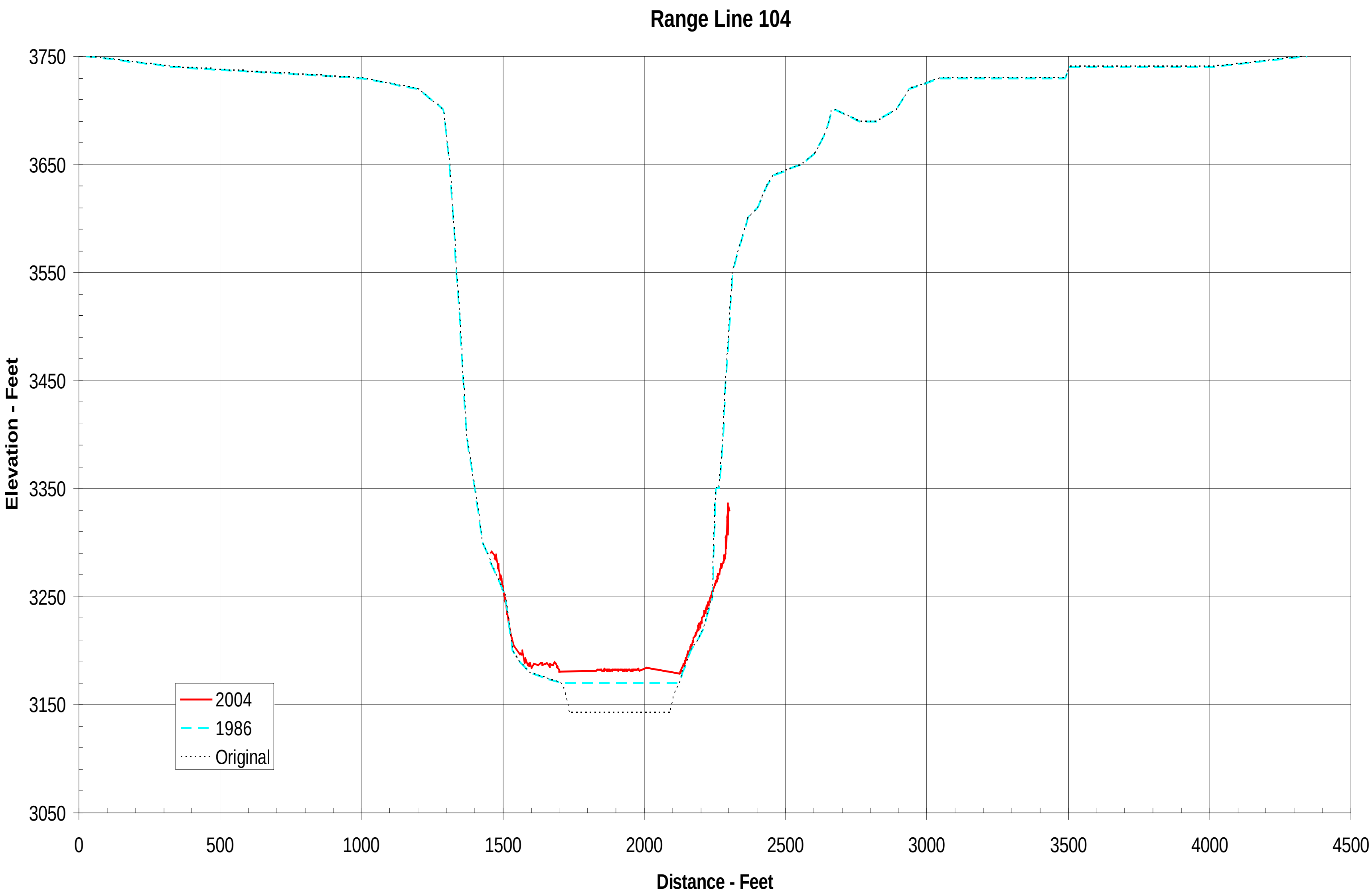
1986
Original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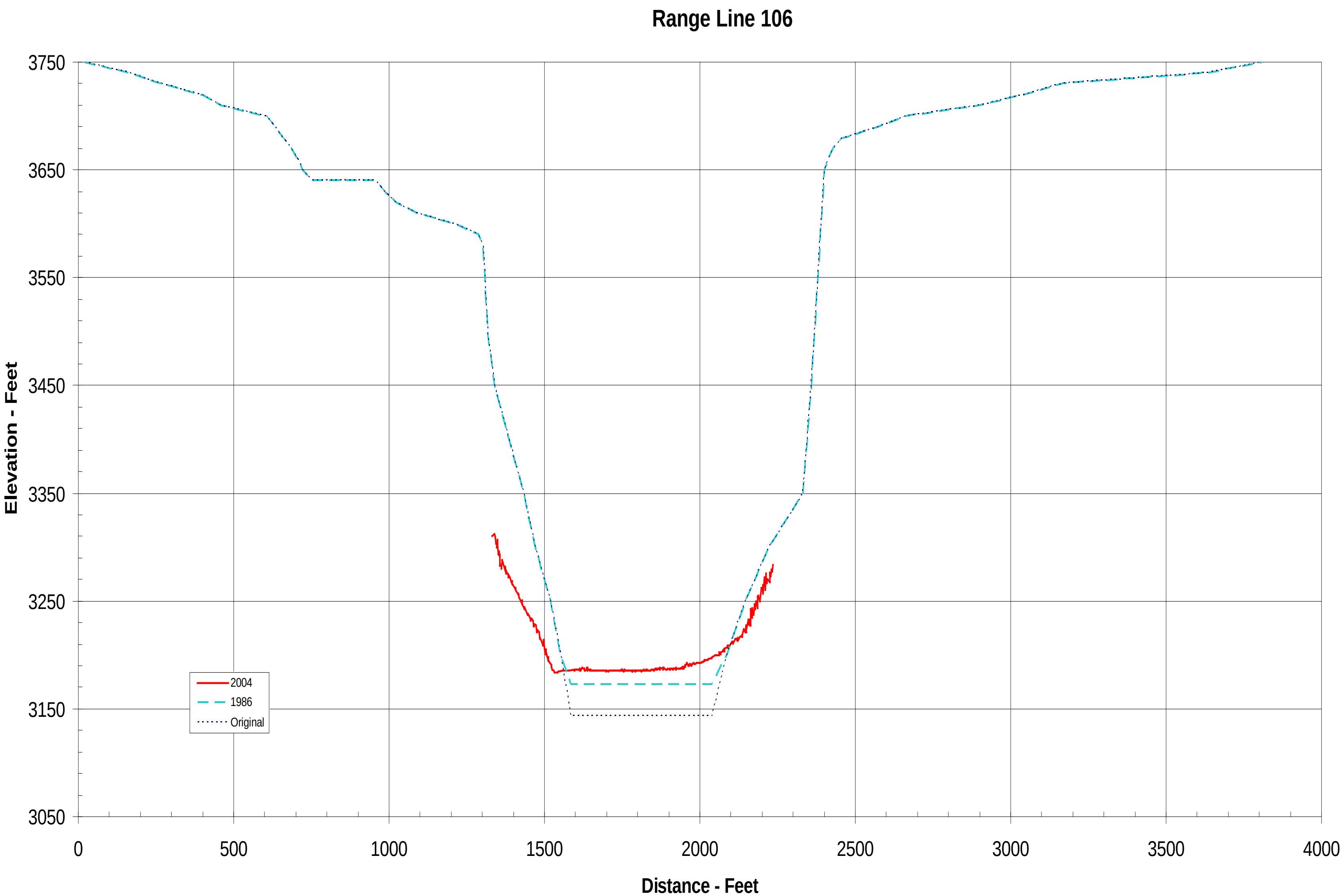
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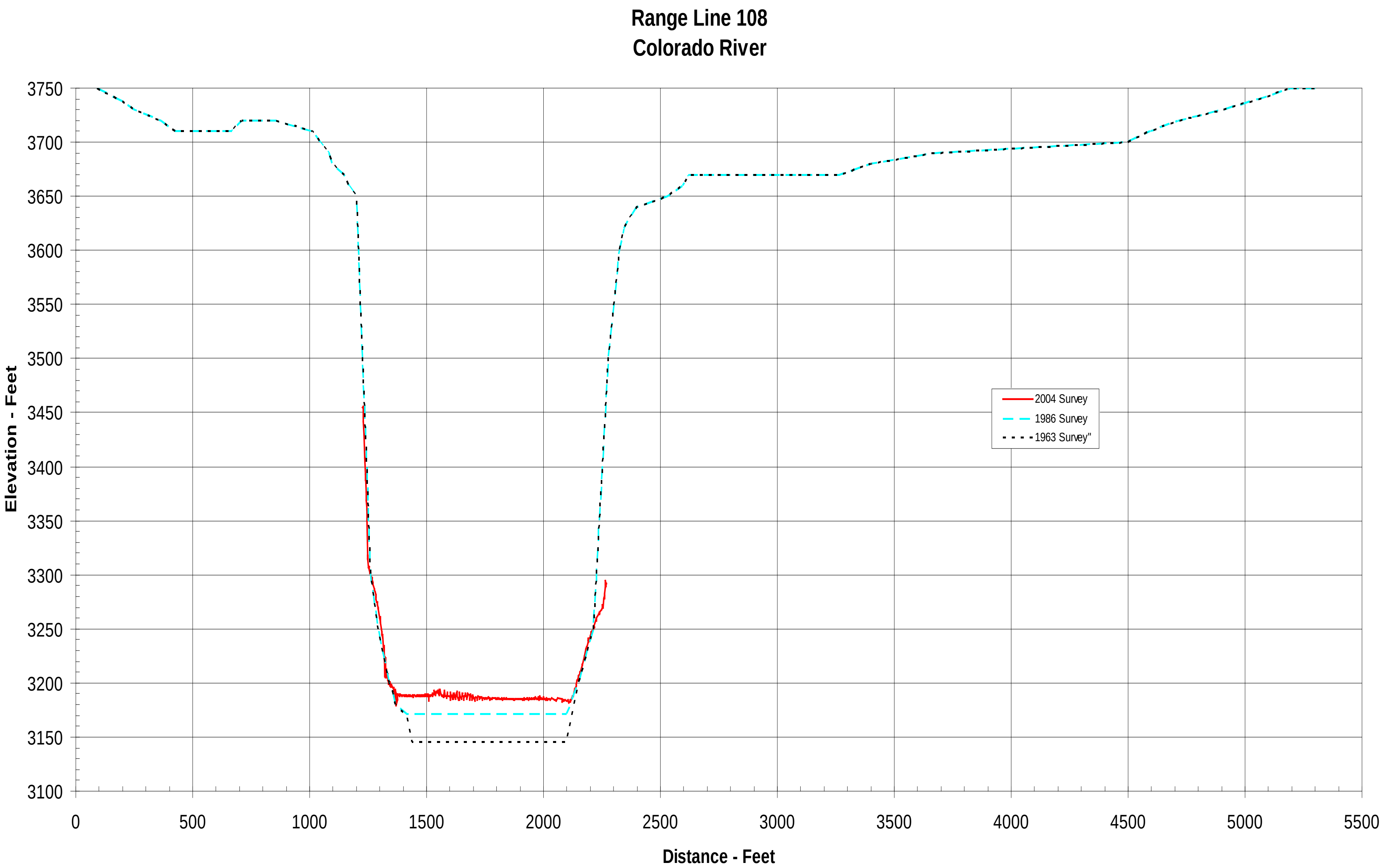
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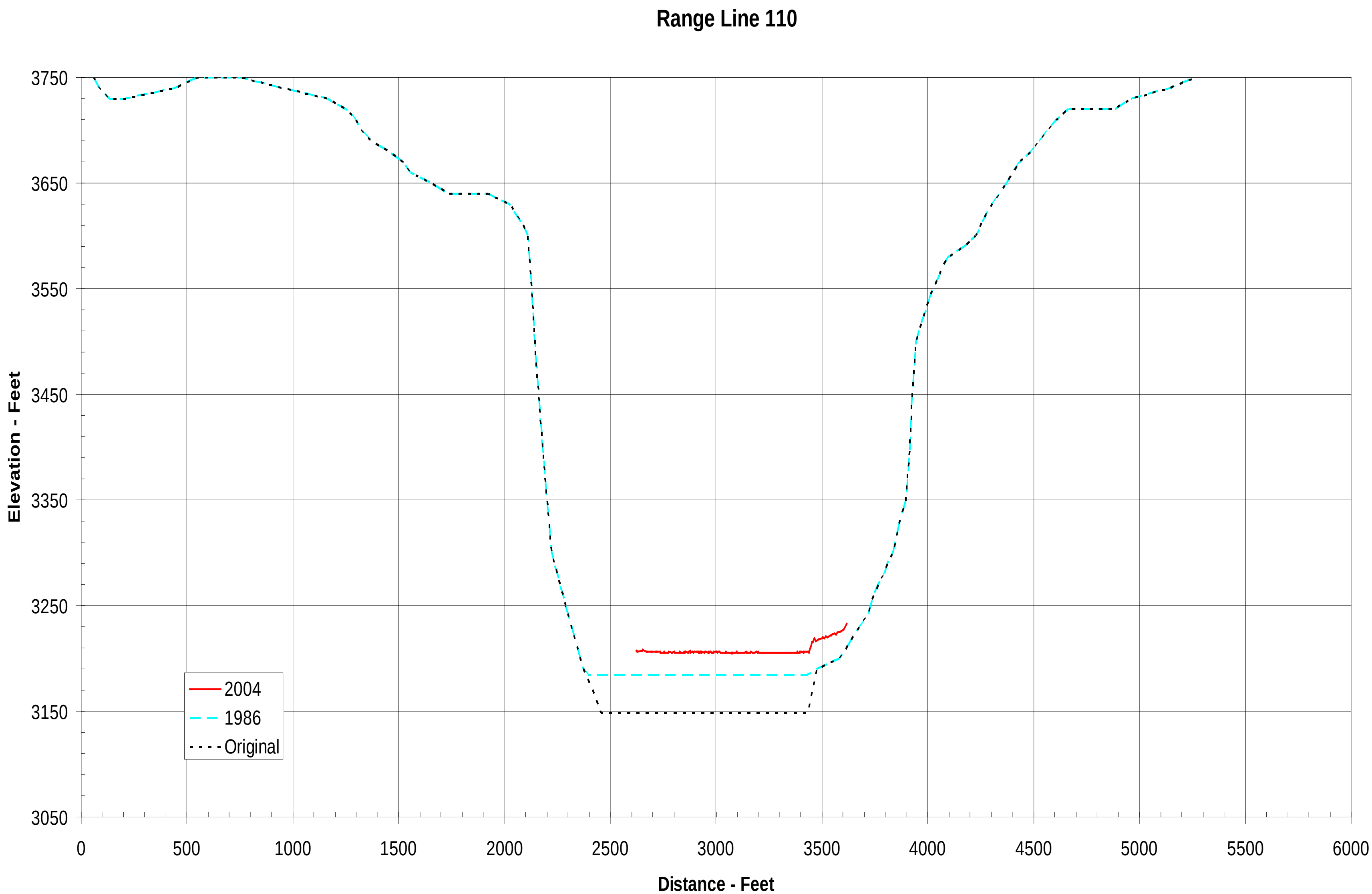

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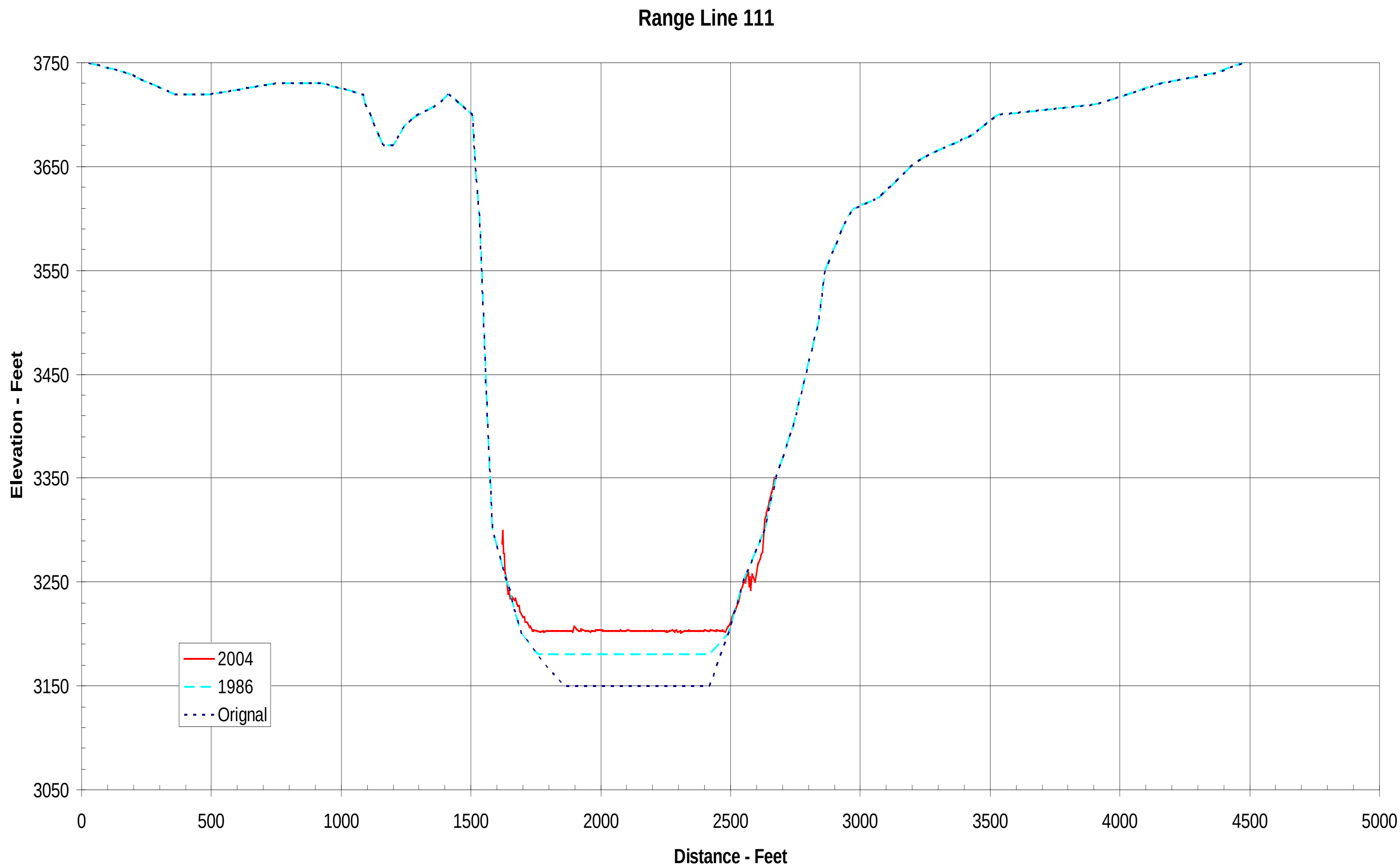
1986
Original



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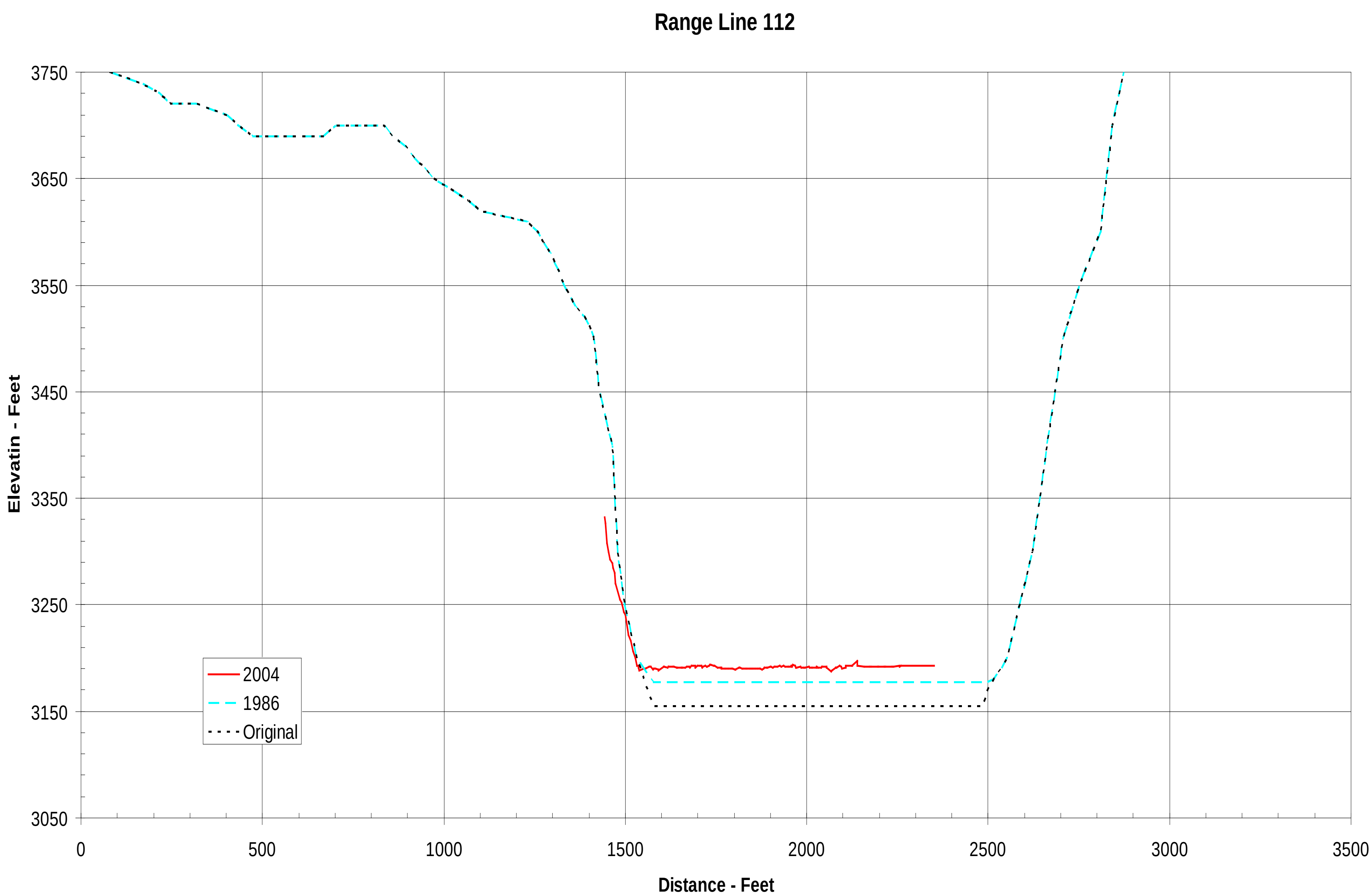
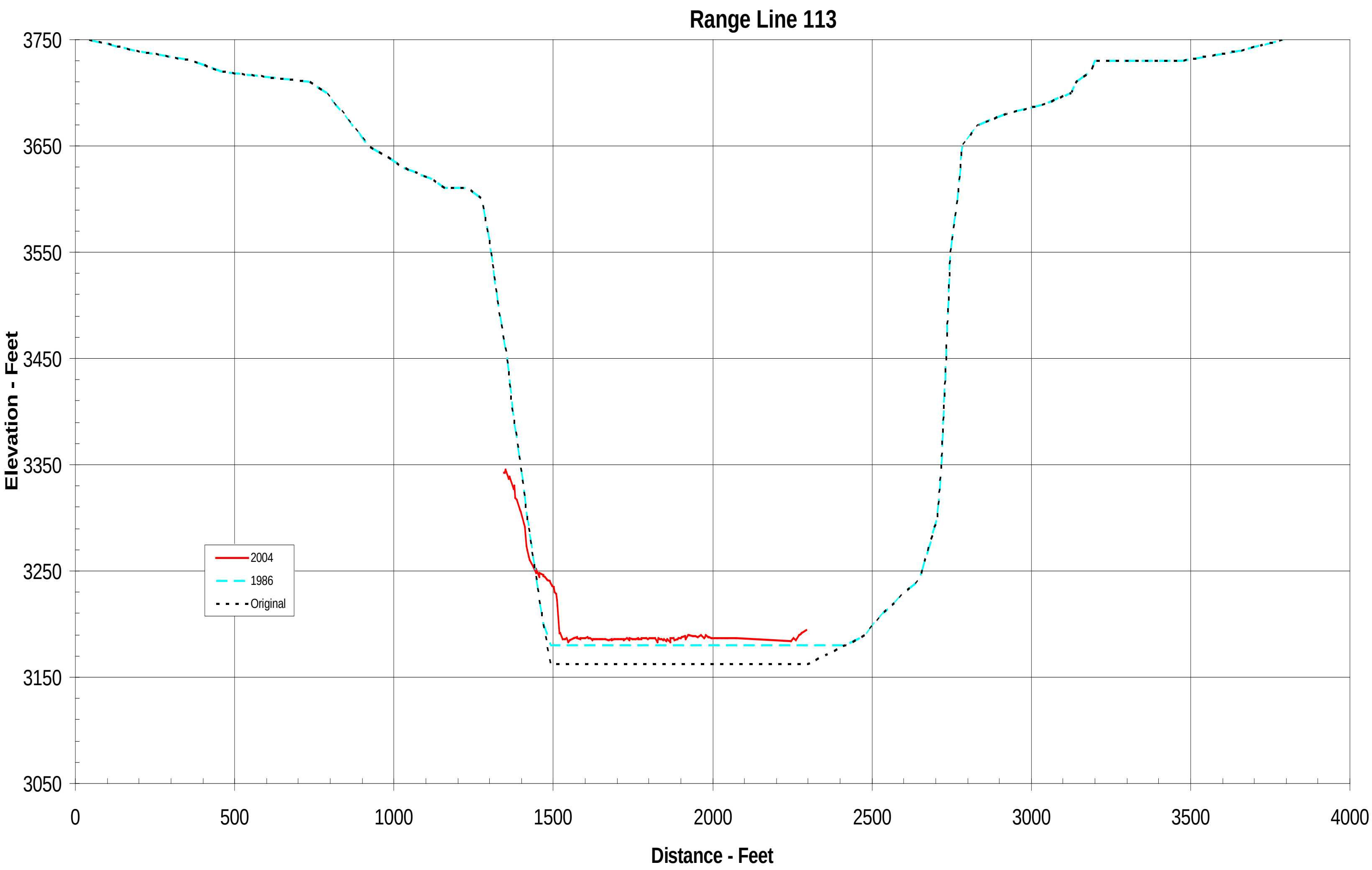
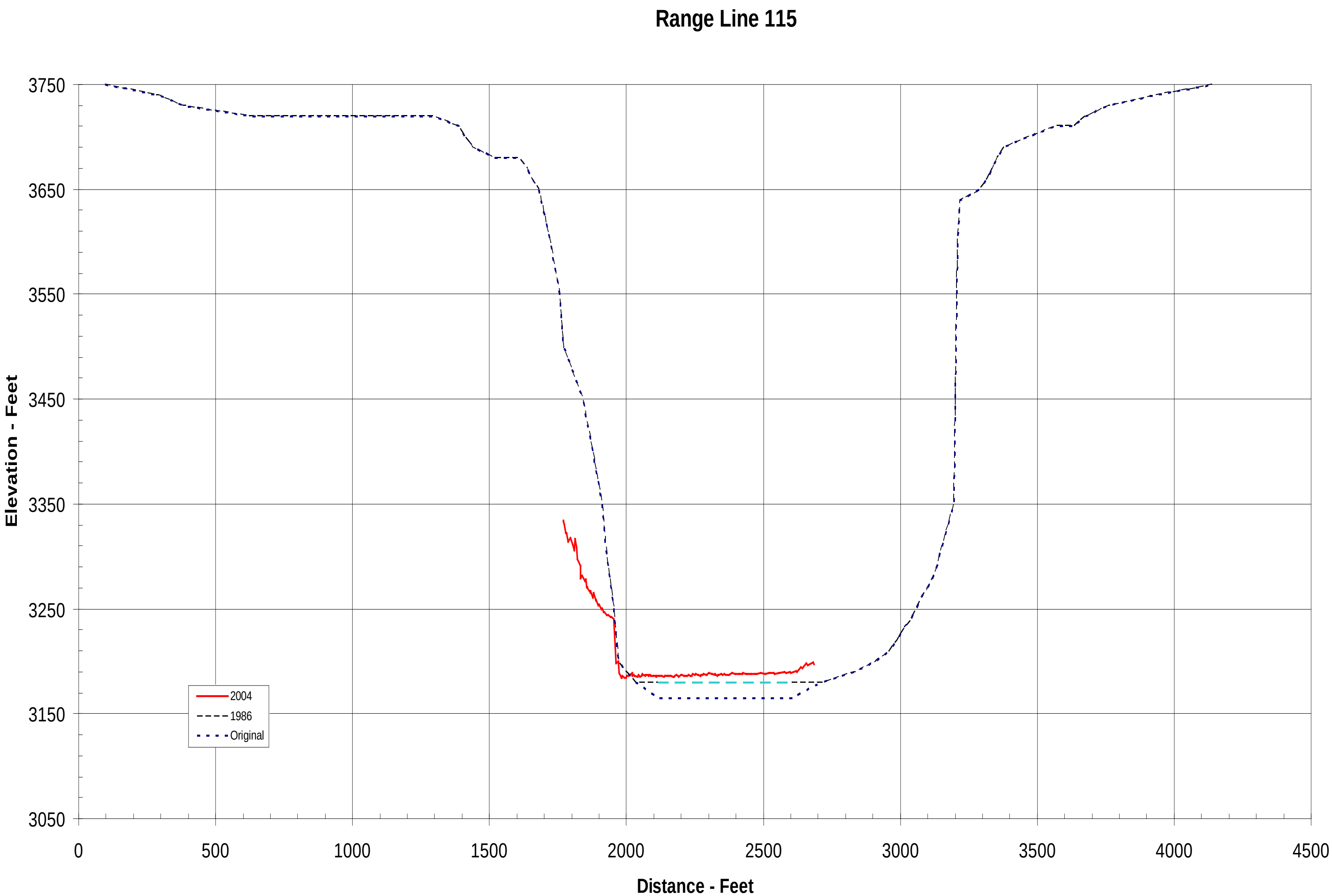
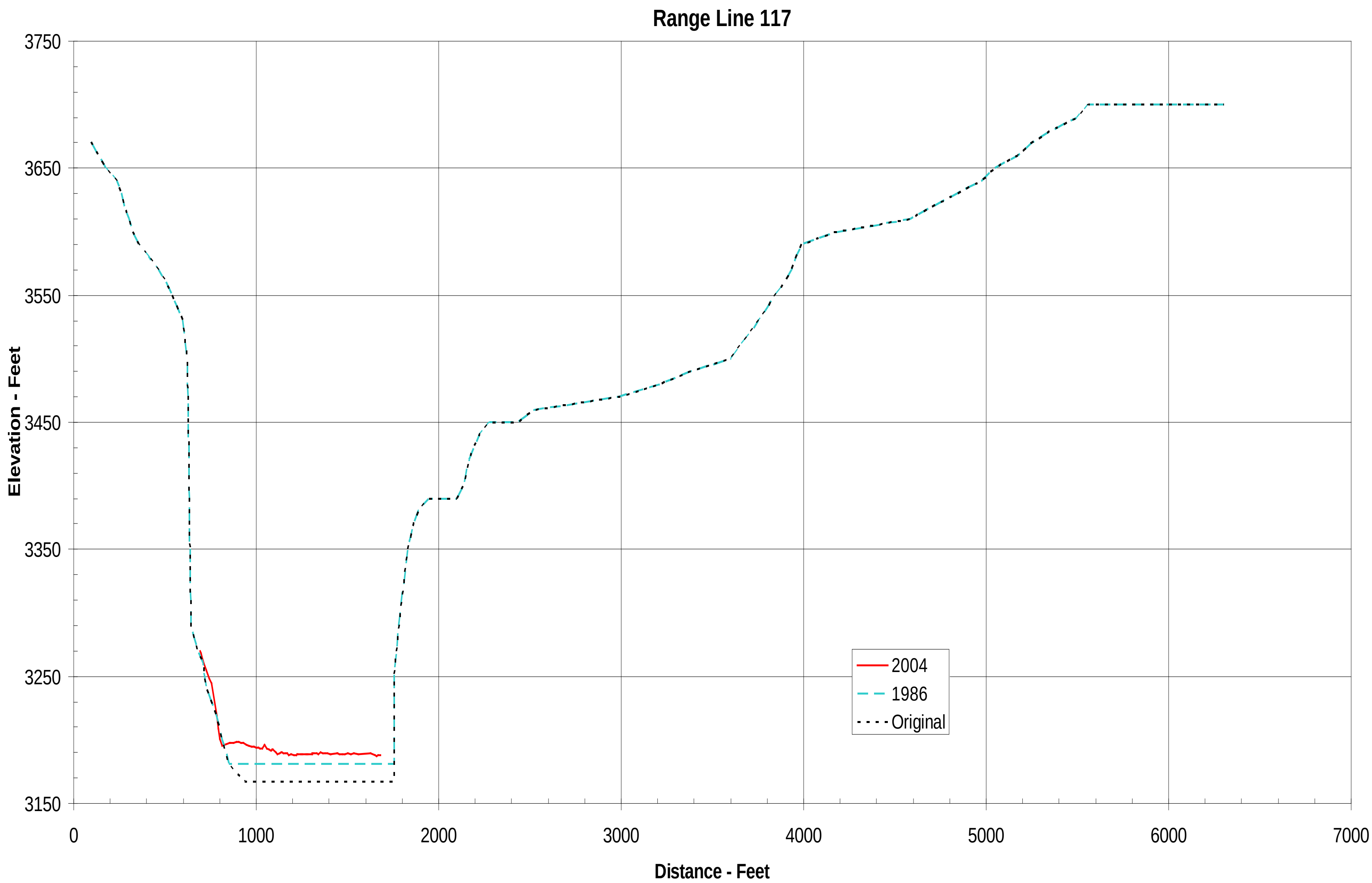
Orignal

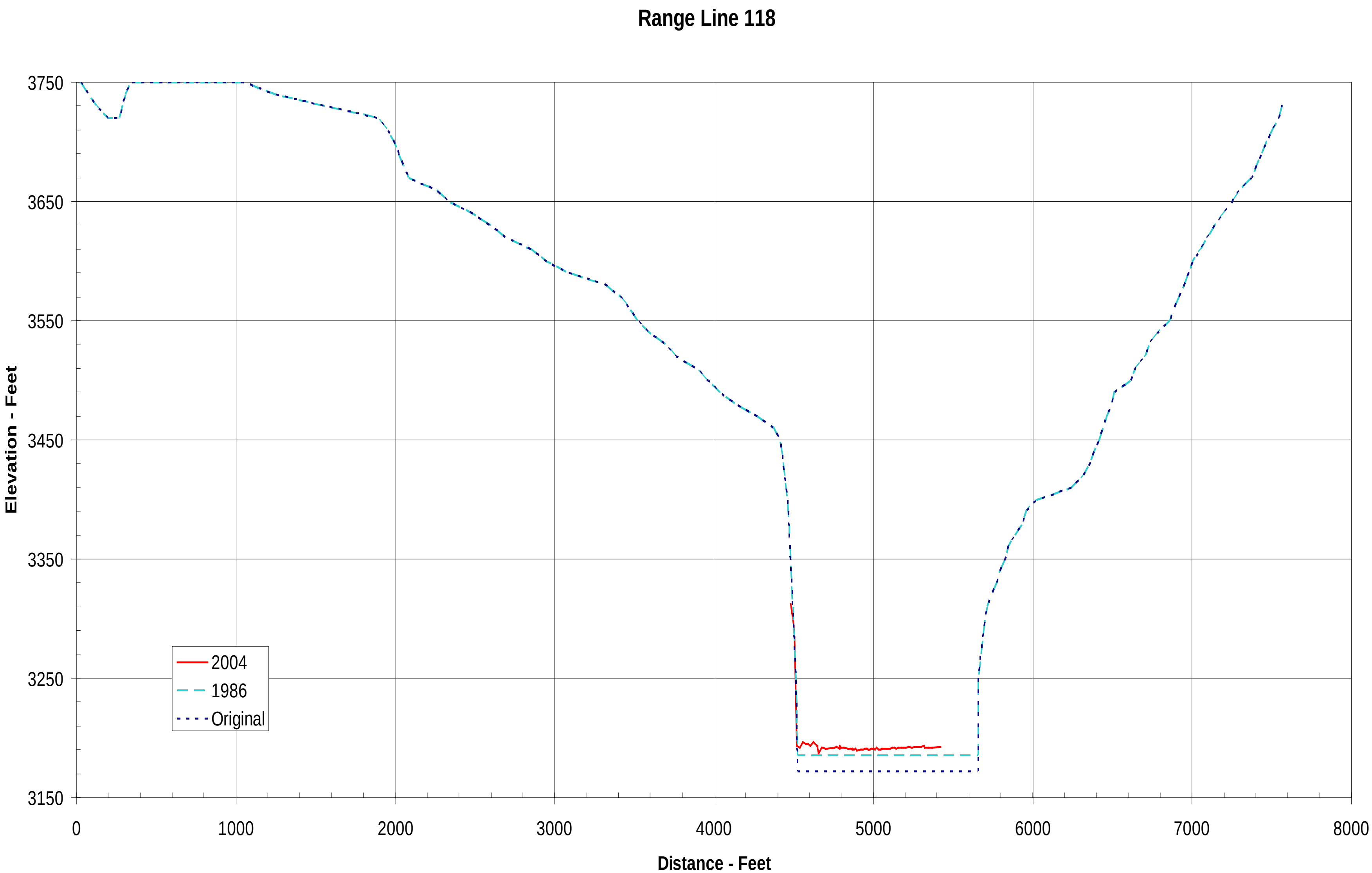

Range Line 112
Elevatin - Feet
3750
3650
3550
3450
3350
3250
3150
3050
0
500
1000
1500
2000
2500
3000
3500
Distance - Feet
2004
1986
Original

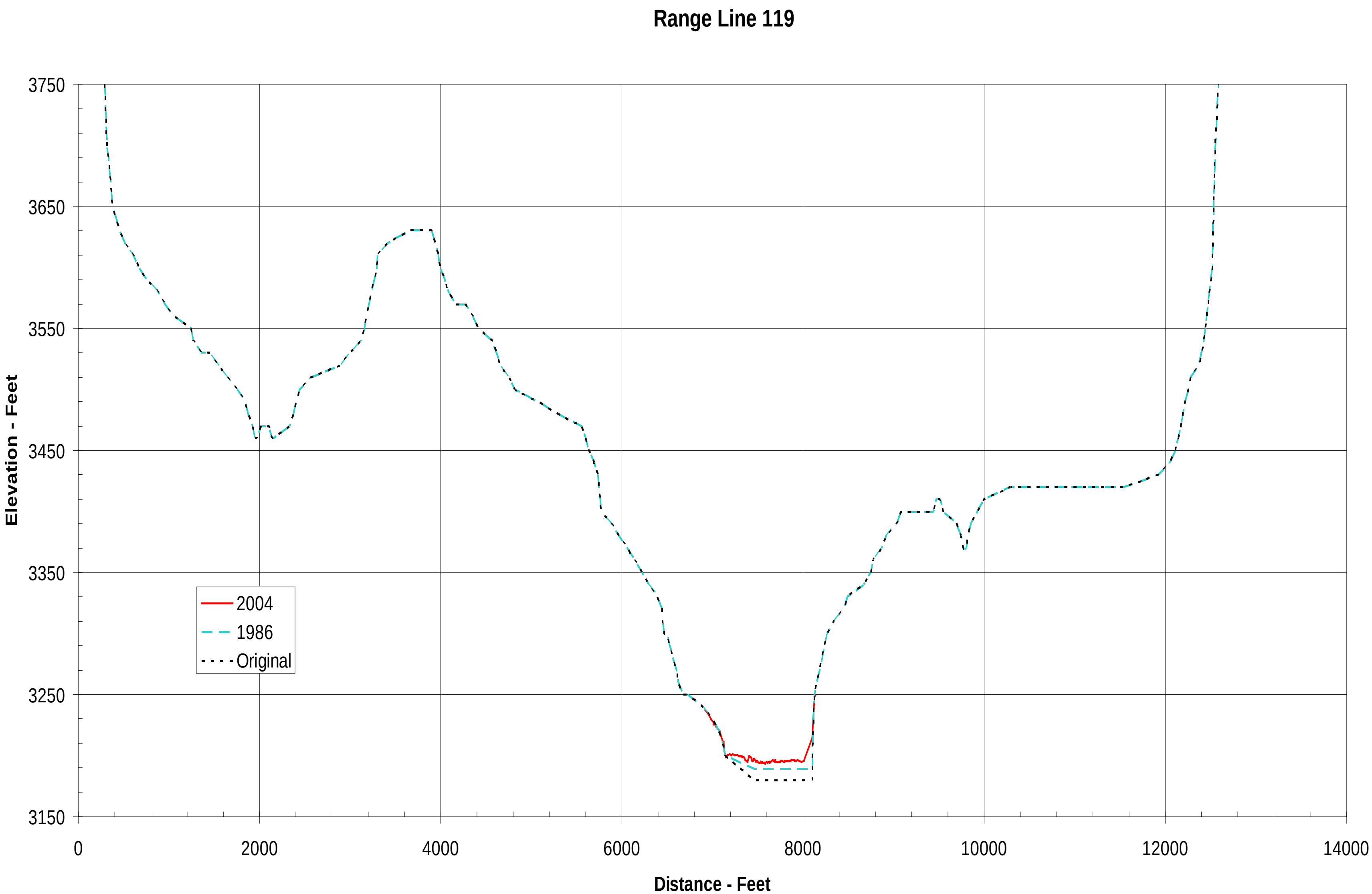


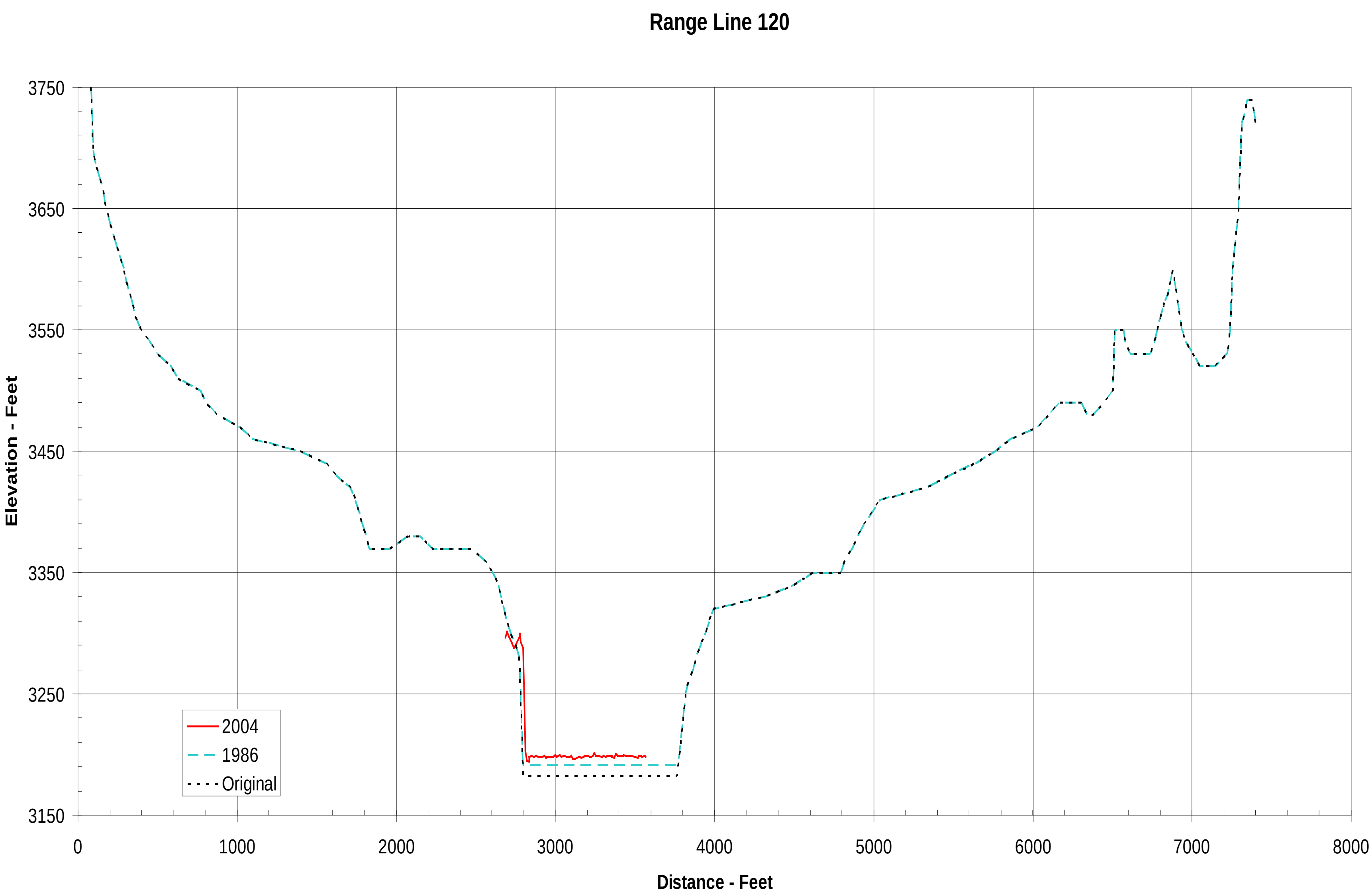
Range Line 113
3750
3650
3550
3450
3350
3250
3150
3050
Elevation - Feet
0
500
1000
1500
2000
2500
3000
3500
4000
Distance - Feet
2004
1986
Original


Range Line 115
Elevation - Feet
3750
3650
3550
3450
3350
3250
3150
3050
0
500
1000
1500
2000
2500
3000
3500
4000
4500
Distance - Feet
2004
1986
Original

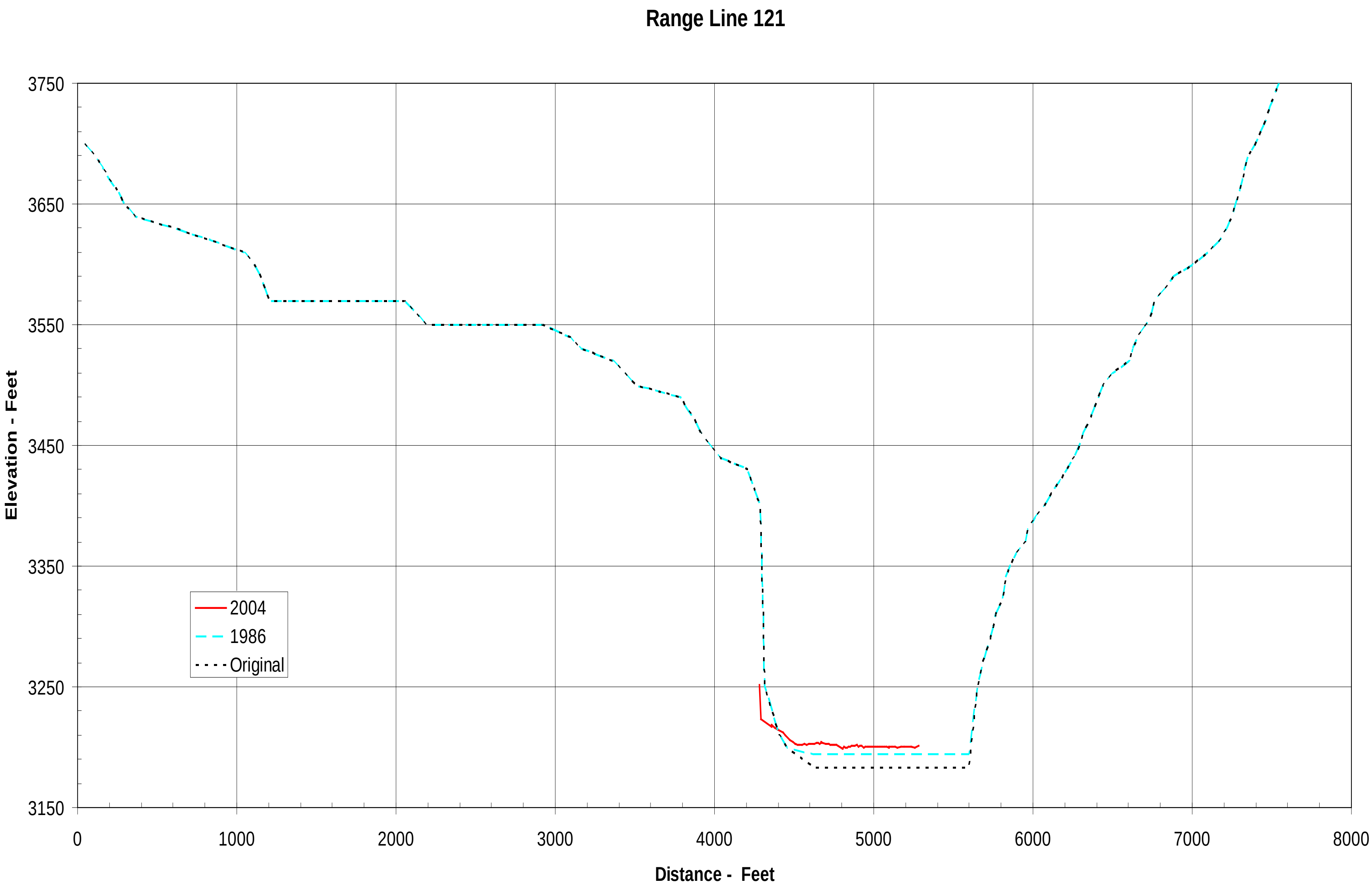

Range Line 117
Elevation - Feet
3750
3650
3550
3450
3350
3250
3150
0
1000
2000
3000
4000
5000
6000
7000
Distance - Feet
2004
1986
Original

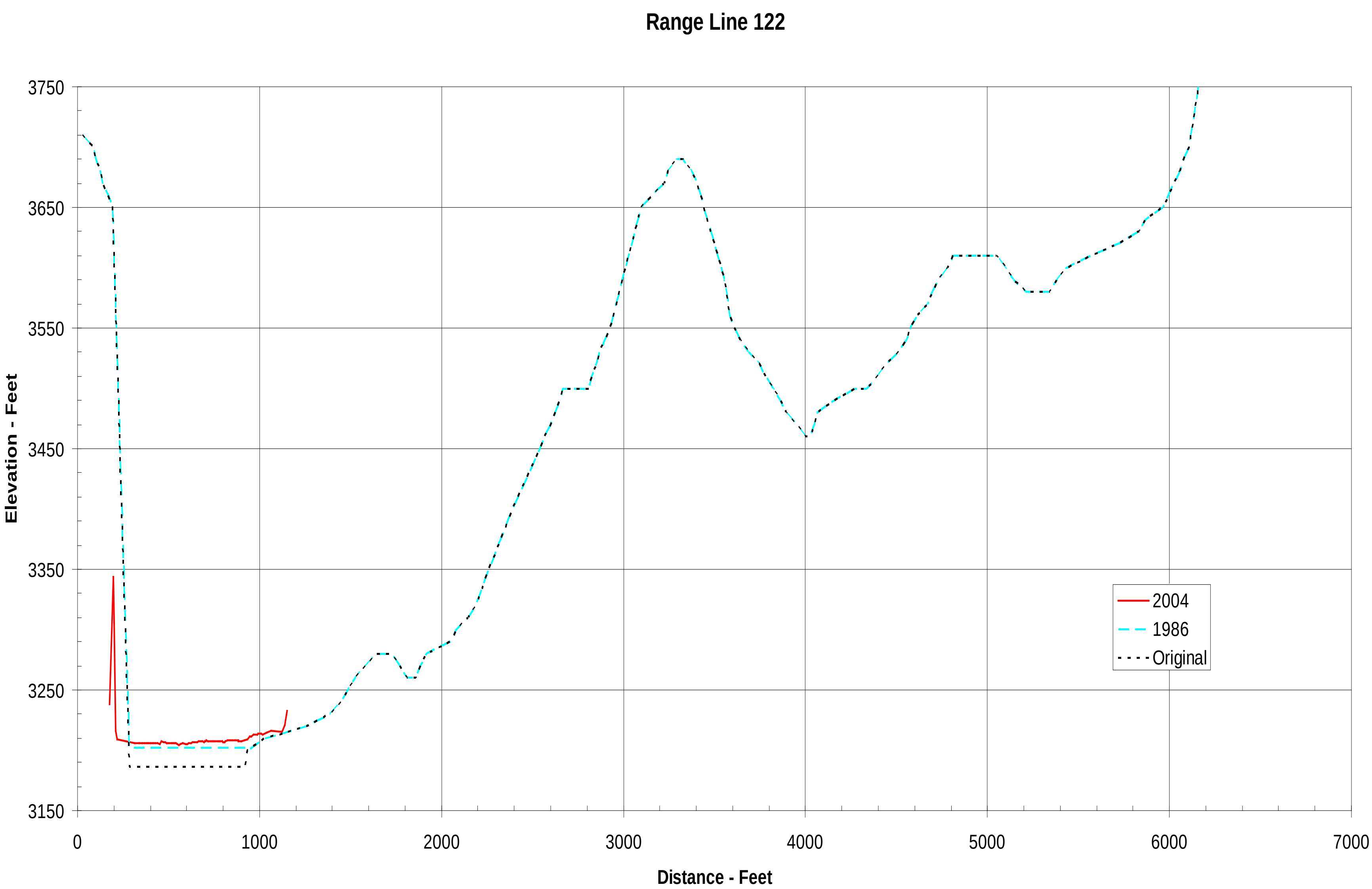

Range Line 118
3750
3650
3550
3450
3350
3250
3150
Elevation - Feet
0
1000
2000
3000
4000
5000
6000
7000
8000
Distance - Feet
2004
1986
Original


Range Line 119
Elevation - Feet
3750
3650
3550
3450
3350
3250
3150
0
2000
4000
6000
8000
10000
12000
14000
Distance - Feet
2004
1986
Original

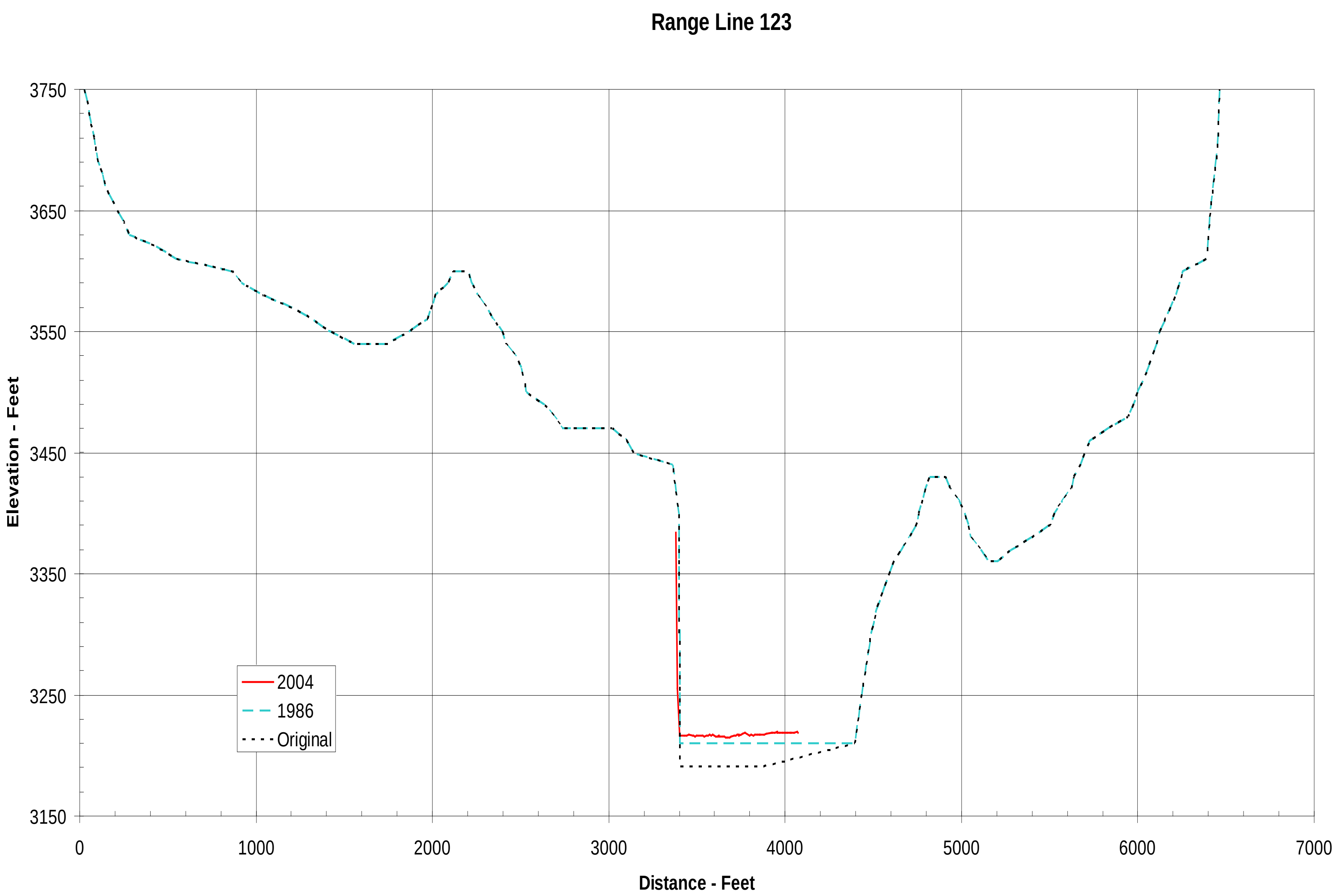


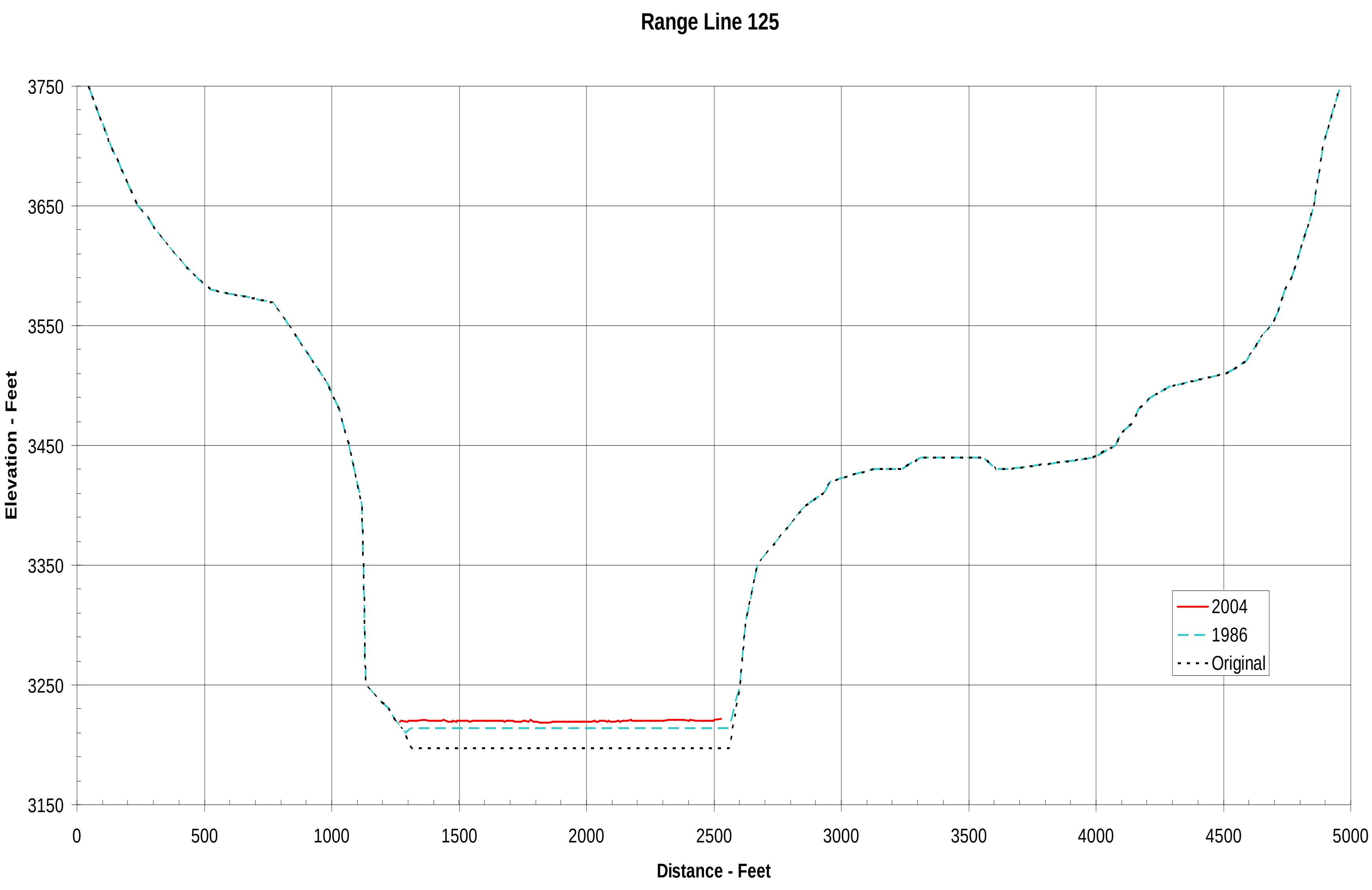
Range Line 120
Elevation - Feet
Distance - Feet
3750
3650
3550
3450
3350
3250
3150
0
1000
2000
3000
4000
5000
6000
7000
8000
2004
1986
Original

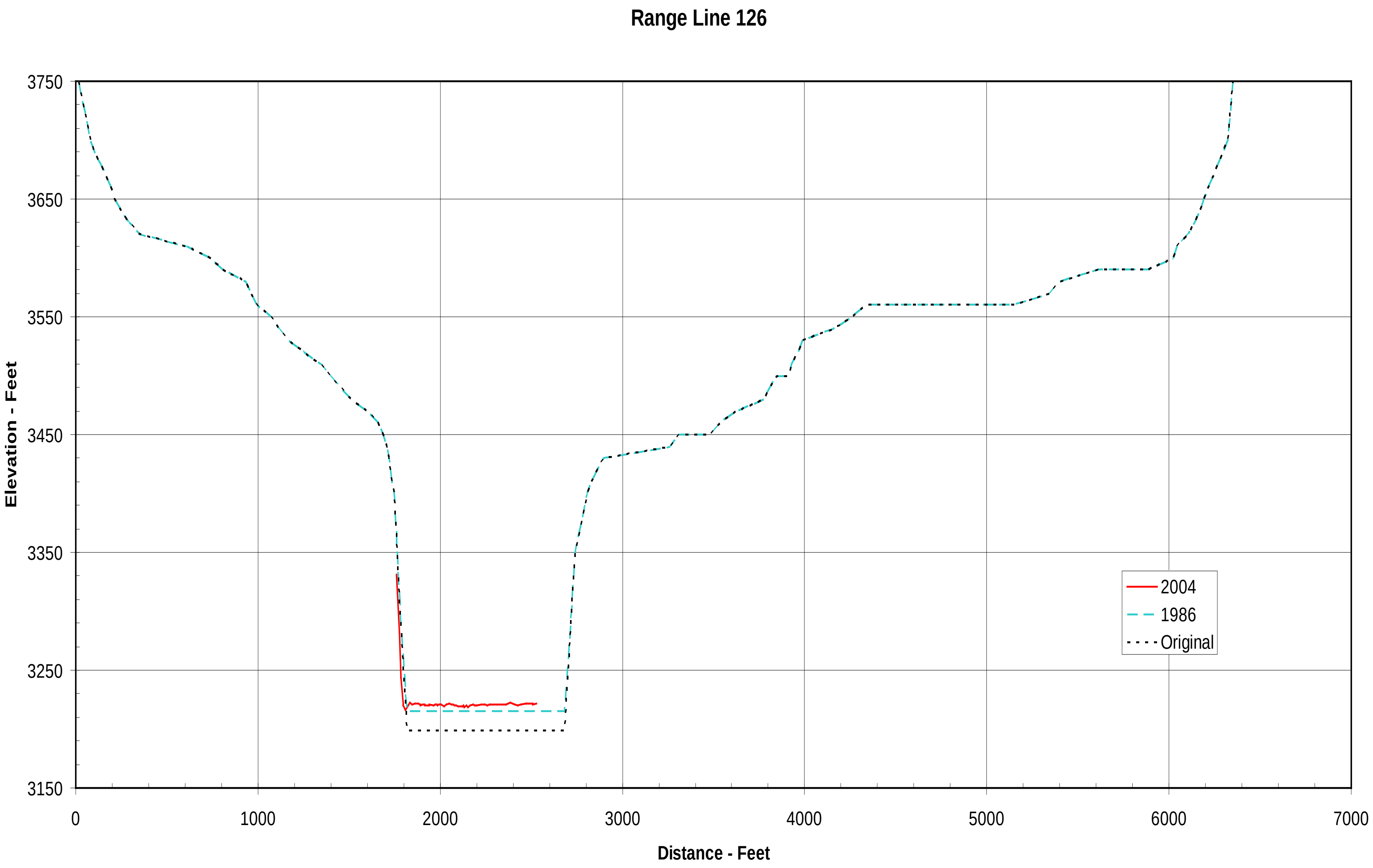

Range Line 121
3750
3650
3550
3450
3350
3250
3150
Elevation - Feet
0
1000
2000
3000
4000
5000
6000
7000
8000
Distance - Feet
2004
1986
Original



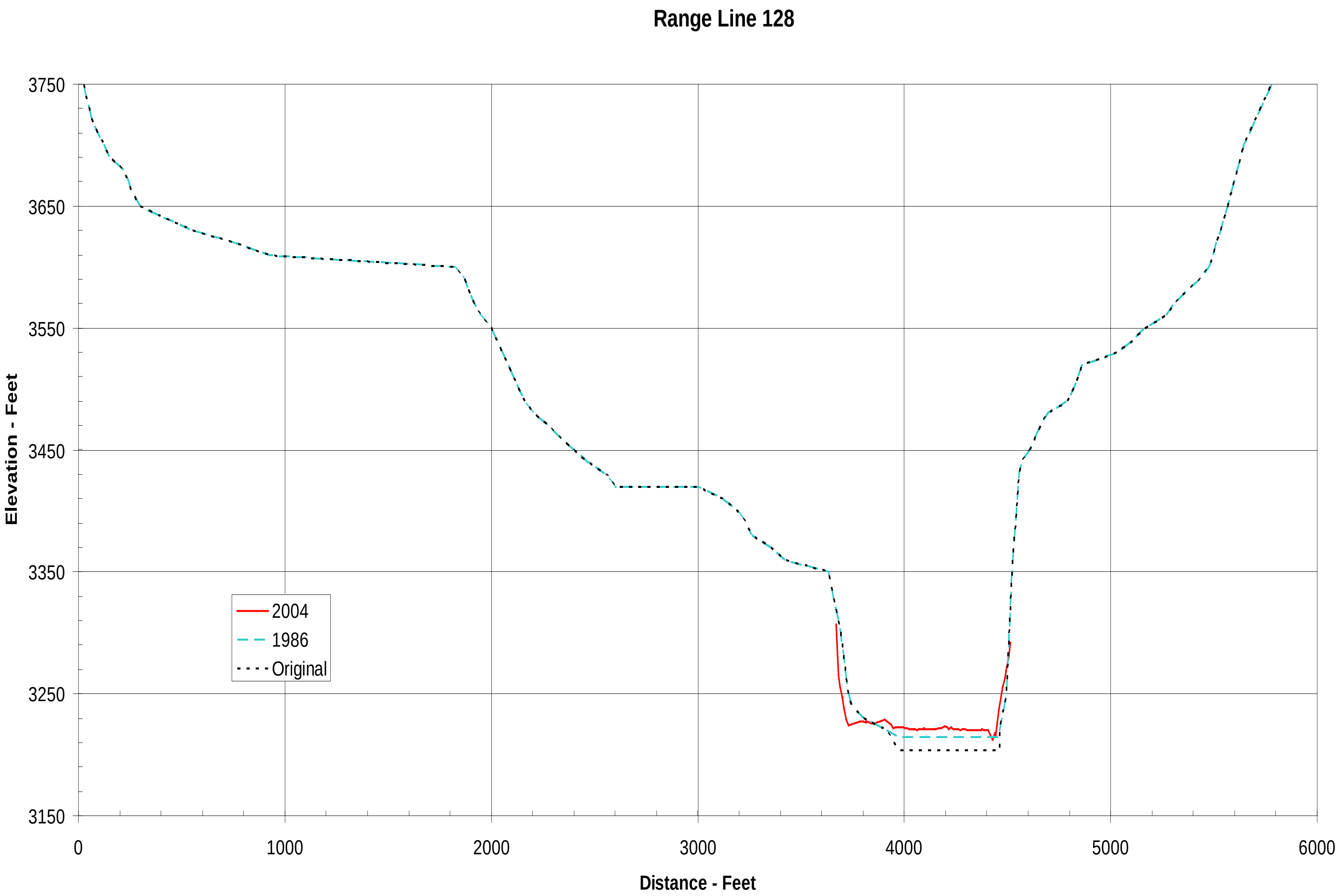
Range Line 122
Elevation - Feet
3750
3650
3550
3450
3350
3250
3150
0
1000
2000
3000
4000
5000
6000
7000
Distance - Feet
2004
1986
Original


Range Line 123
Elevation - Feet
Distance - Feet
3750
3650
3550
3450
3350
3250
3150
0
1000
2000
3000
4000
5000
6000
7000
2004
1986
Original

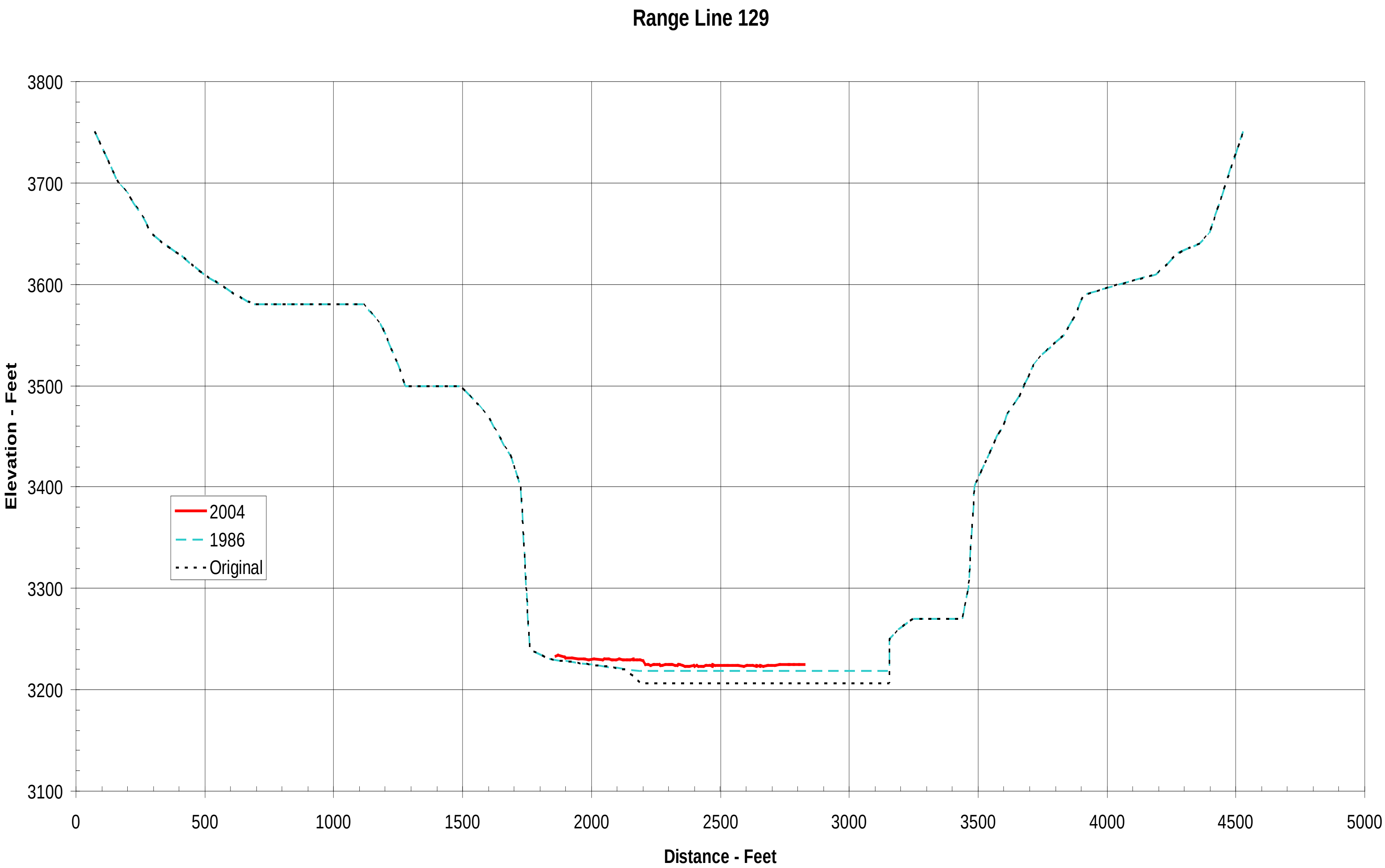

Range Line 125
Elevation - Feet
3750
3650
3550
3450
3350
3250
3150
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
Distance - Feet
2004
1986
Original



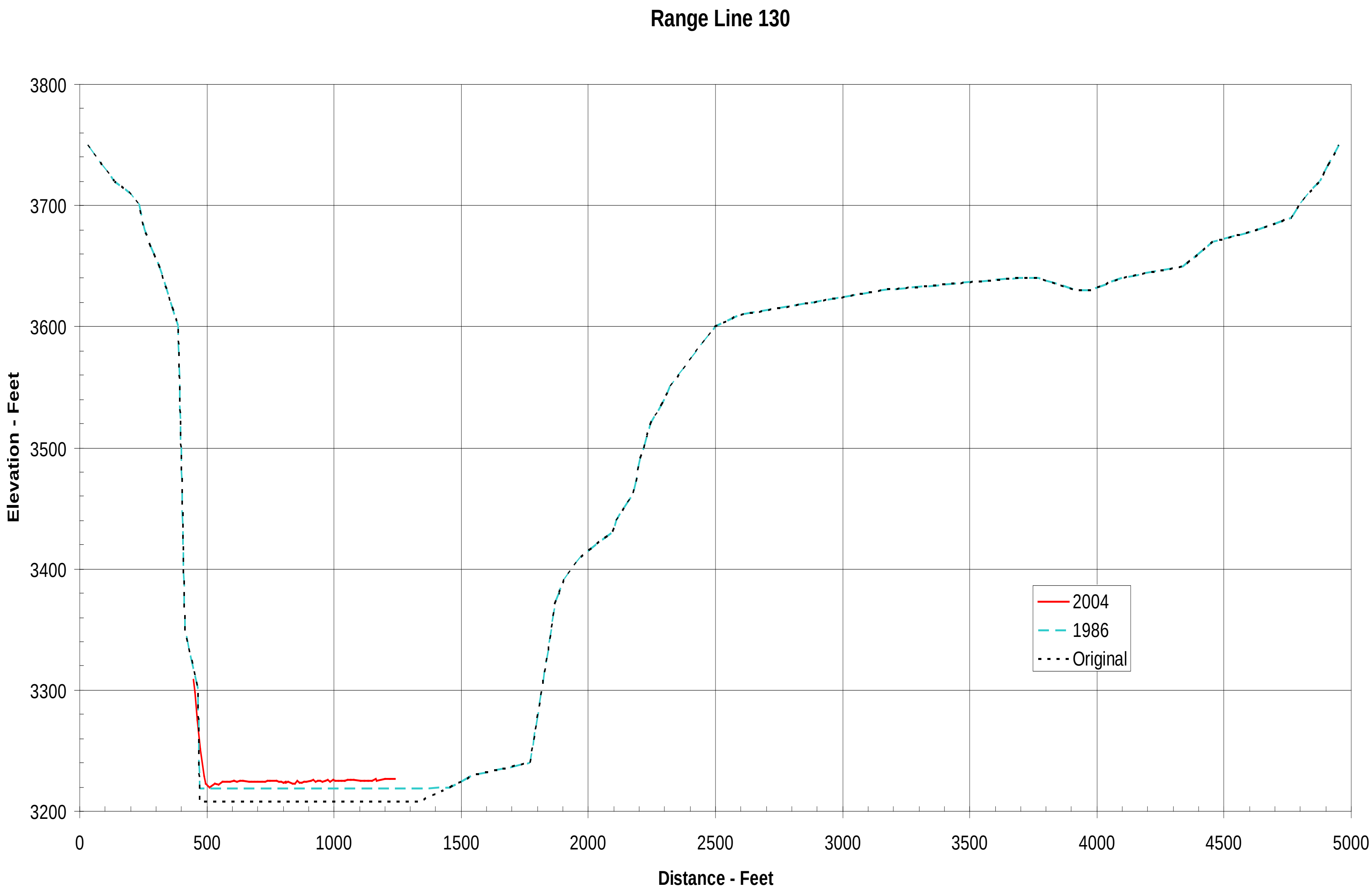
Range Line 126
Elevation - Feet
3750
3650
3550
3450
3350
3250
3150
0
1000
2000
3000
4000
5000
6000
7000
Distance - Feet
2004
1986
Original



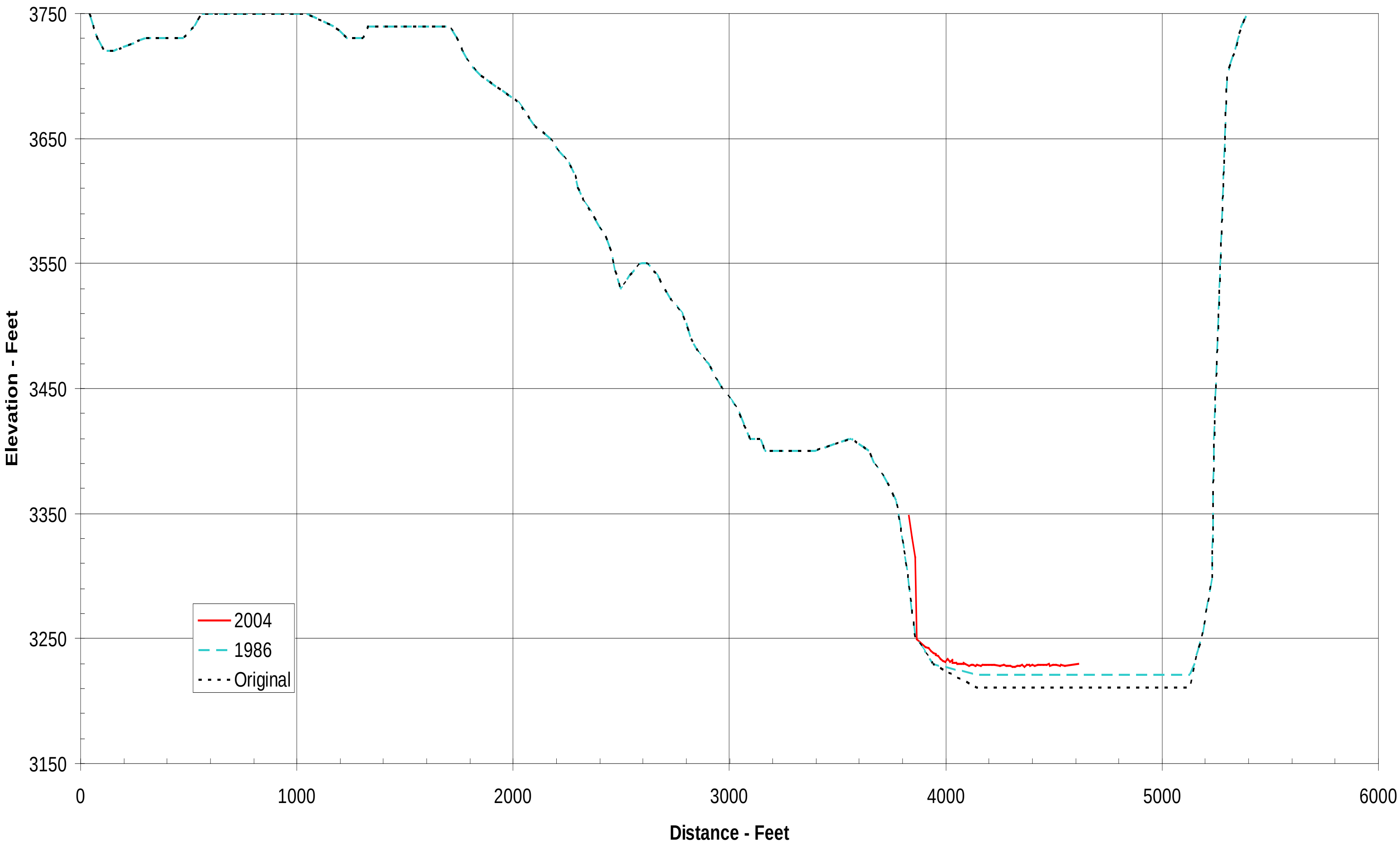
Range Line 128
3750
3650
3550
3450
3350
3250
3150
Elevation - Feet
2004
1986
Original
0
1000
2000
3000
4000
5000
6000
Distance - Feet

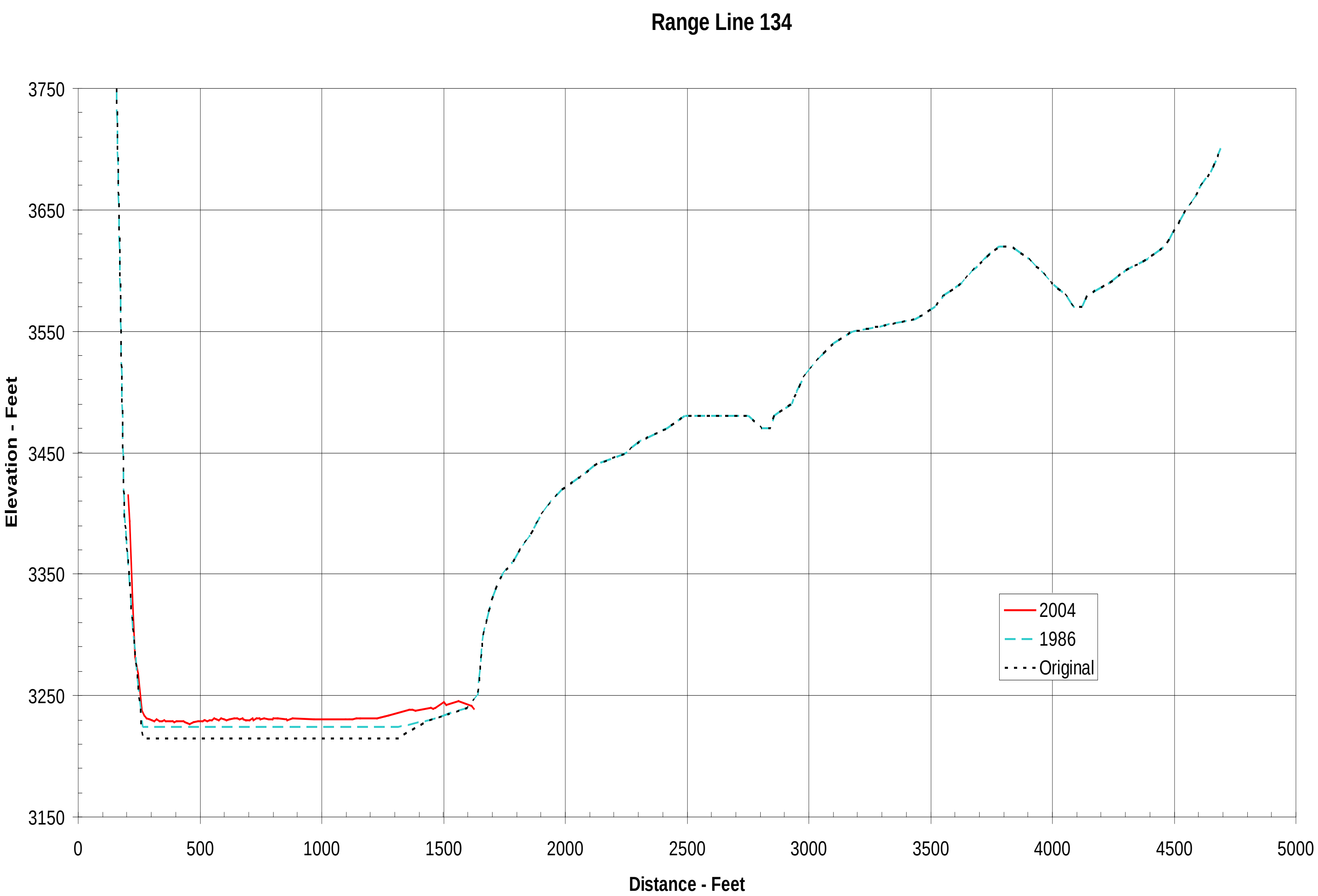


Range Line 129
3800
3700
3600
3500
3400
3300
3200
3100
Elevation - Feet
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
Distance - Feet
2004
1986
Original

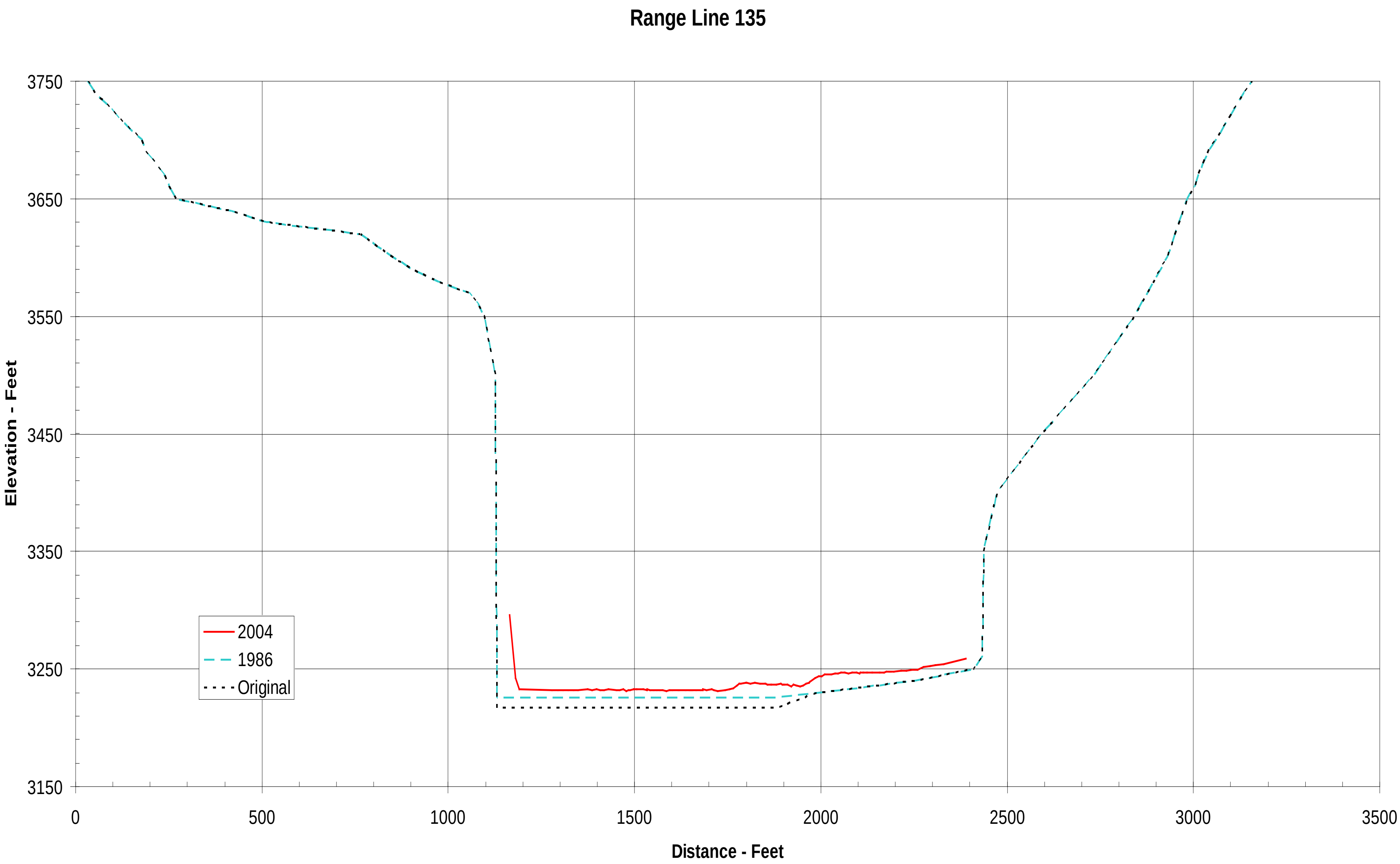

Range Line 130
Elevation - Feet
3800
3700
3600
3500
3400
3300
3200
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
Distance - Feet
2004
1986
Original

Range Line 132

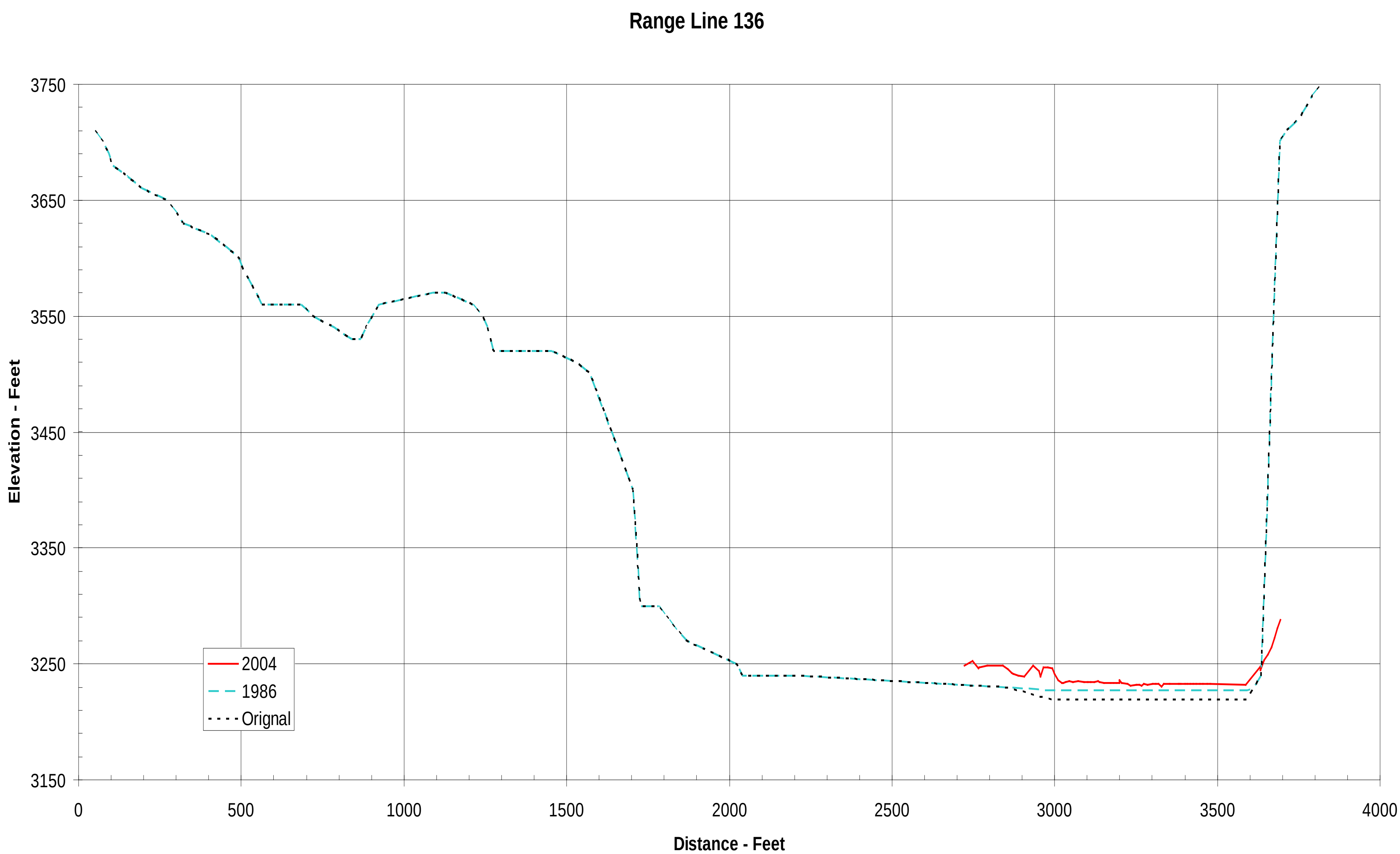




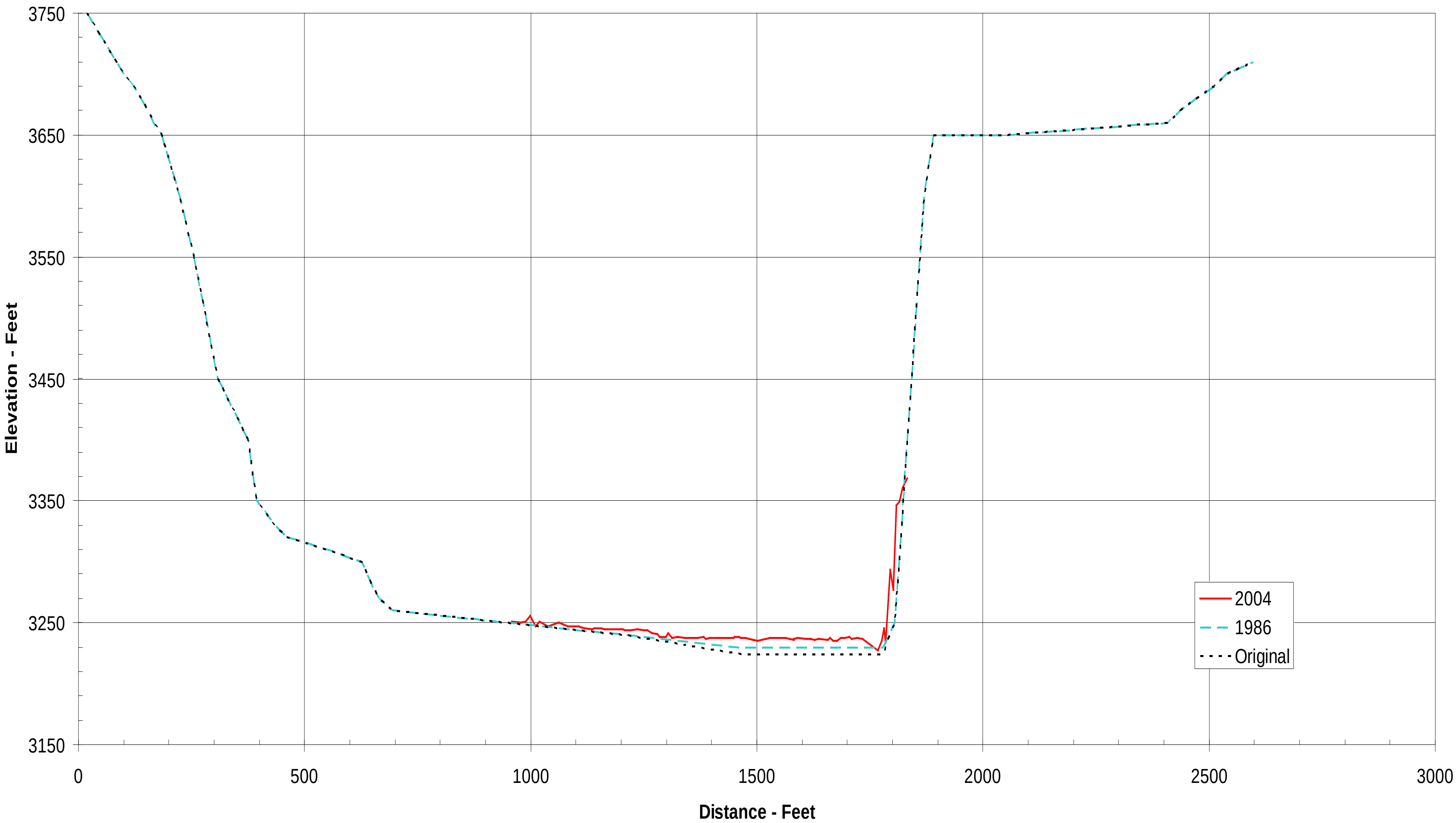
Range Line 134
Elevation - Feet
3750
3650
3550
3450
3350
3250
3150
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
Distance - Feet
2004
1986
Original

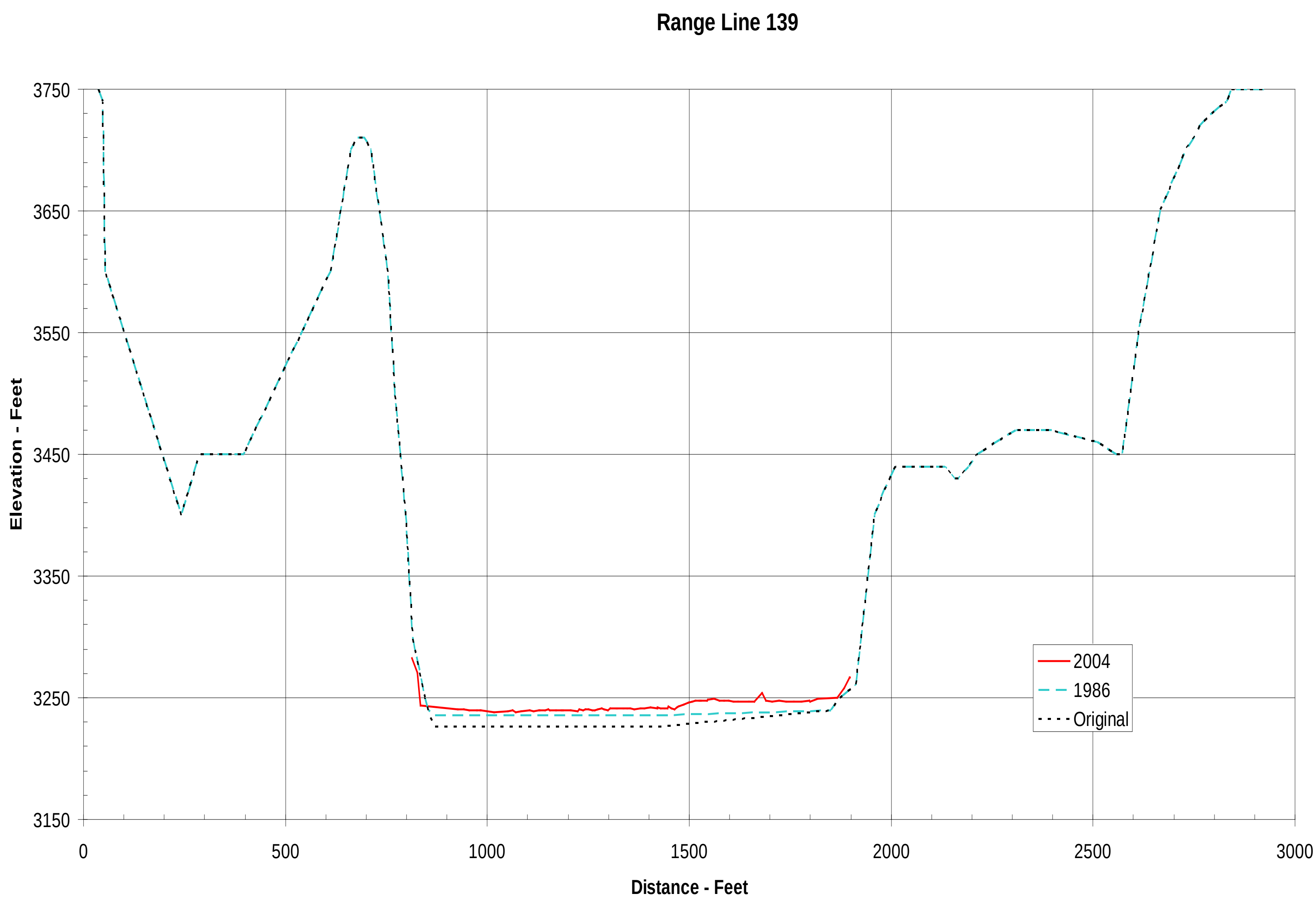


Range Line 135
3750
3650
3550
3450
3350
3250
3150
Elevation - Feet
0
500
1000
1500
2000
2500
3000
3500
Distance - Feet
2004
1986
Original

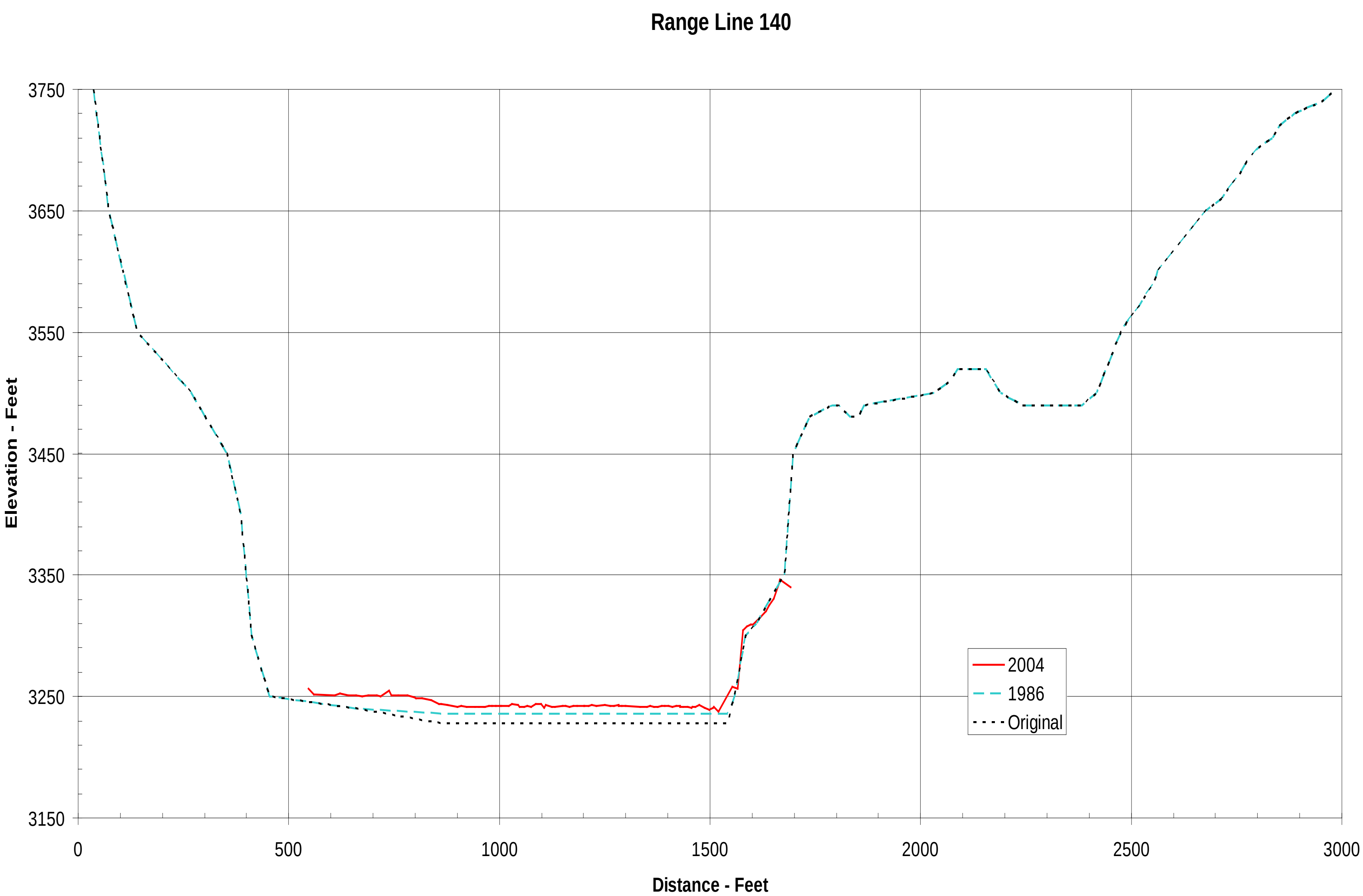

Range Line 136
3750
3650
3550
3450
3350
3250
3150
Elevation - Feet
0
500
1000
1500
2000
2500
3000
3500
4000
Distance - Feet
2004
1986
Orignal

Range Line 138

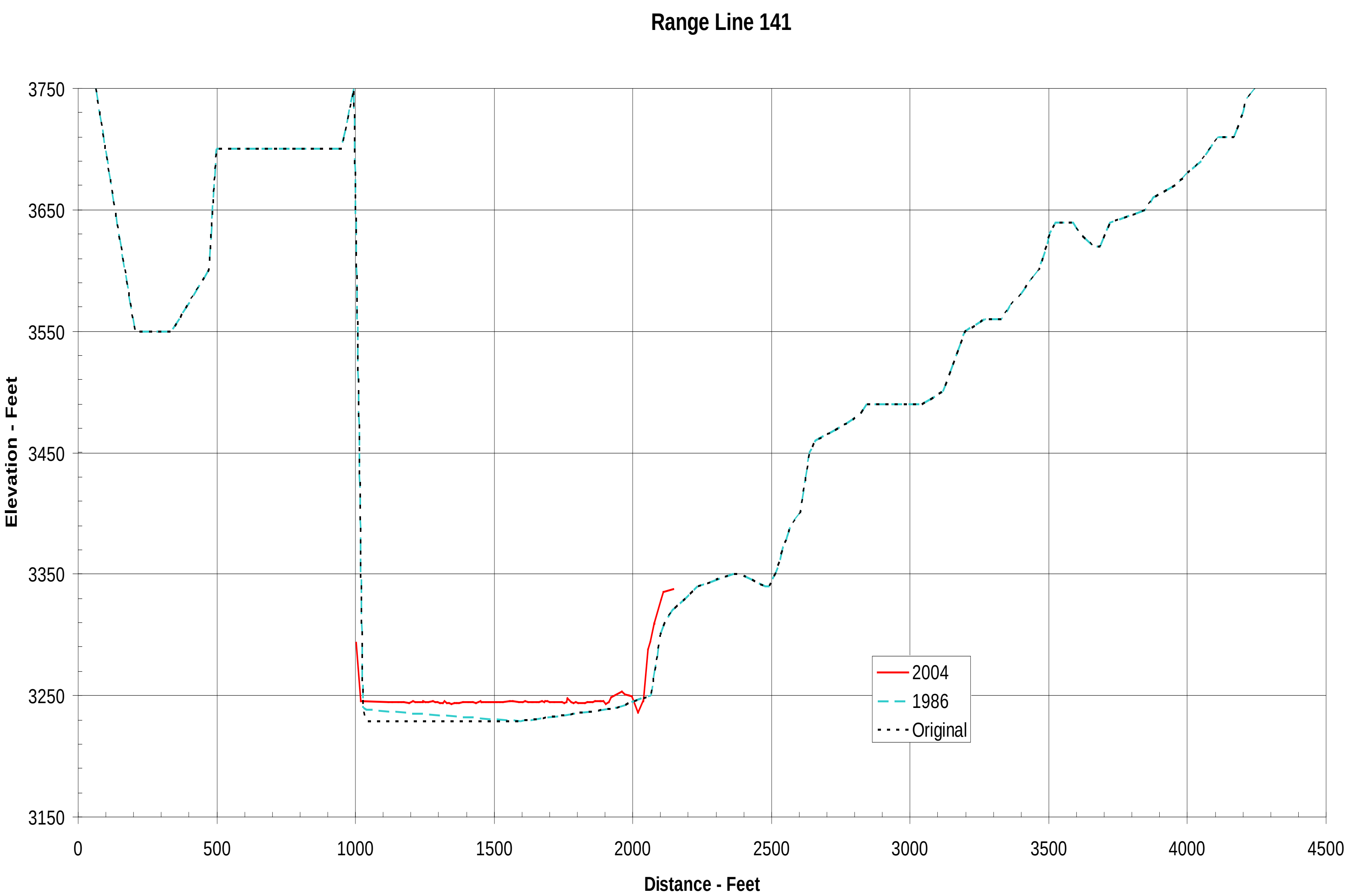




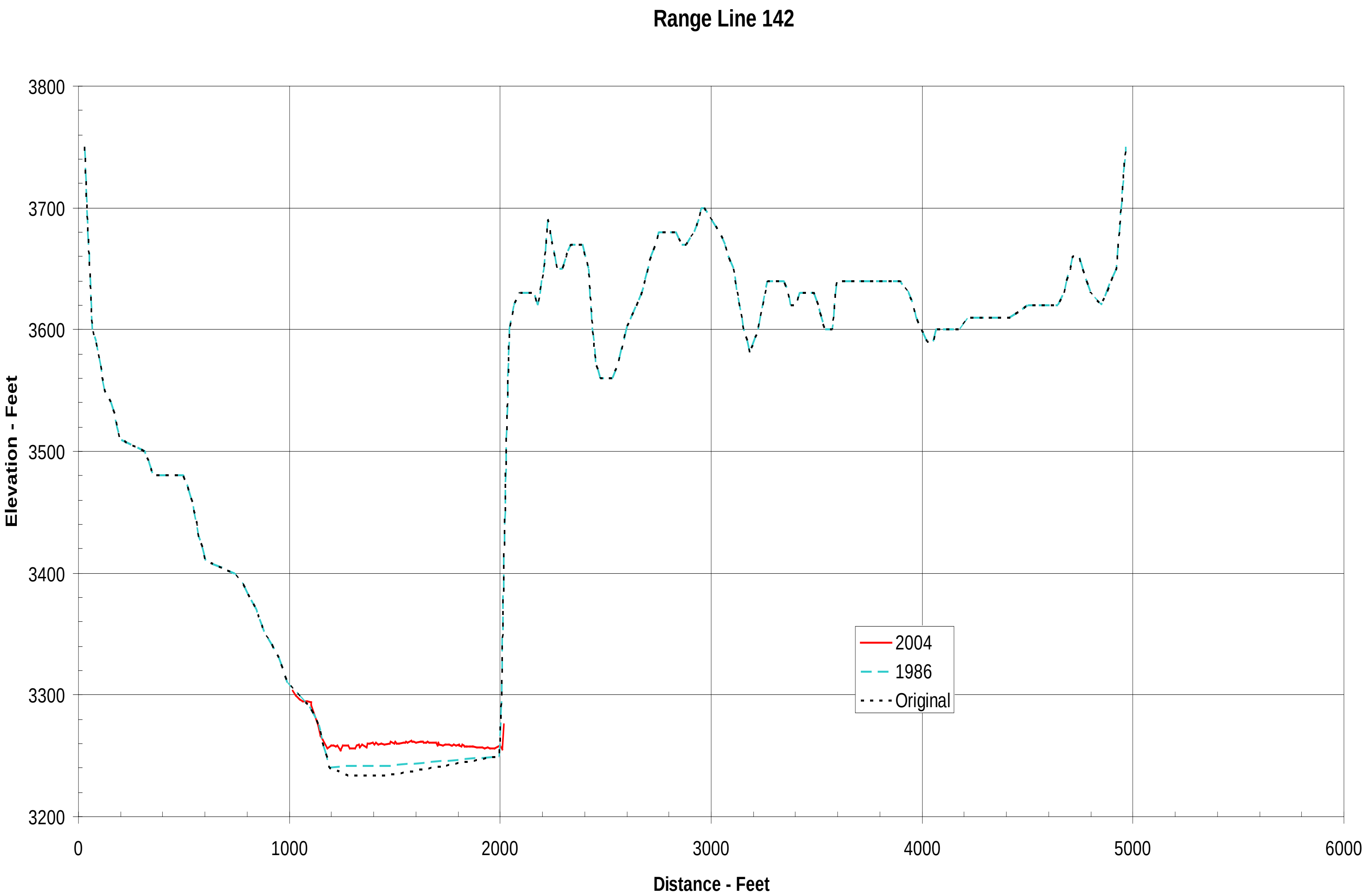
Range Line 139
3750
3650
3550
3450
3350
3250
3150
Elevation - Feet
0
500
1000
1500
2000
2500
3000
Distance - Feet
2004
1986
Original

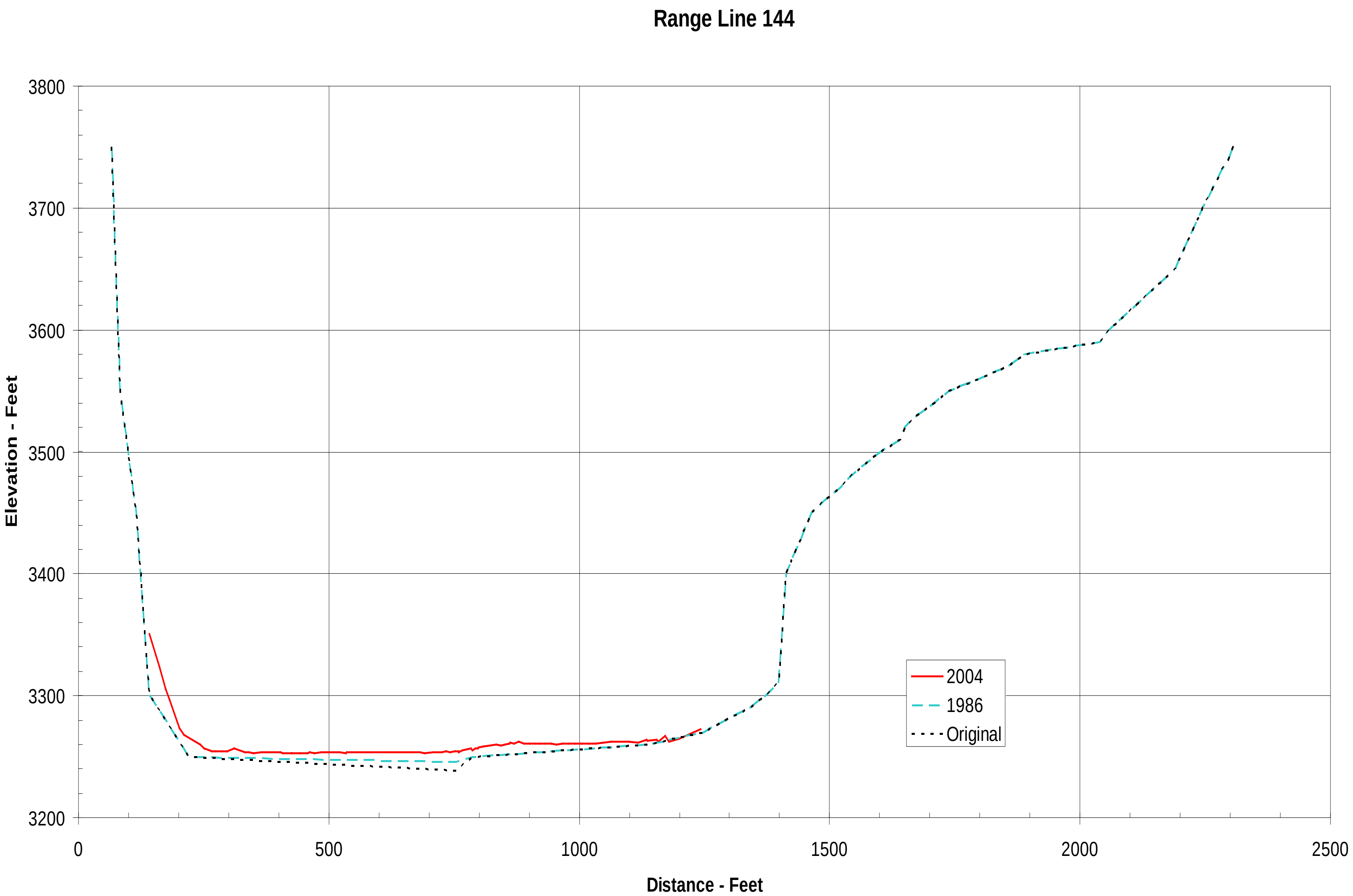


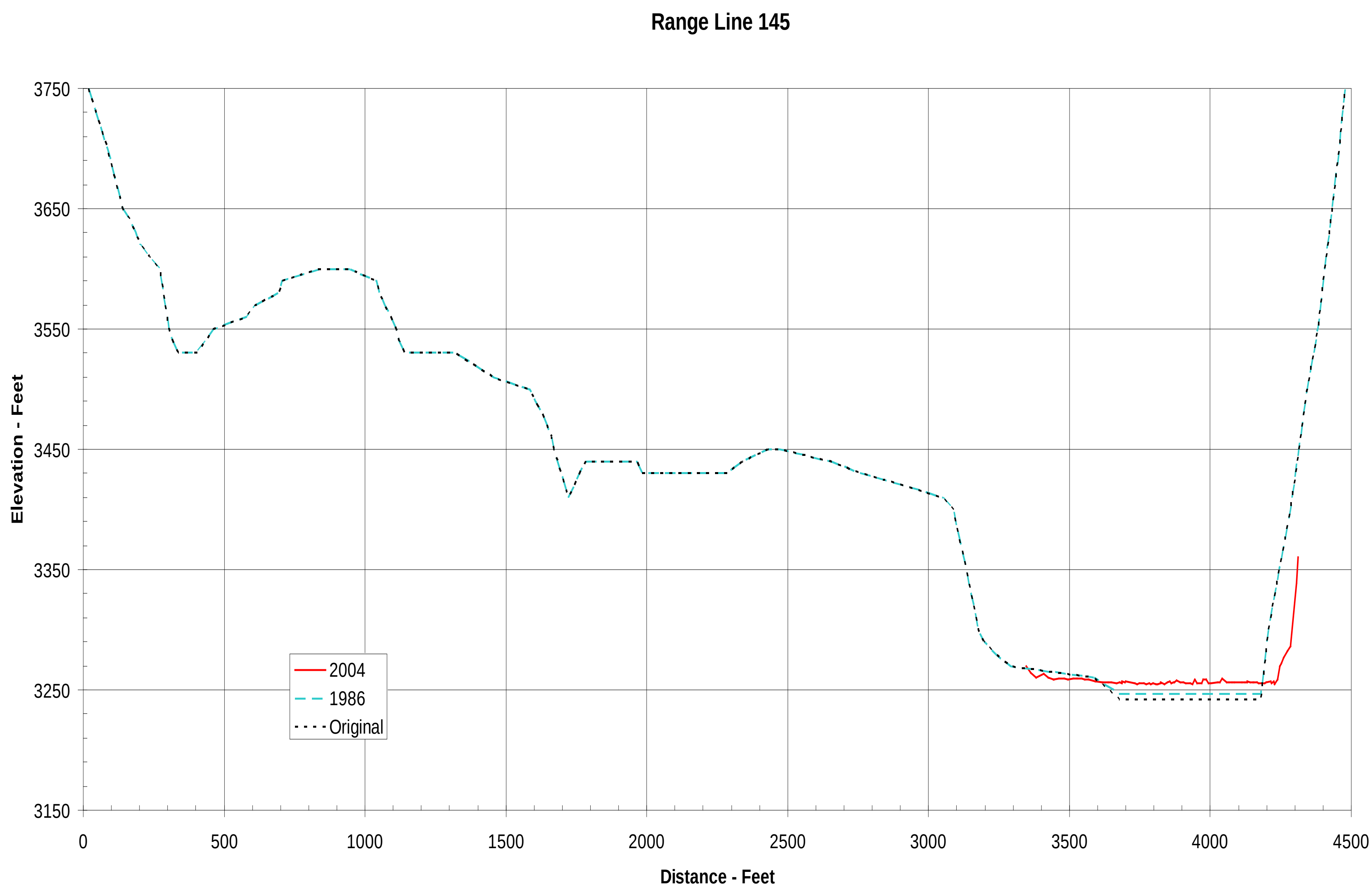
Range Line 140
Elevation - Feet
3750
3650
3550
3450
3350
3250
3150
0
500
1000
1500
2000
2500
3000
Distance - Feet
2004
1986
Original

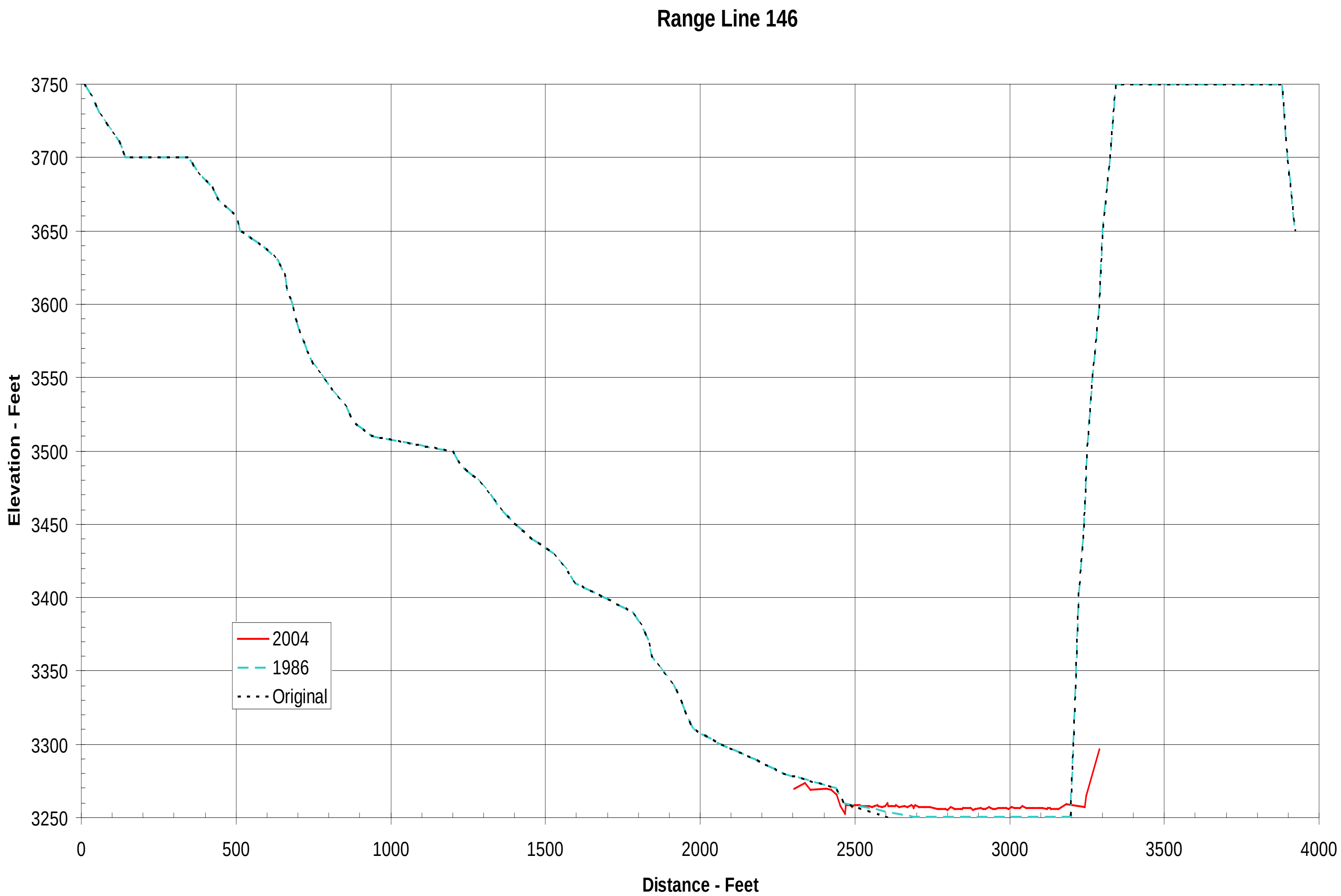


Range Line 141
Elevation - Feet
3750
3650
3550
3450
3350
3250
3150
0
500
1000
1500
2000
2500
3000
3500
4000
4500
Distance - Feet
2004
1986
Original

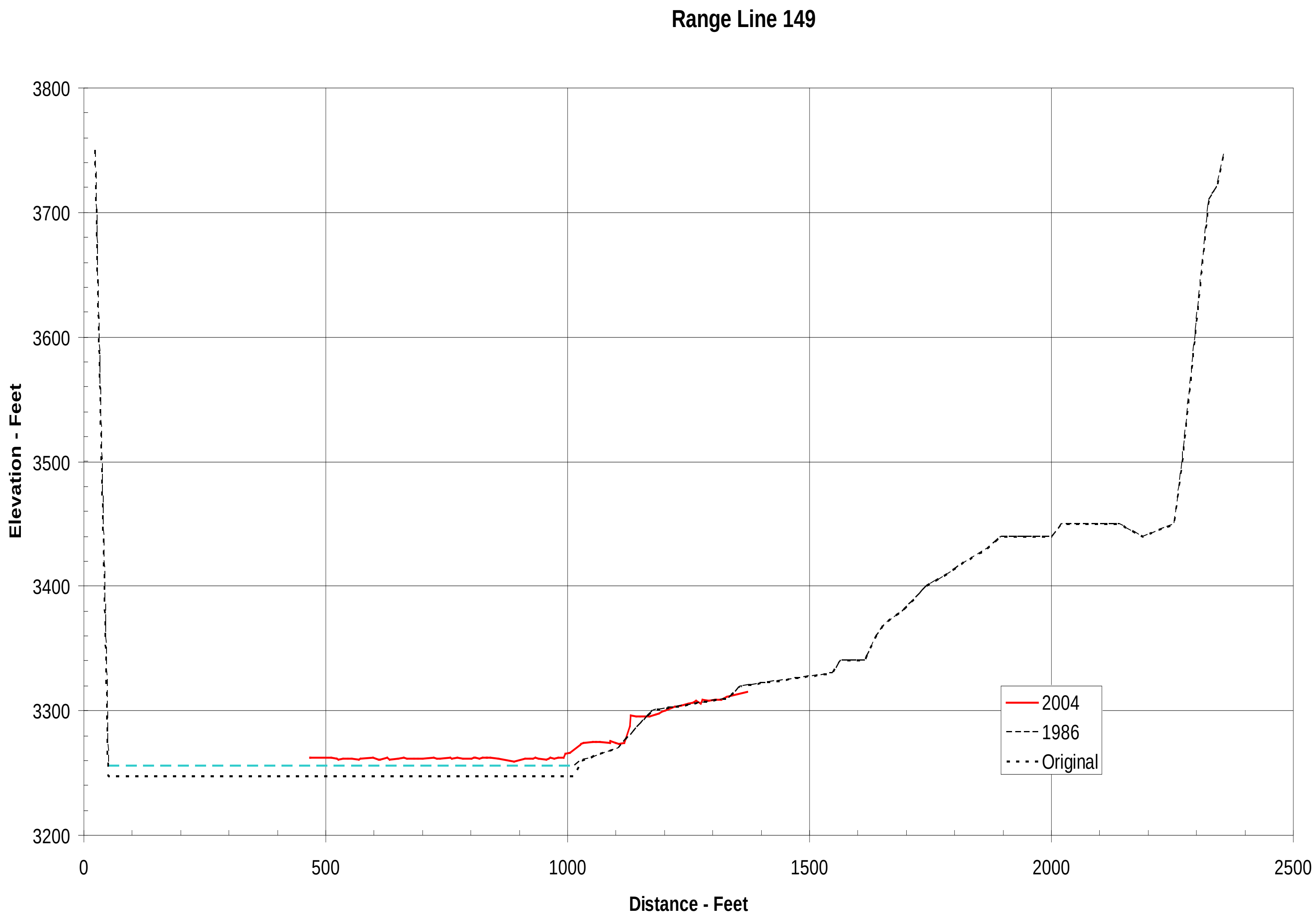

Range Line 142
3800
3700
3600
3500
3400
3300
3200
Elevation - Feet
0
1000
2000
3000
4000
5000
6000
Distance - Feet
2004
1986
Original


Range Line 144
3800
3700
3600
3500
3400
3300
3200
Elevation - Feet
0
500
1000
1500
2000
2500
Distance - Feet
2004
1986
Original

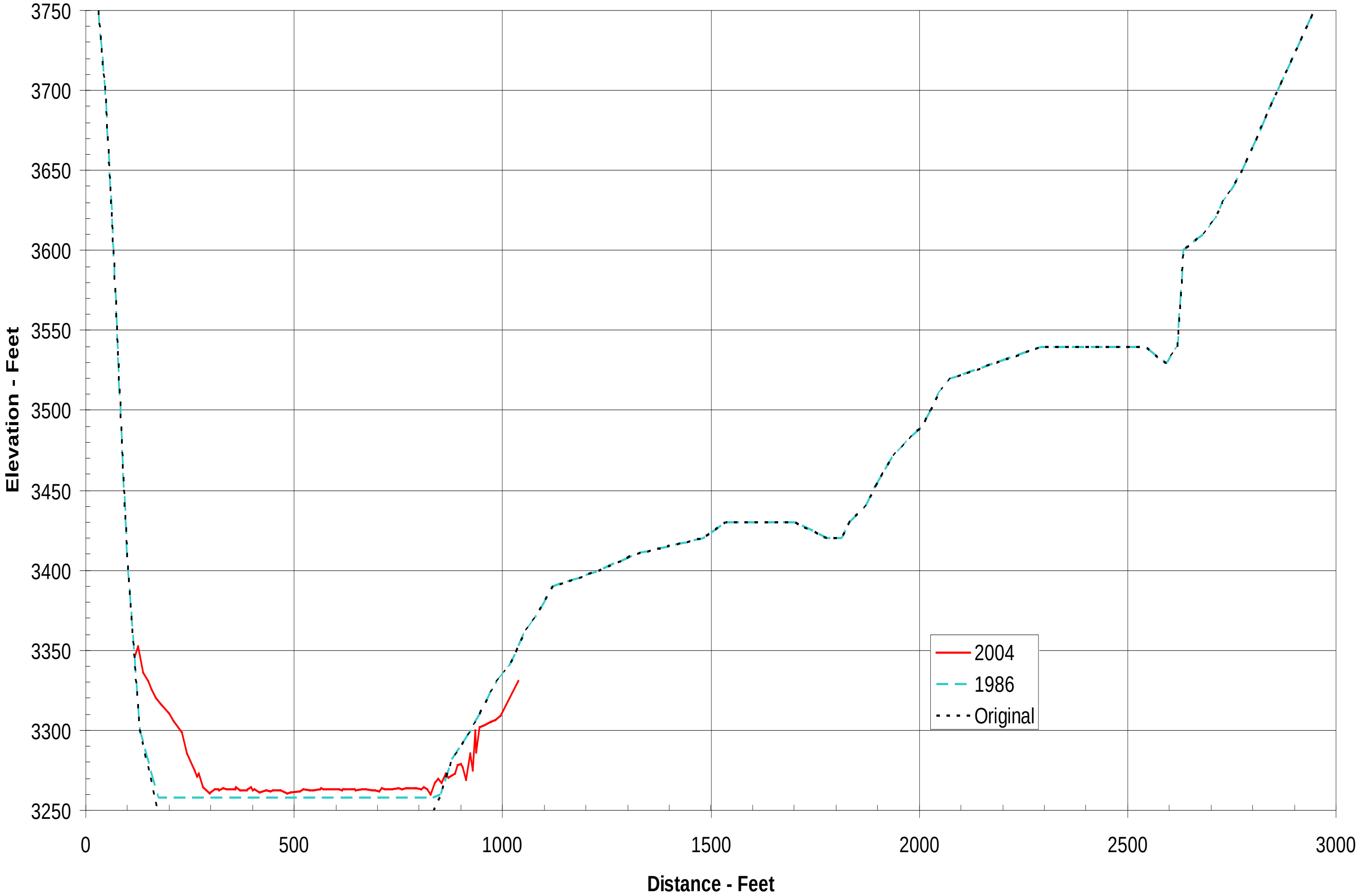

Range Line 145
3750
3650
3550
3450
3350
3250
3150
Elevation - Feet
0
500
1000
1500
2000
2500
3000
3500
4000
4500
Distance - Feet
2004
1986
Original



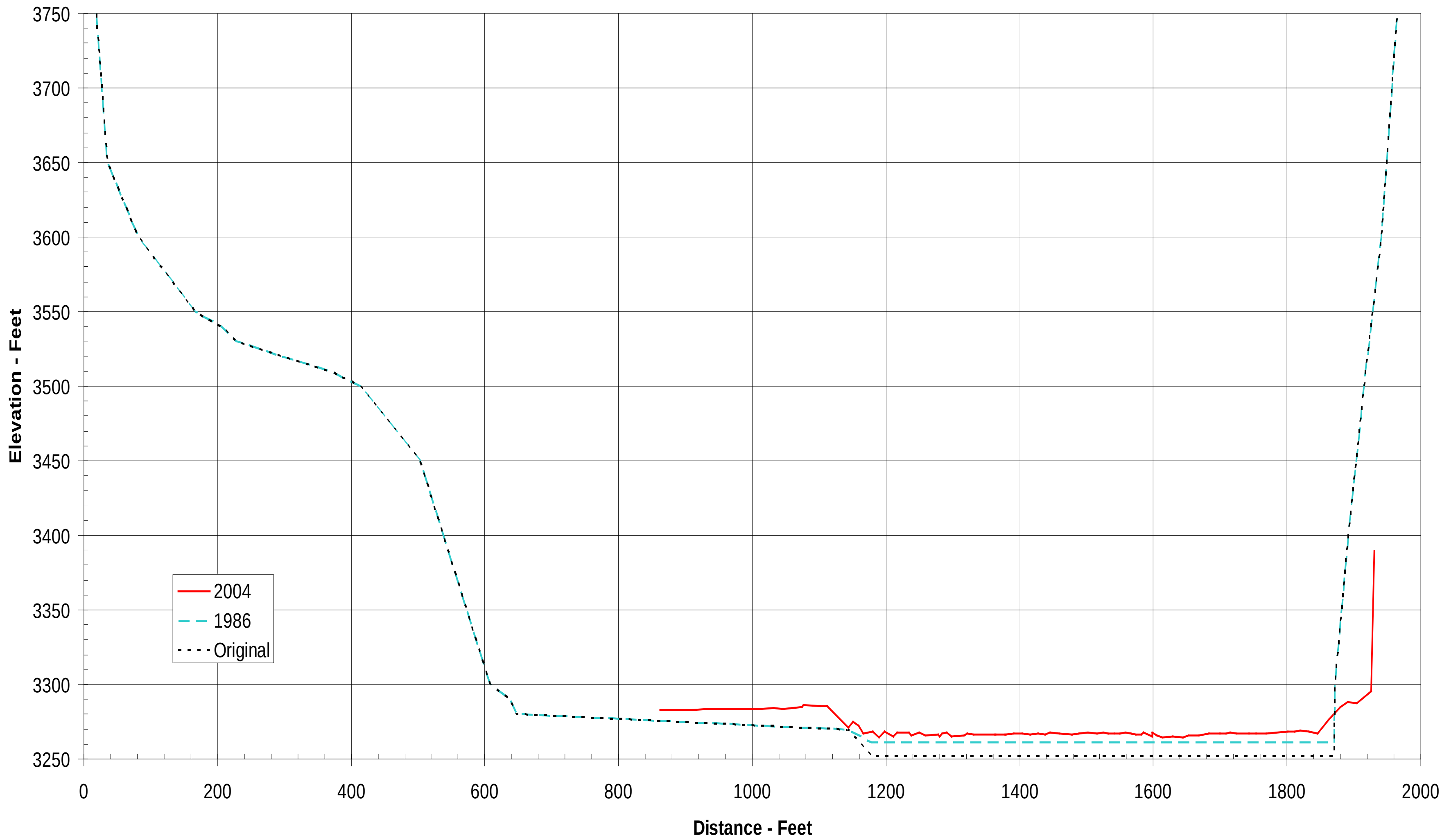
Range Line 146
Elevation - Feet
3750
3700
3650
3600
3550
3500
3450
3400
3350
3300
3250
0
500
1000
1500
2000
2500
3000
3500
4000
Distance - Feet
2004
1986
Original


Range Line 149
Elevation - Feet
3800
3700
3600
3500
3400
3300
3200
0
500
1000
1500
2000
2500
Distance - Feet
2004
1986
Original

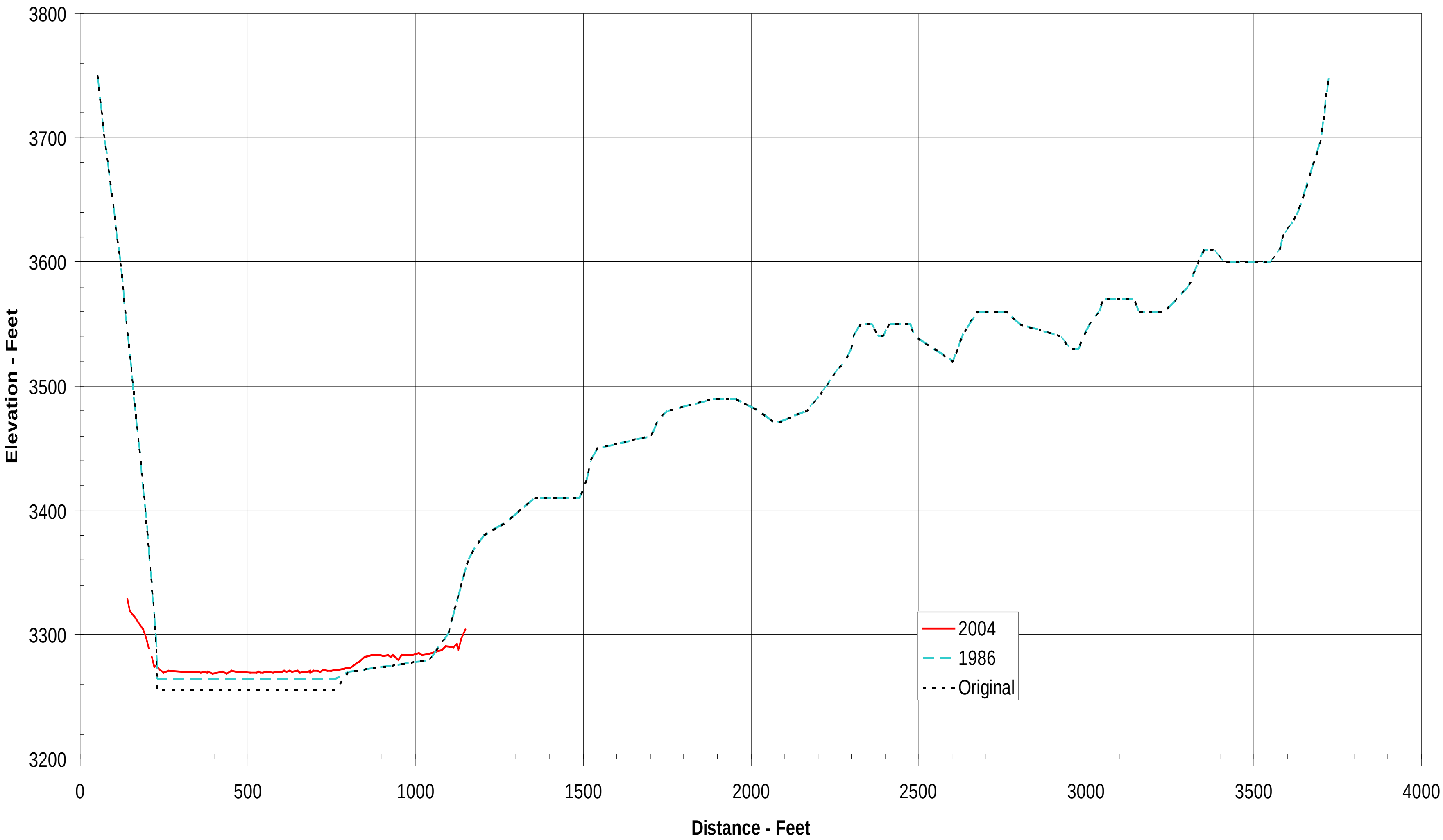
Range Line 150

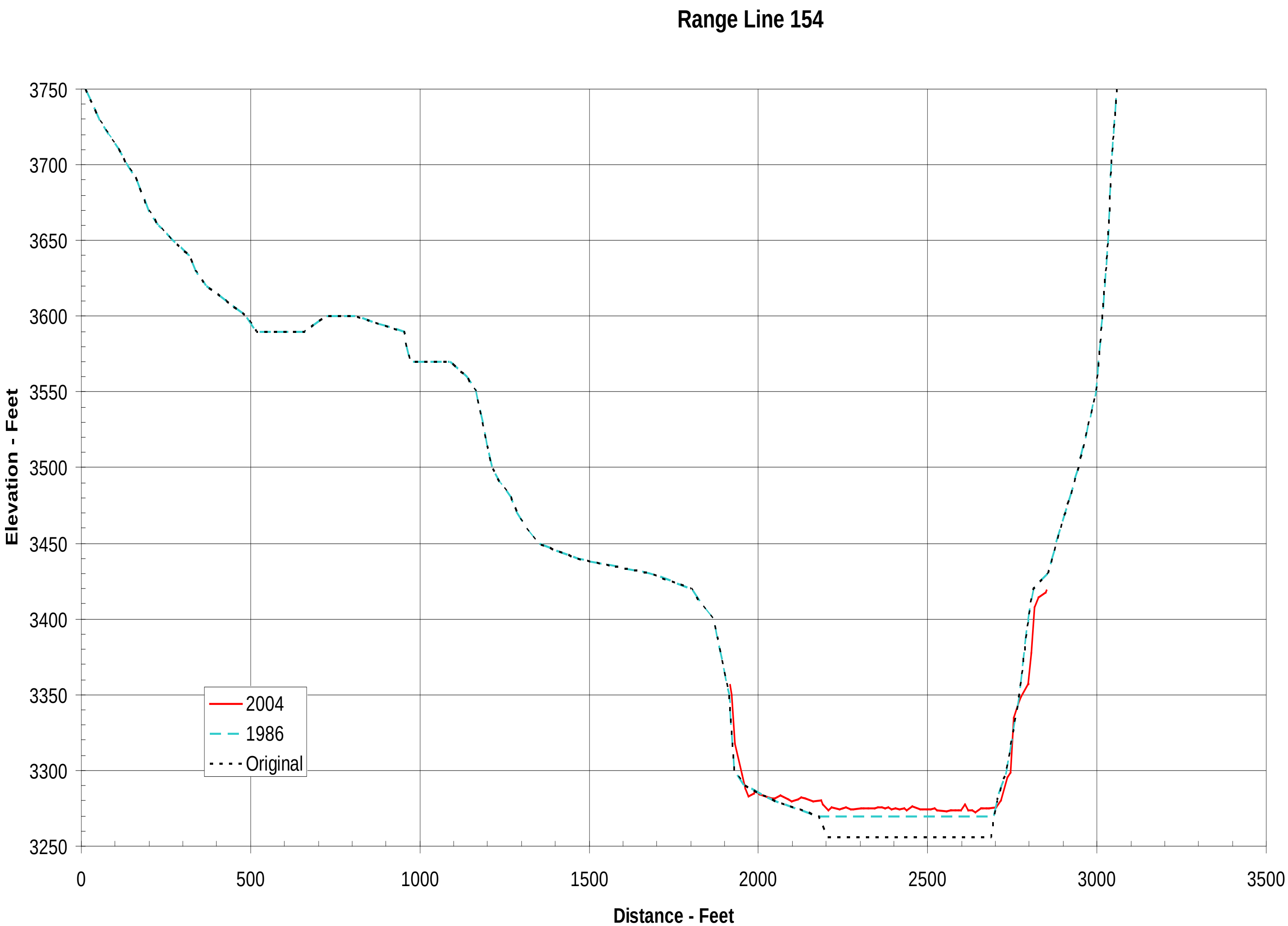


Range Line 151



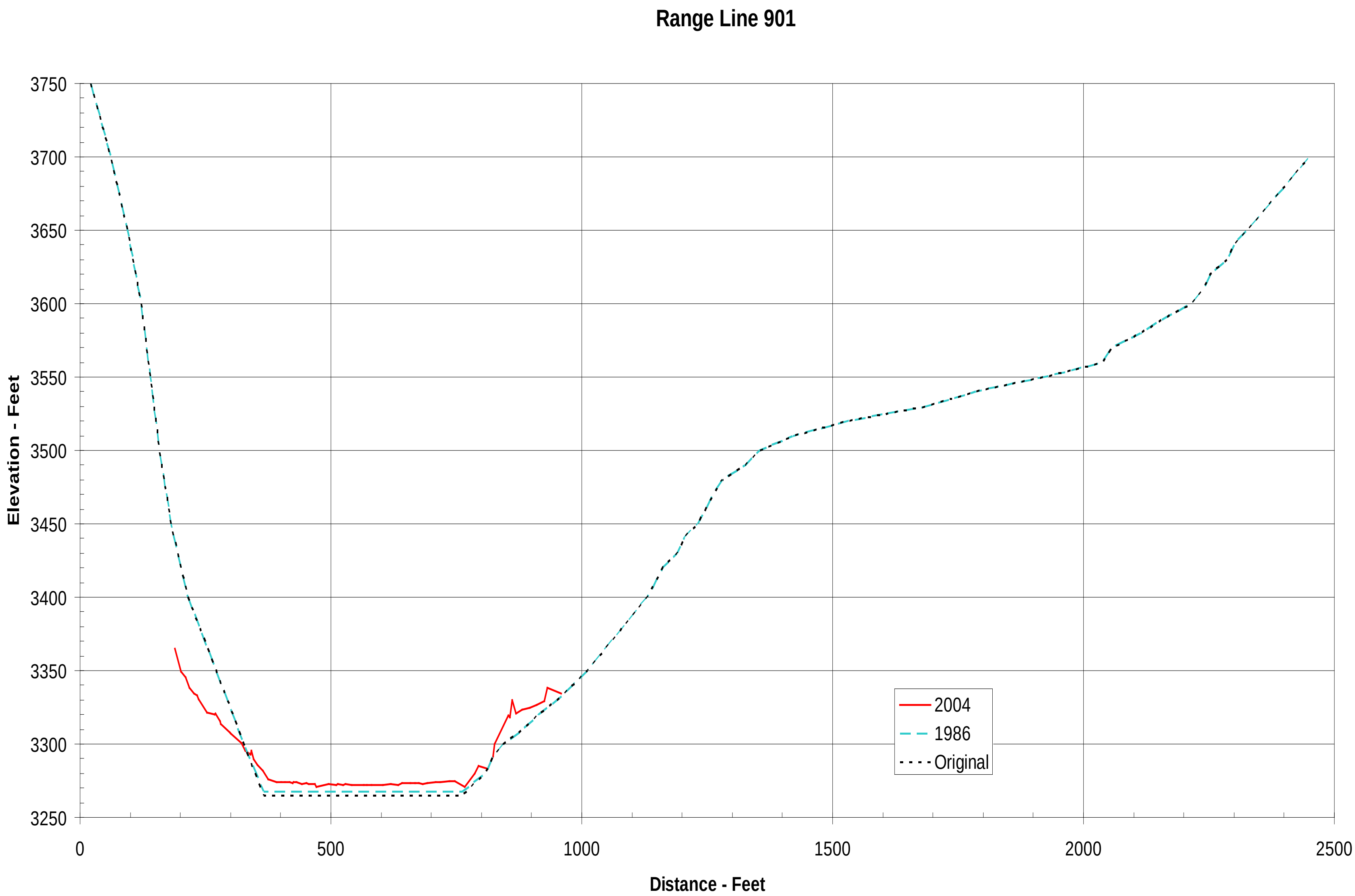
Range Line 153



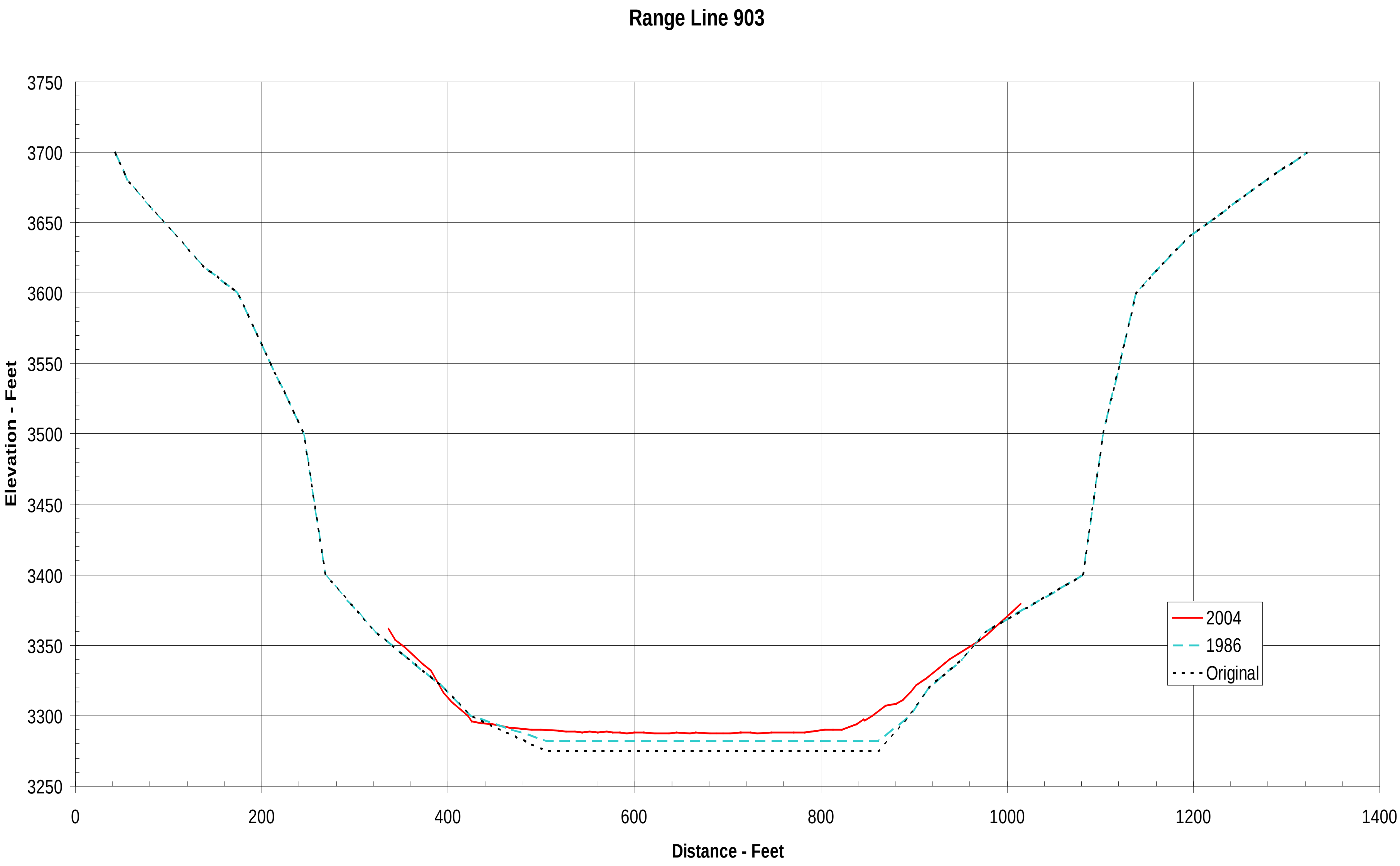

Range Line 154
Elevation - Feet
3750
3700
3650
3600
3550
3500
3450
3400
3350
3300
3250
0
500
1000
1500
2000
2500
3000
3500
Distance - Feet
2004
1986
Original

Appendix III --

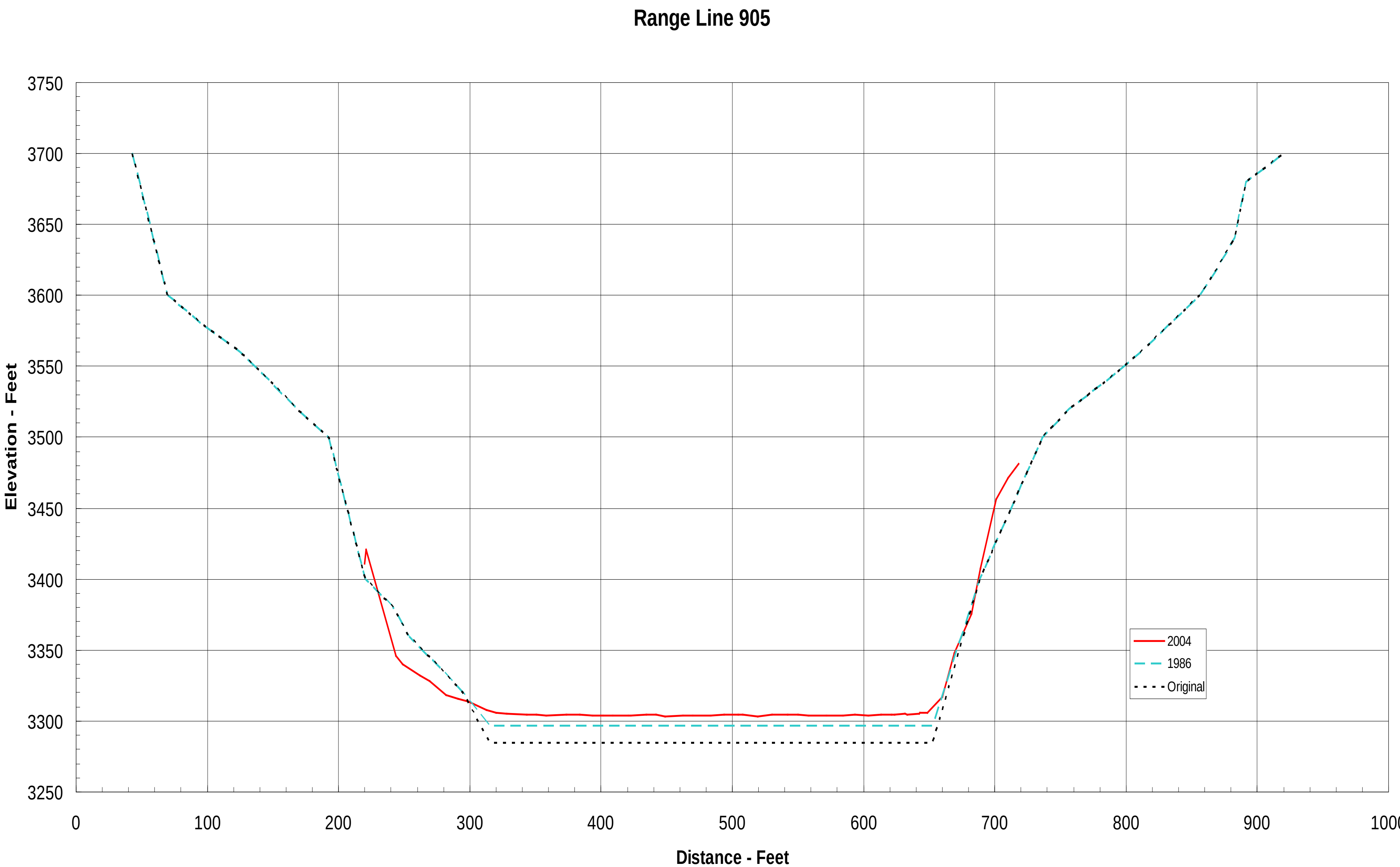
San Juan River Range Line Plots

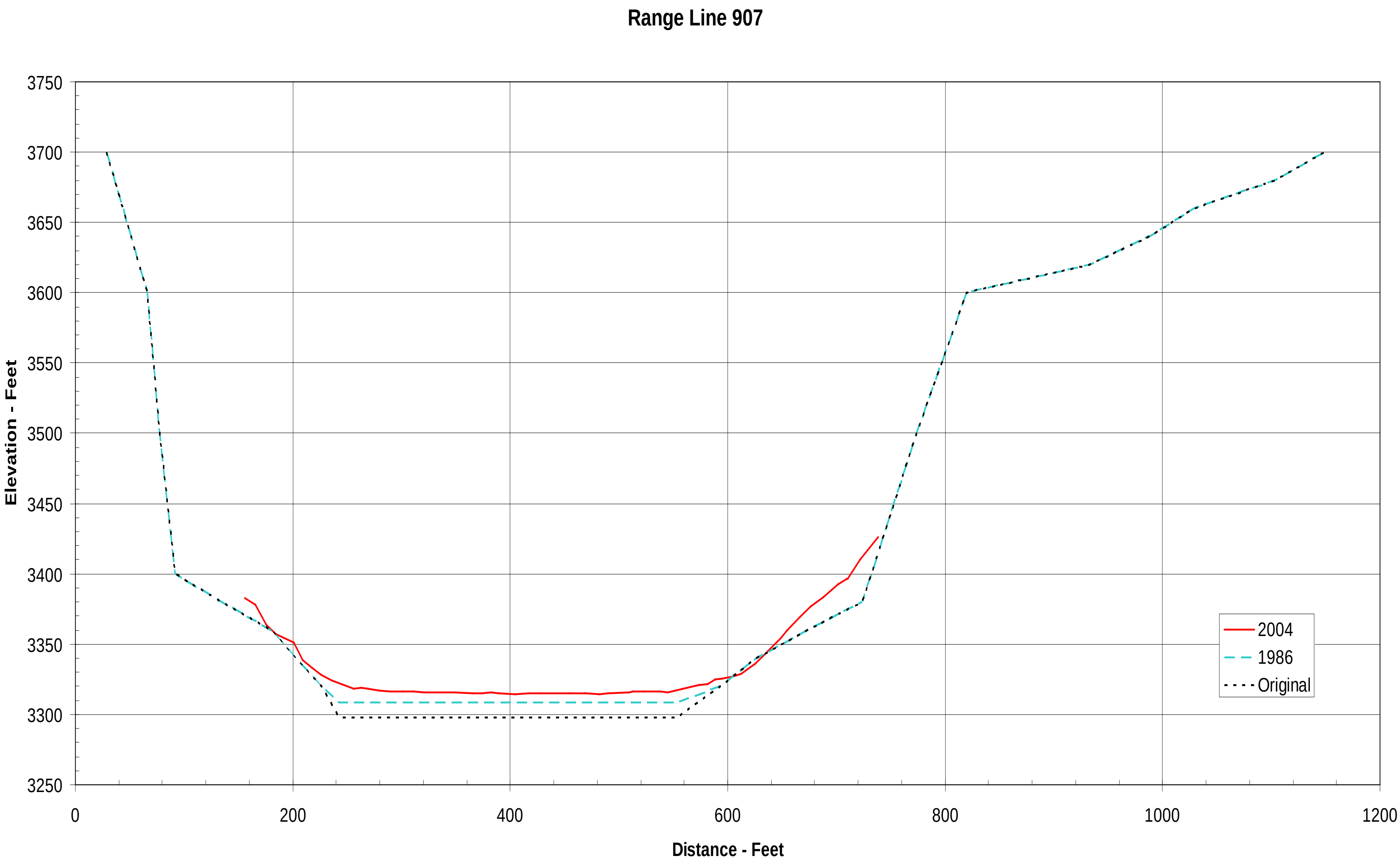


Range Line 901
Elevation - Feet
Distance - Feet
3750
3700
3650
3600
3550
3500
3450
3400
3350
3300
3250
0
500
1000
1500
2000
2500
2004
1986
Original

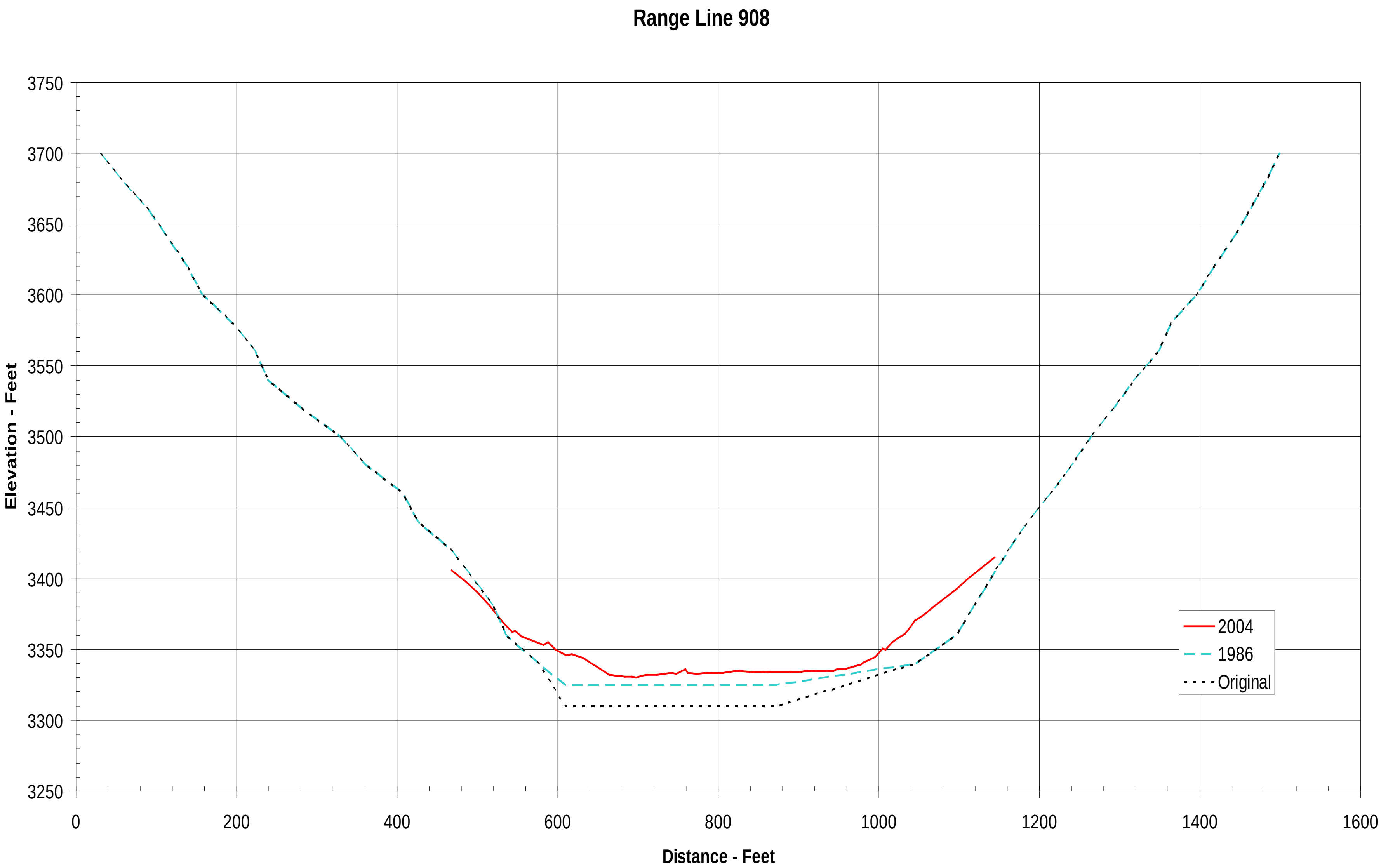


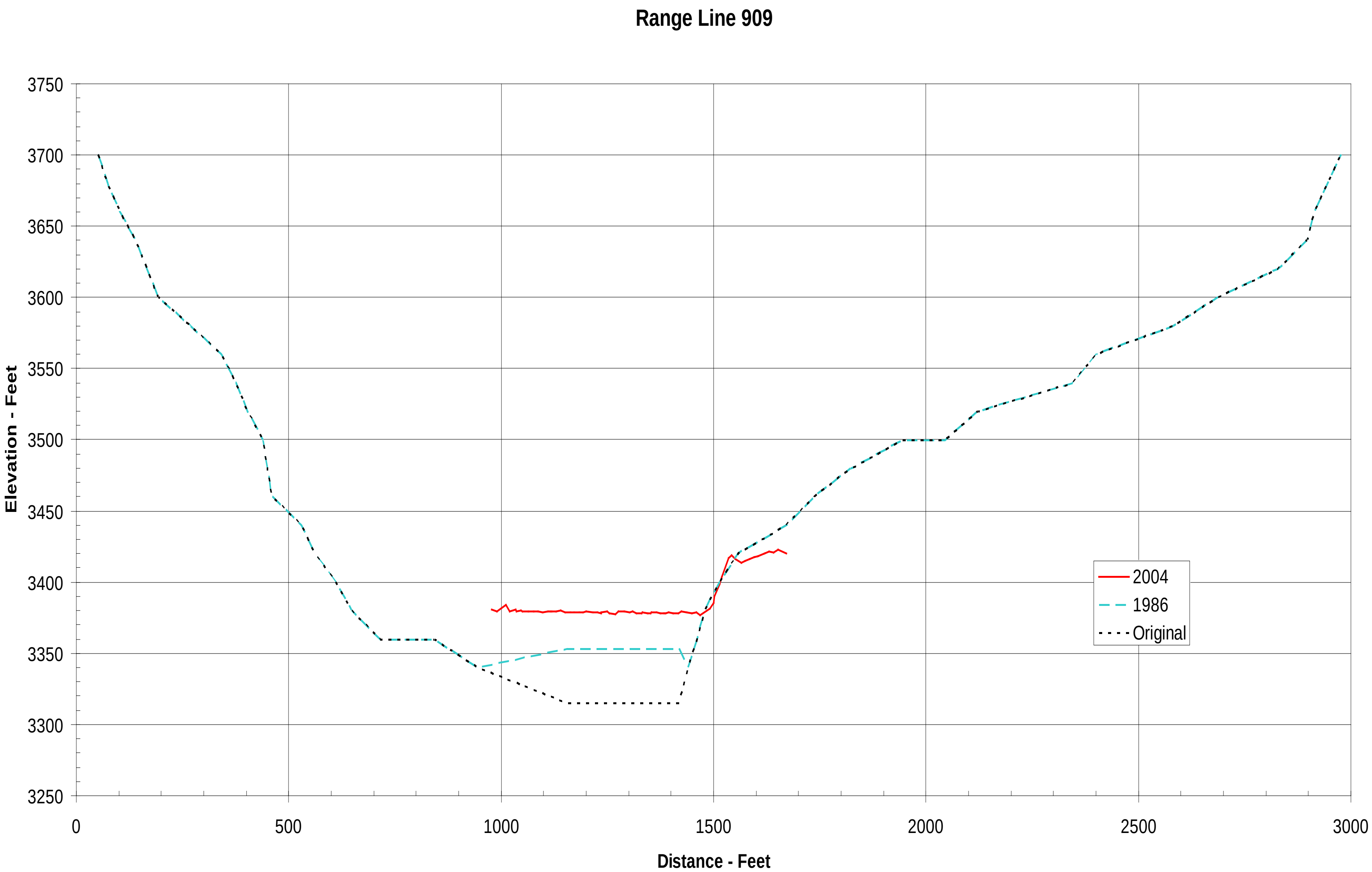
Range Line 903
Elevation - Feet
3750
3700
3650
3600
3550
3500
3450
3400
3350
3300
3250
0
200
400
600
800
1000
1200
1400
Distance - Feet
2004
1986
Original


Range Line 905
3750
3700
3650
3600
3550
3500
3450
3400
3350
3300
3250
Elevation - Feet
0
100
200
300
400
500
600
700
800
900
1000
Distance - Feet
2004
1986
Original

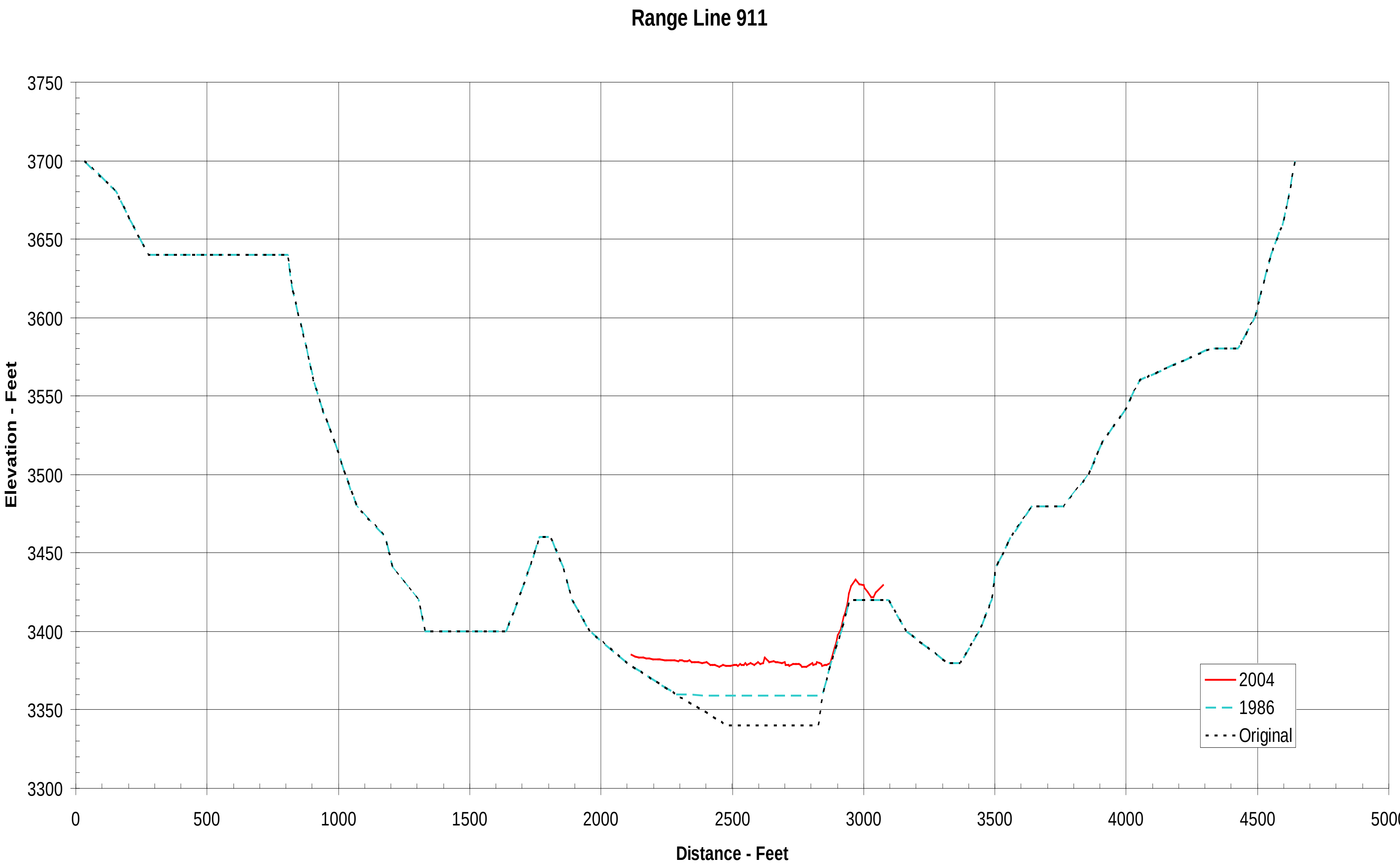


Range Line 907
3750
3700
3650
3600
3550
3500
3450
3400
3350
3300
3250
Elevation - Feet
0
200
400
600
800
1000
1200
Distance - Feet
2004
1986
Original

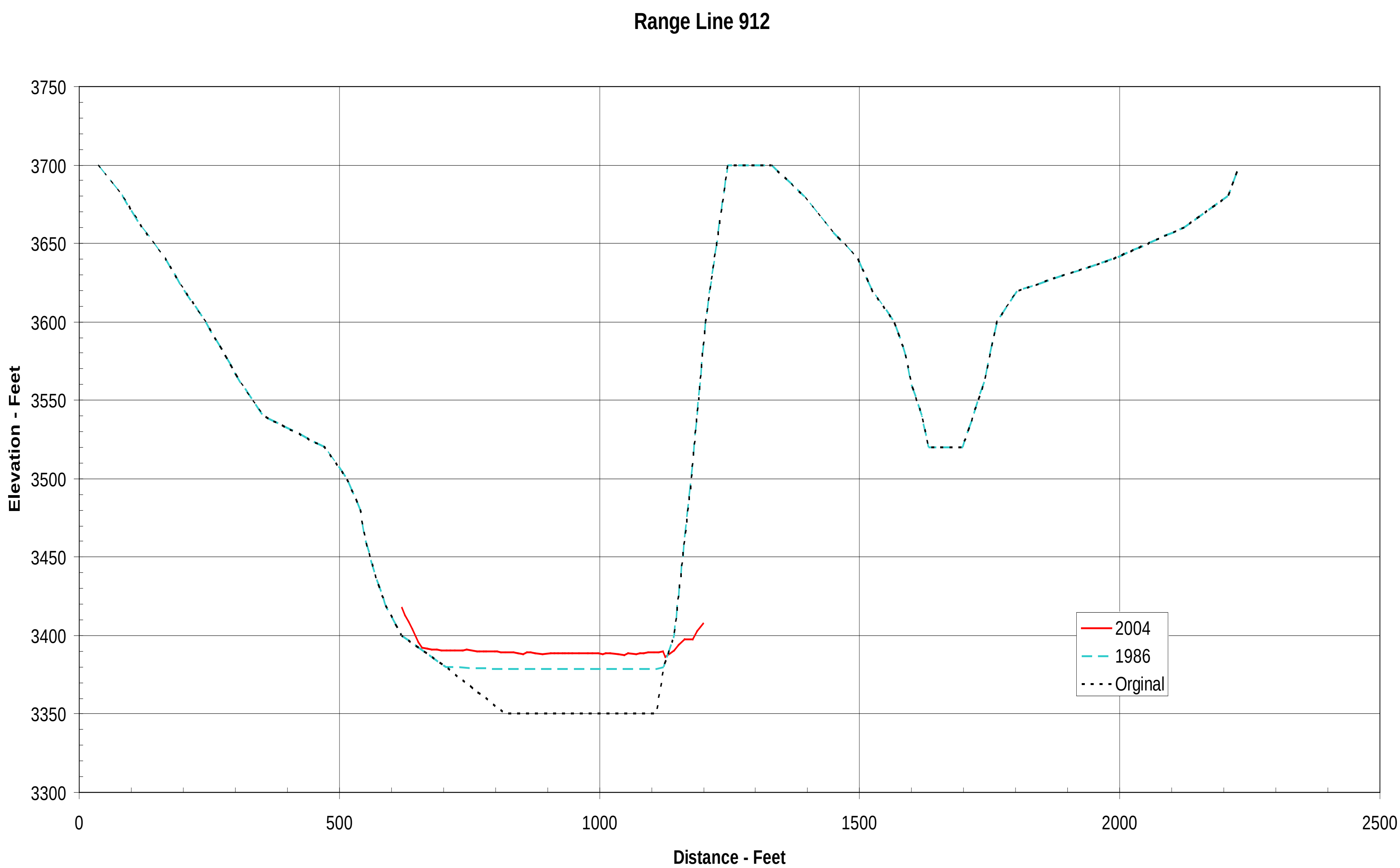

Range Line 908
Elevation - Feet
3750
3700
3650
3600
3550
3500
3450
3400
3350
3300
3250
0
200
400
600
800
1000
1200
1400
1600
Distance - Feet
2004
1986
Original



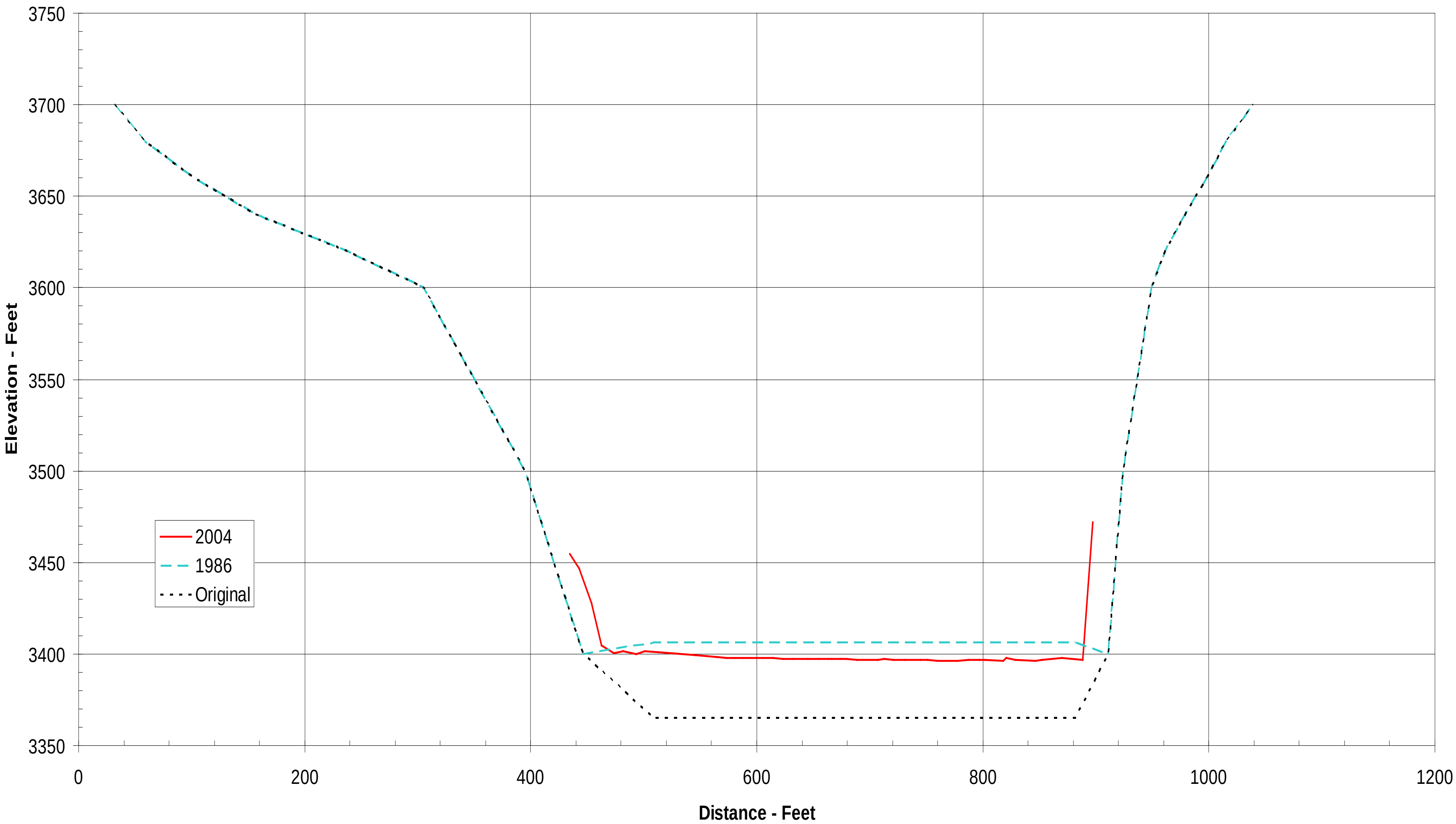
Range Line 909
Elevation - Feet
3750
3700
3650
3600
3550
3500
3450
3400
3350
3300
3250
0
500
1000
1500
2000
2500
3000
Distance - Feet
2004
1986
Original



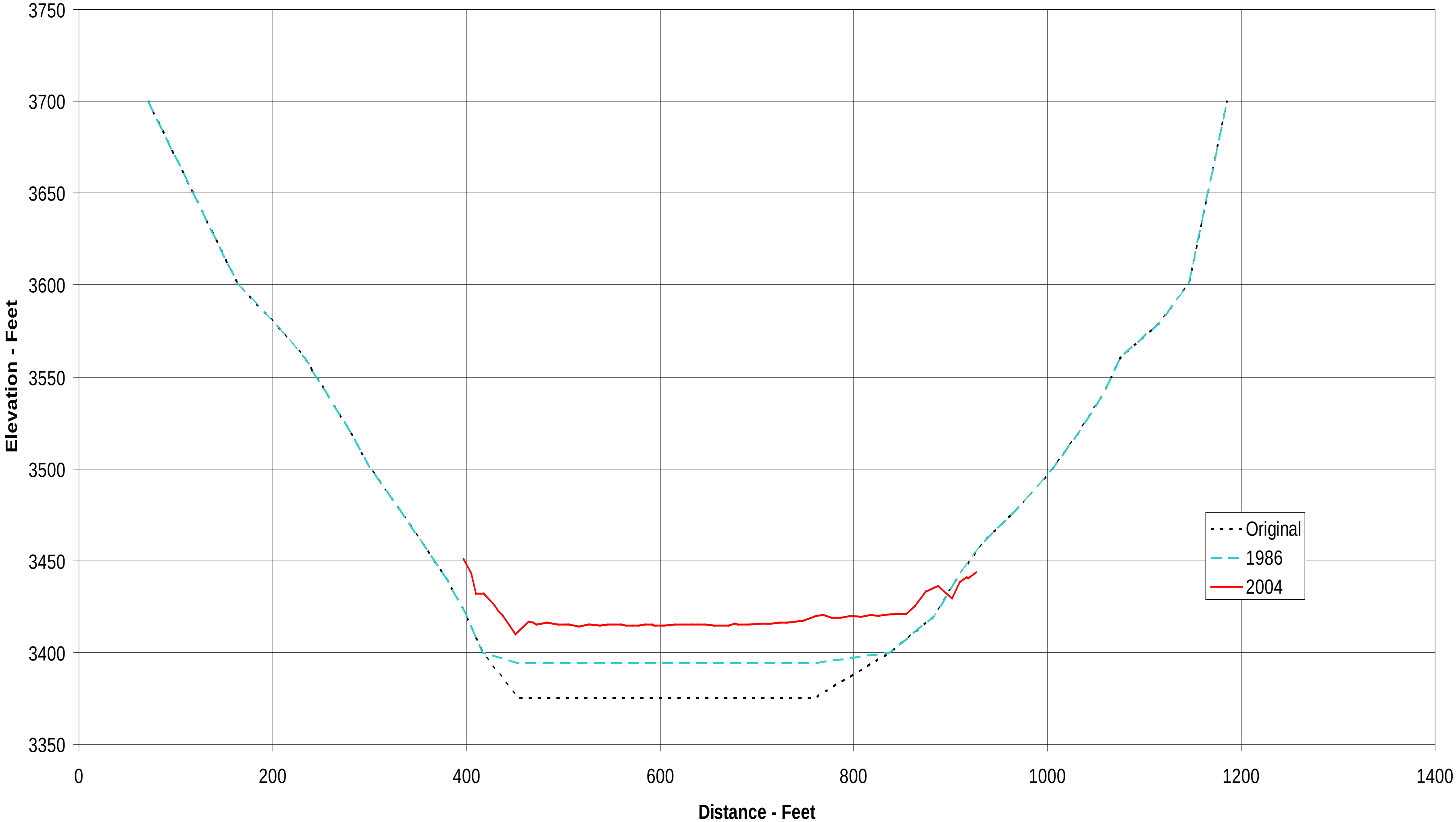
Range Line 911
3750
3700
3650
3600
3550
3500
3450
3400
3350
3300
Elevation - Feet
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
Distance - Feet
2004
1986
Original

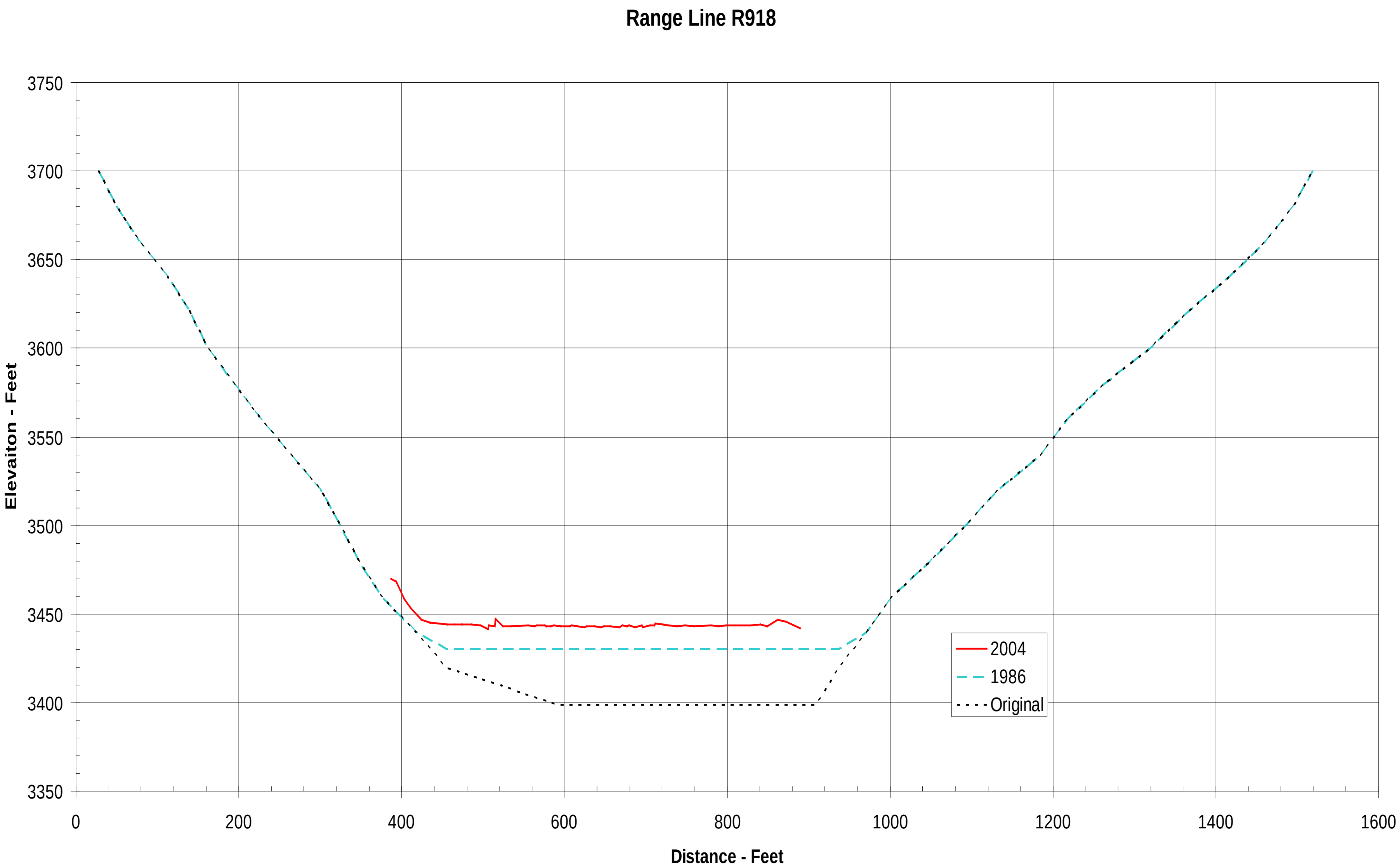

Range Line 912
3750
3700
3650
3600
3550
3500
3450
3400
3350
3300
Elevation - Feet
0
500
1000
1500
2000
2500
Distance - Feet
2004
1986
Orginal

Range Line 914



Range Line 915




Range Line R918
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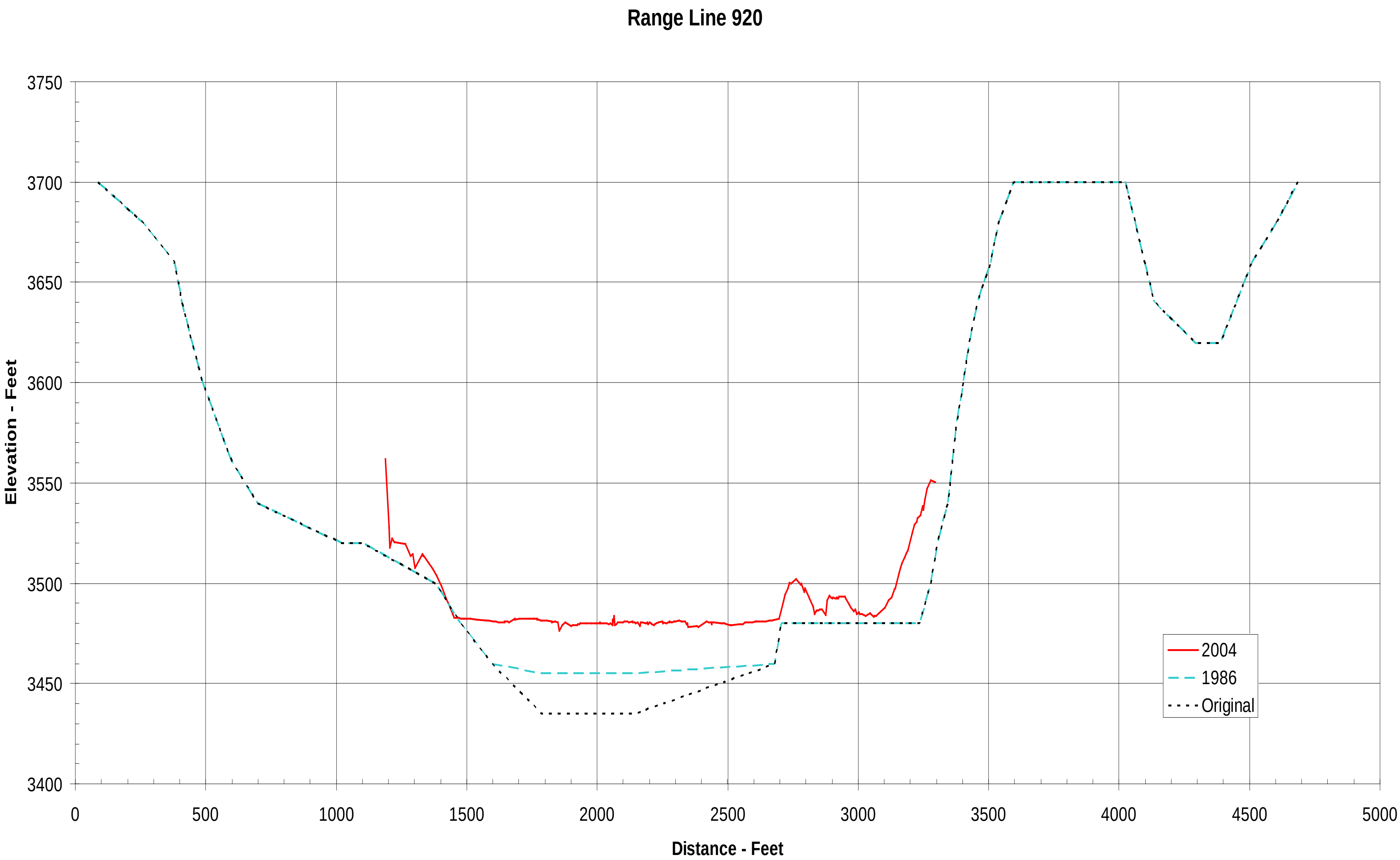
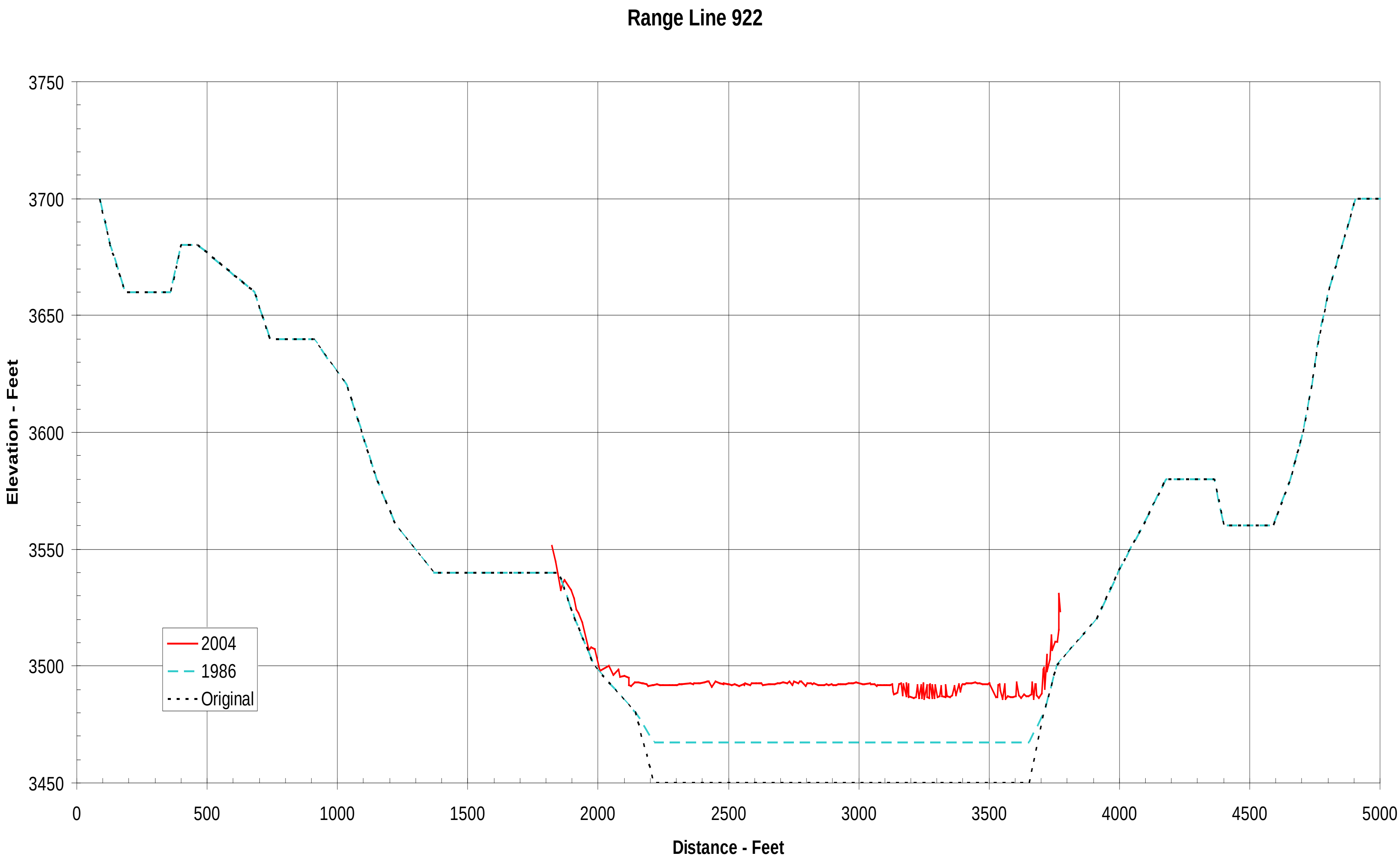
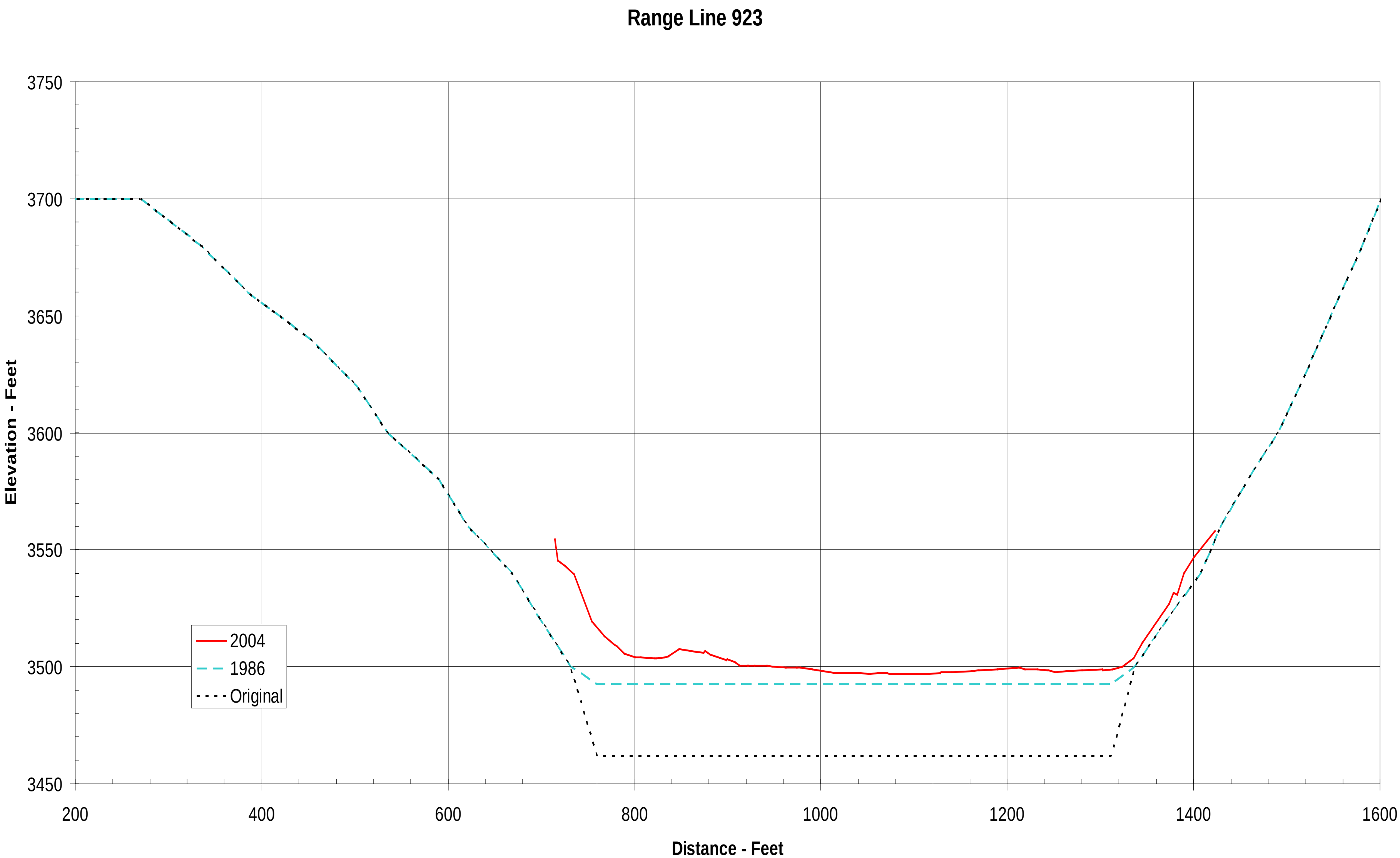
3700
3650
3600
3550
3500
3450
3400
3350
Elevaiton - Feet
0
200
400
600
800
1000
1200
1400
1600
Distance - Feet
2004
1986
Original



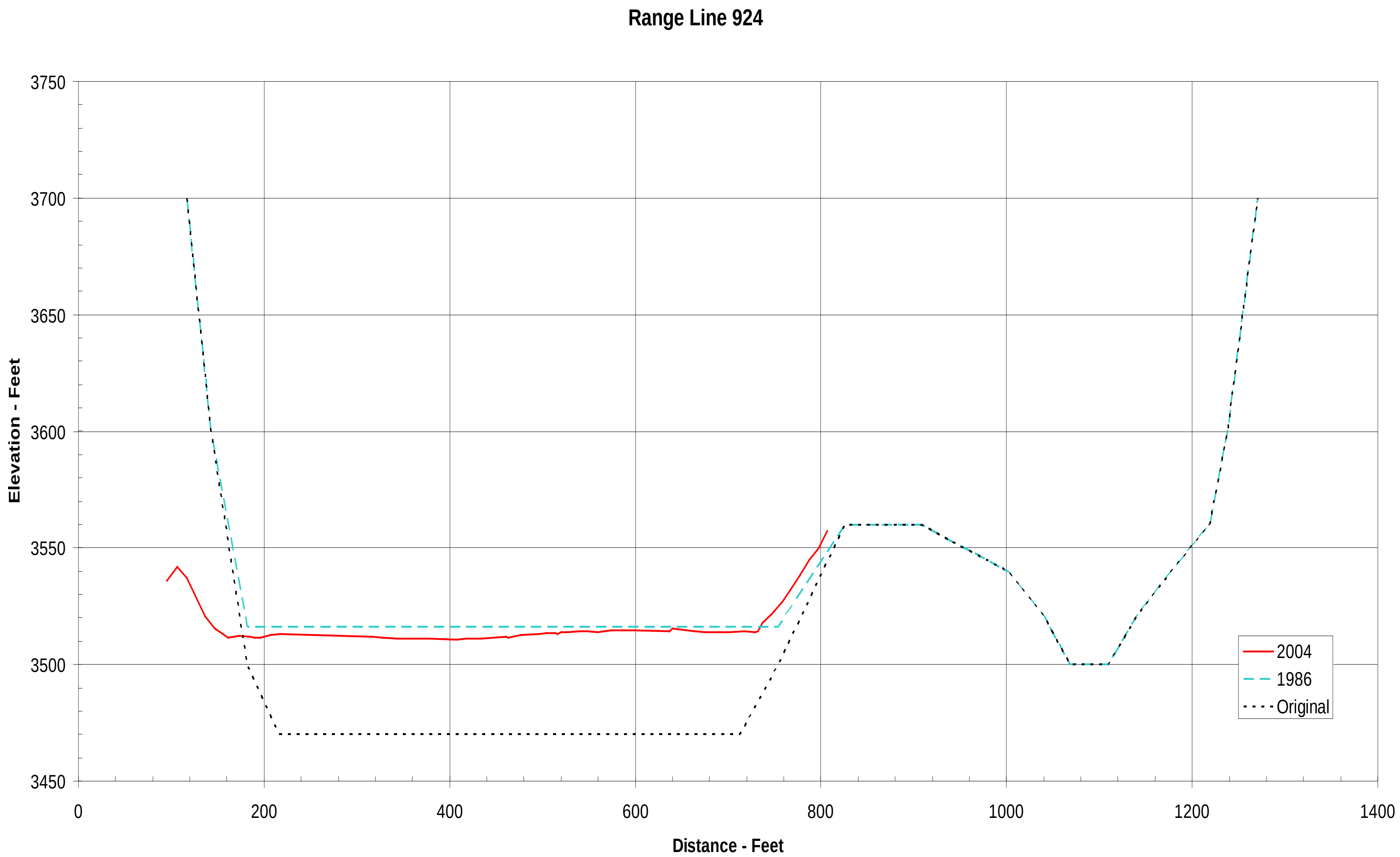
Range Line 920
Elevation - Feet
3750
3700
3650
3600
3550
3500
3450
3400
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
Distance - Feet
2004
1986
Original

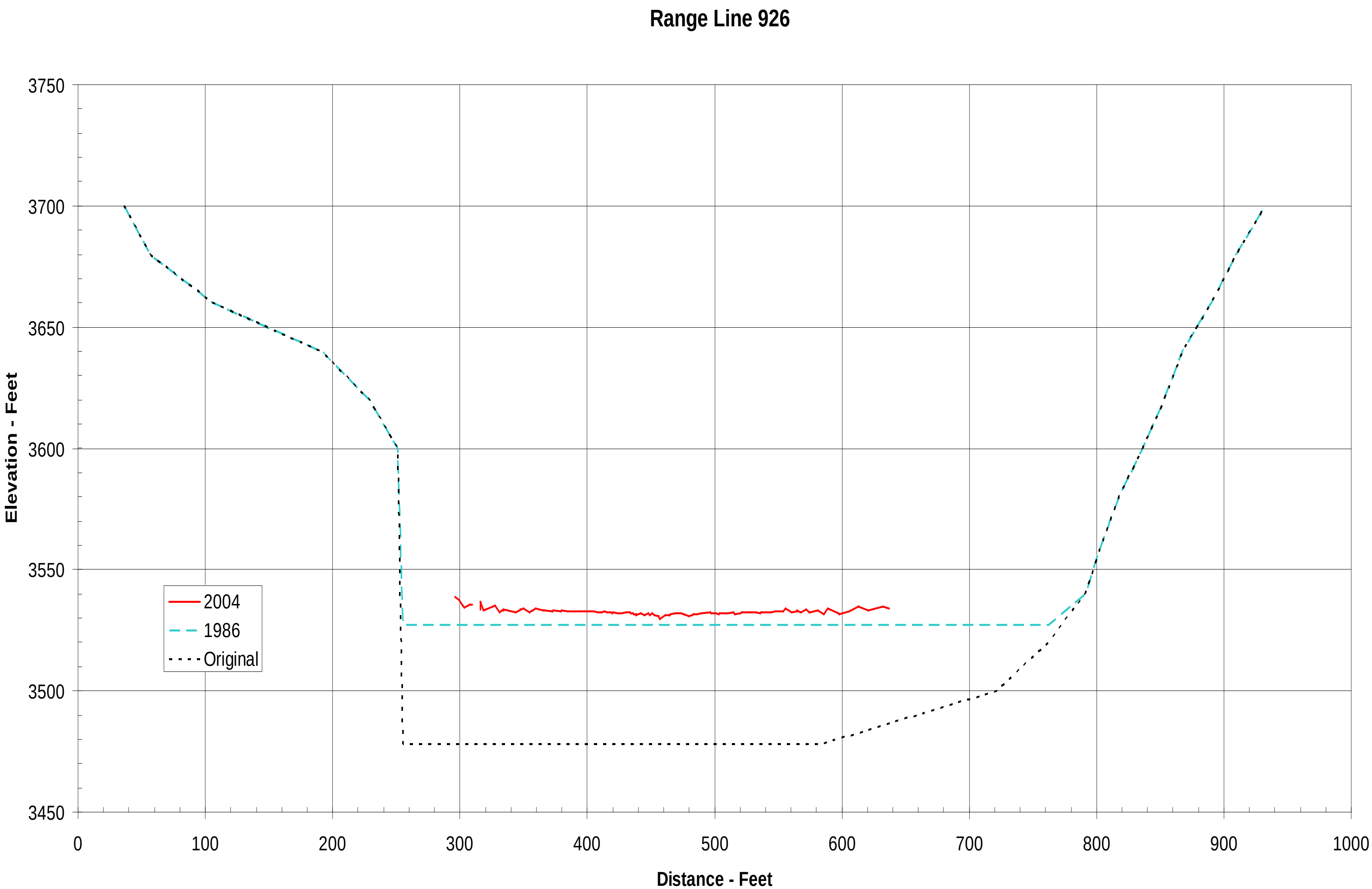


Range Line 922
3750
3700
3650
3600
3550
3500
3450
Elevation - Feet
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
Distance - Feet
2004
1986
Original

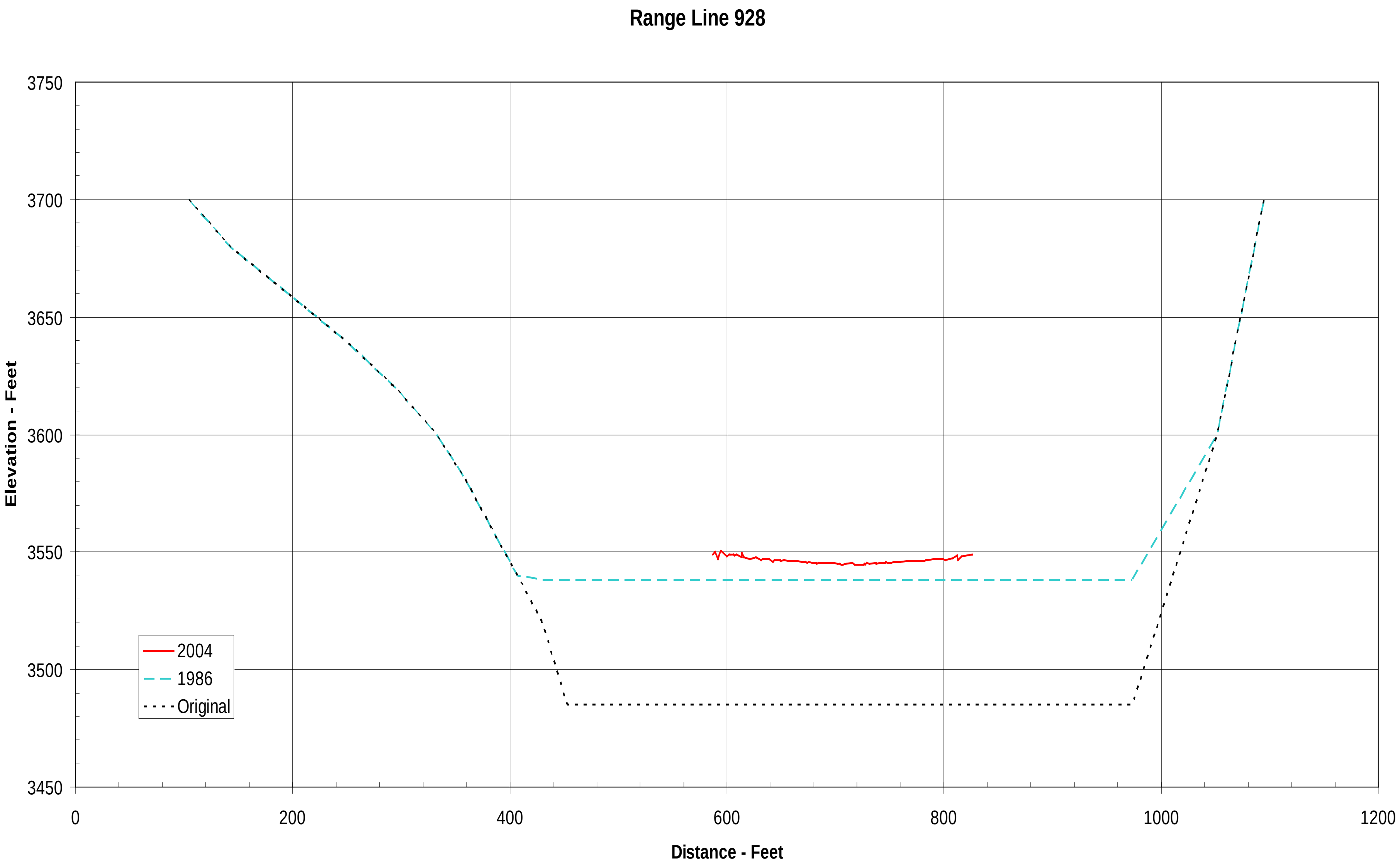


Range Line 923
Elevation - Feet
3750
3700
3650
3600
3550
3500
3450
200
400
600
800
1000
1200
1400
1600
Distance - Feet
2004
1986
Original


Range Line 924
3750
3700
3650
3600
3550
3500
3450
Elevation - Feet
0
200
400
600
800
1000
1200
1400
Distance - Feet
2004
1986
Original



Range Line 926
3750
3700
3650
3600
3550
3500
3450
Elevation - Feet
0
100
200
300
400
500
600
700
800
900
1000
Distance - Feet
2004
1986
Original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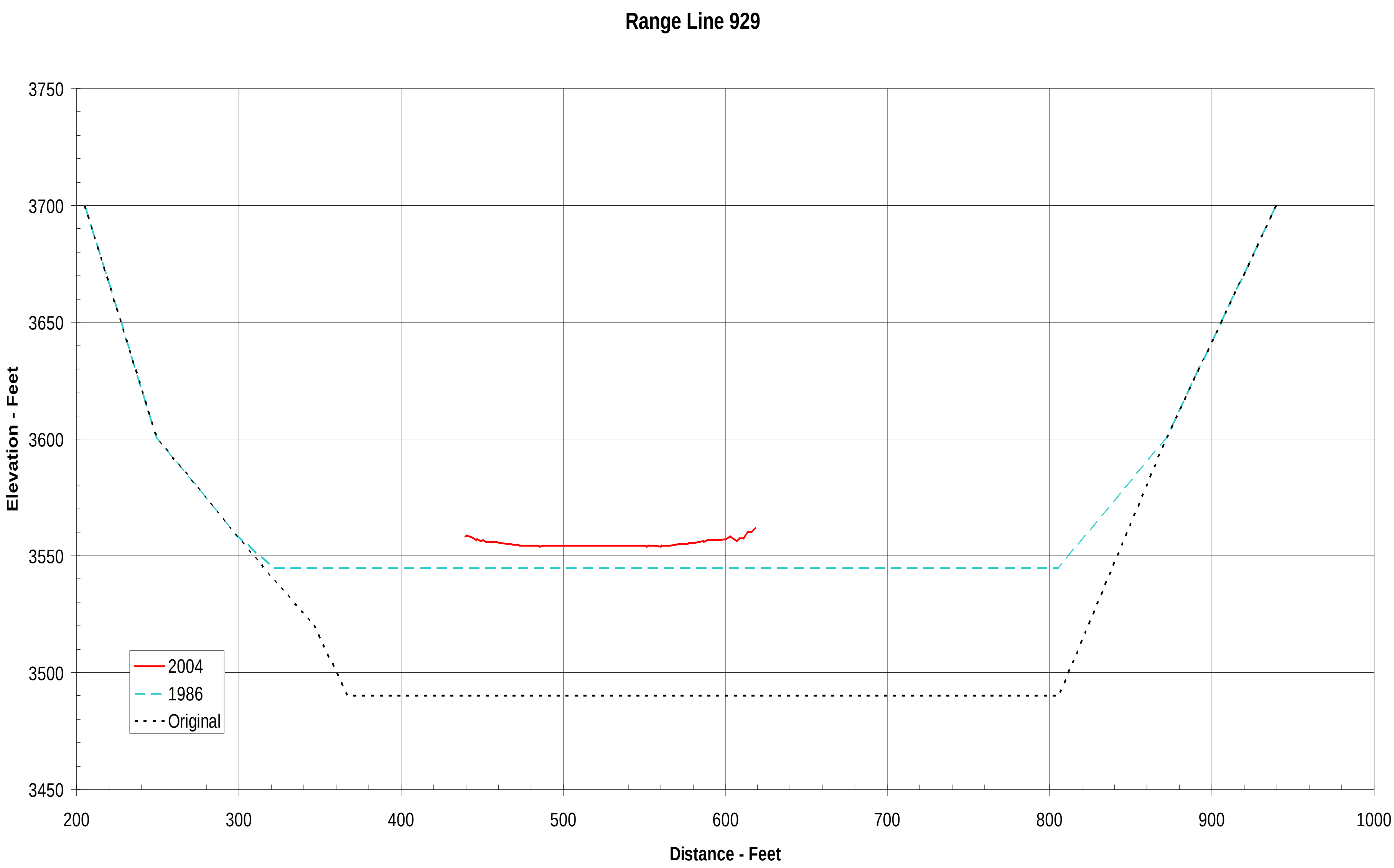
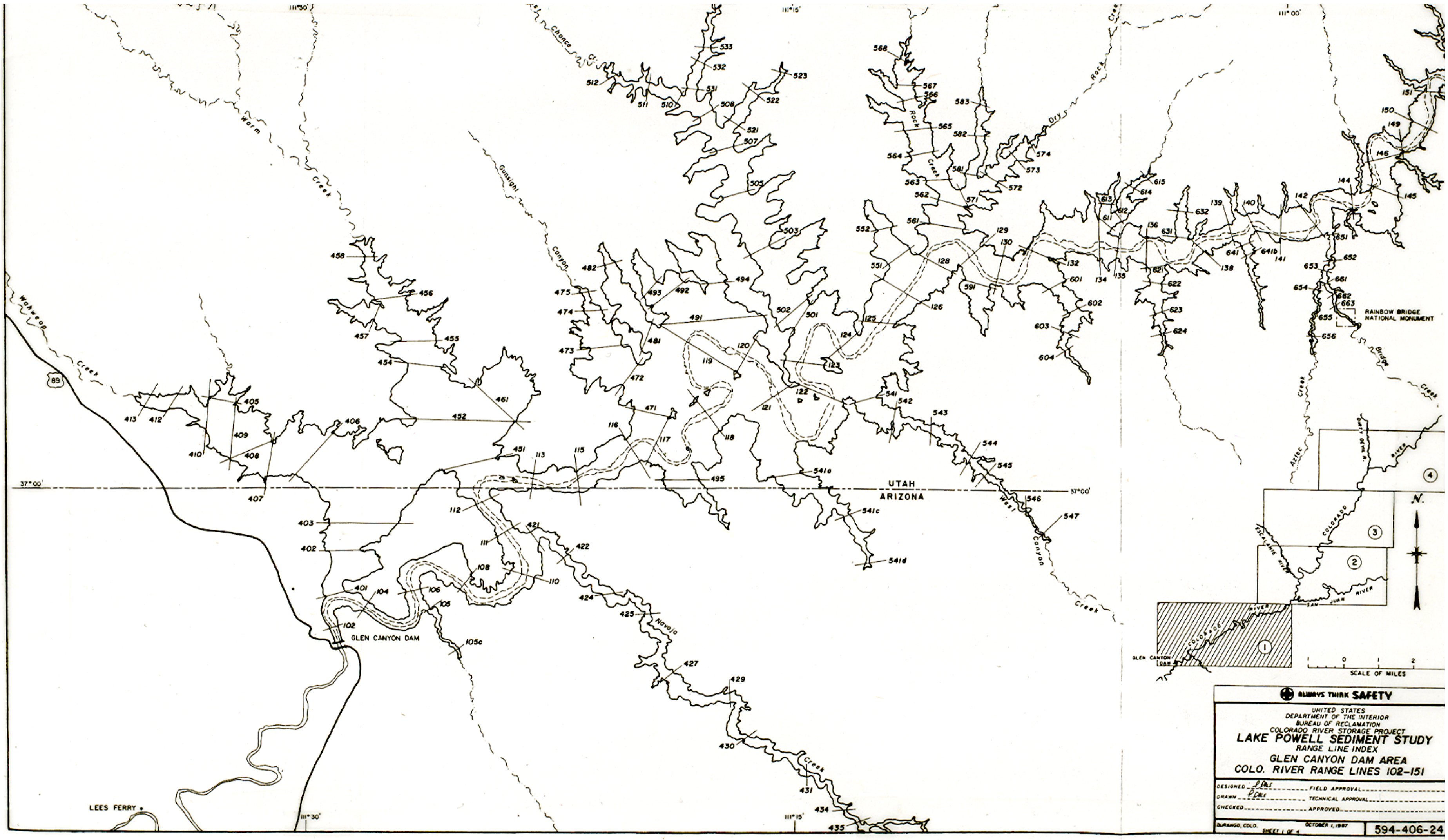
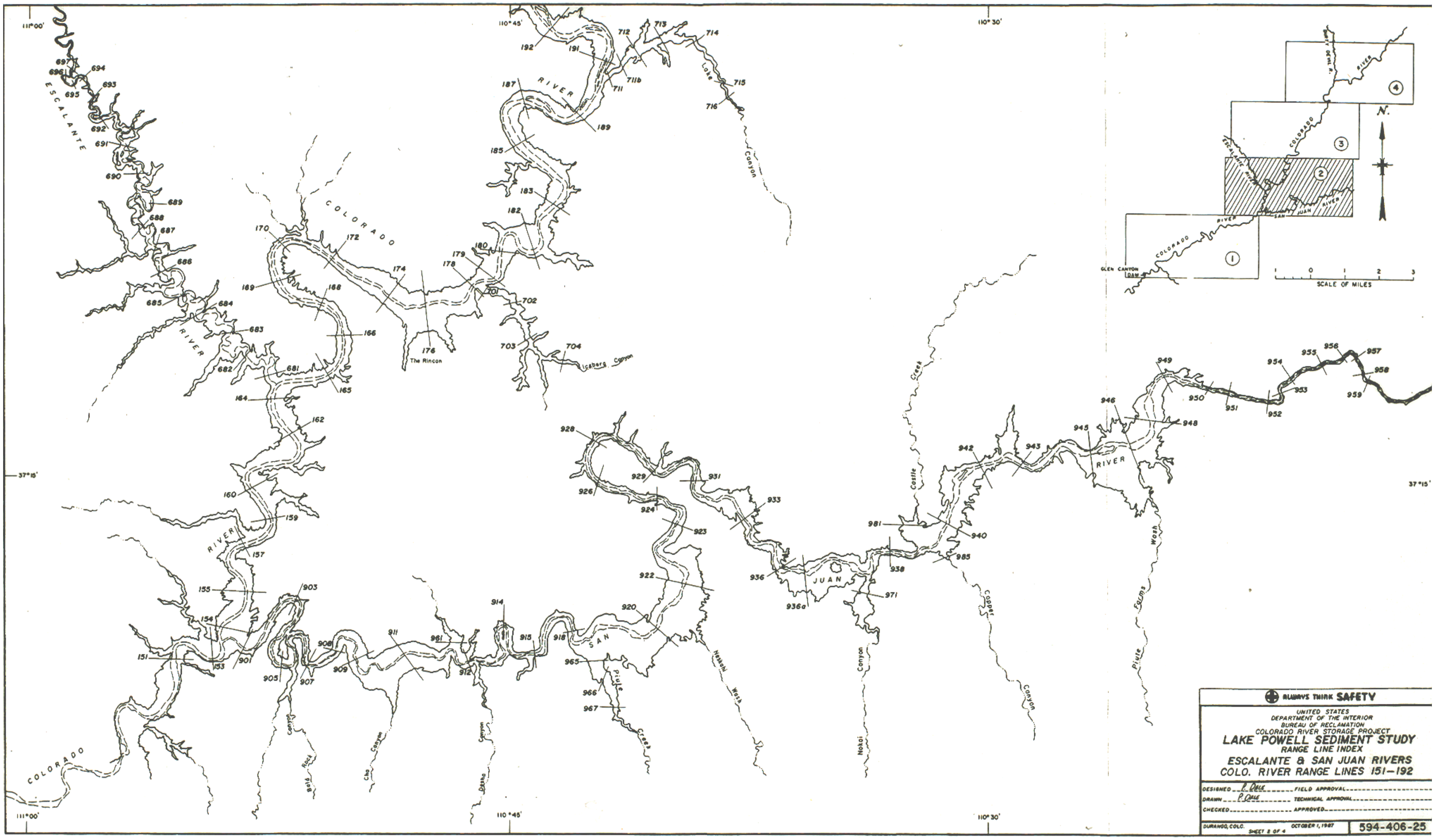
3750
3700
3650
3600
3550
3500
3450
Elevation - Feet
0
200
400
600
800
1000
1200
Distance - Feet
2004
1986
Original

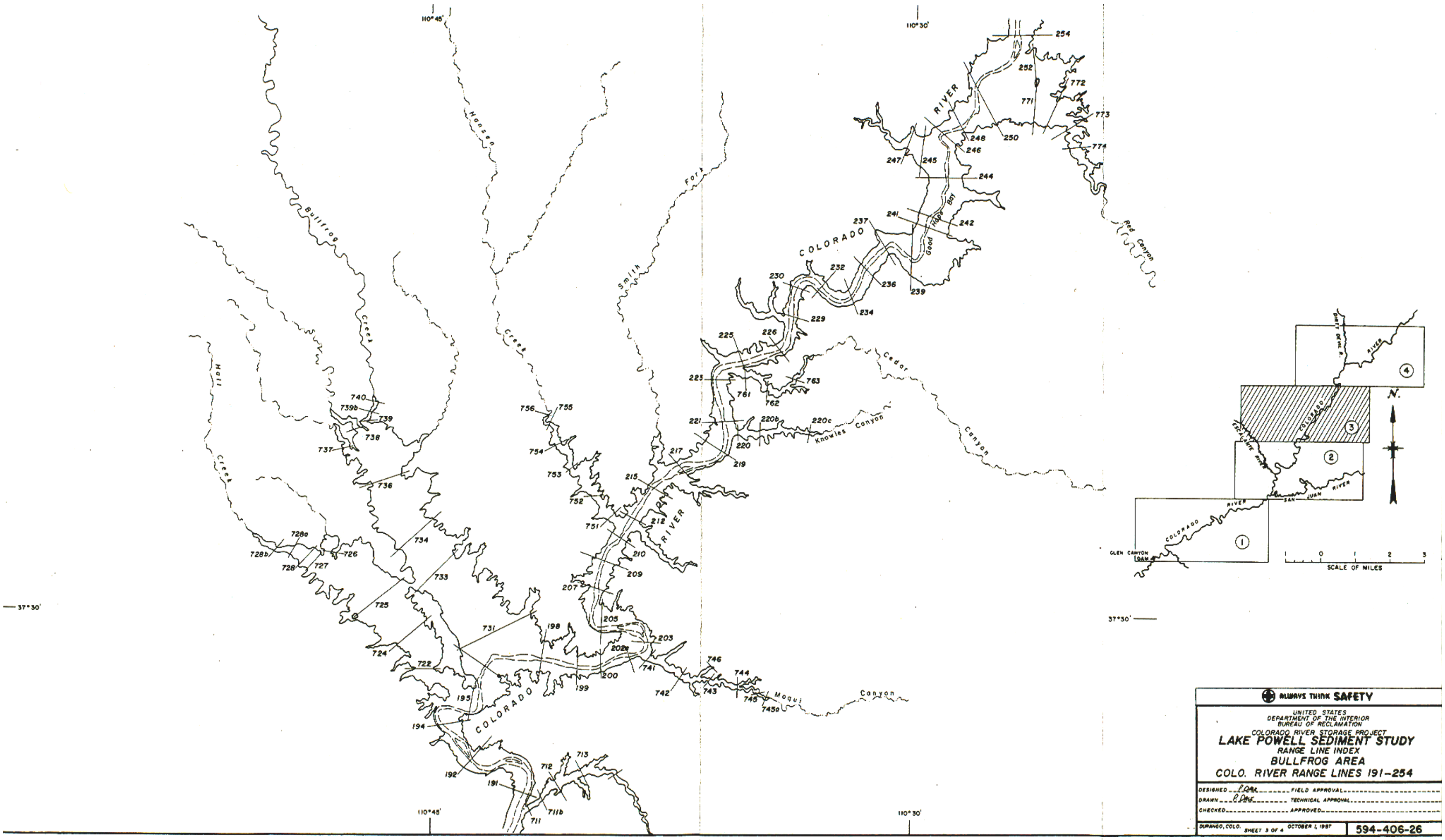

Range Line 929
3750
3700
3650
3600
3550
3500
3450
Elevation - Feet
200
300
400
500
600
700
800
900
1000
Distance - Feet
2004
1986
Original

Appendix IV --

Lake Powell 1986 Range Line Locations


UTAH
ARIZONA
GLEN CANYON DAM
LEES FERRY
RAINBOW BRIDGE NATIONAL MONUMENT
SCALE OF MILES
ALWAYS THINK SAFETY
UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
COLORADO RIVER STORAGE PROJECT
LAKE POWELL SEDIMENT STUDY
RANGE LINE INDEX
GLEN CANYON DAM AREA
COLO. RIVER RANGE LINES 102-151
DURANGO, COLO.
OCTOBER 1, 1967
594-406-24


ALWAYS THINK SAFETY
UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
COLORADO RIVER STORAGE PROJECT
LAKE POWELL SEDIMENT STUDY
RANGE LINE INDEX
ESCALANTE & SAN JUAN RIVERS
COLO. RIVER RANGE LINES 151–192
DESIGNED P. Dale
FIELD APPROVAL
DRAWN P. Dale
TECHNICAL APPROVAL
CHECKED
APPROVED
DURANGO, COLO.
SHEET 2 OF 4
OCTOBER 1, 1987
594-406-25
COLORADO
RIVER
ESCALANTE
SAN JUAN
The Rincon
SCALE OF MILES
GLEN CANYON DAM



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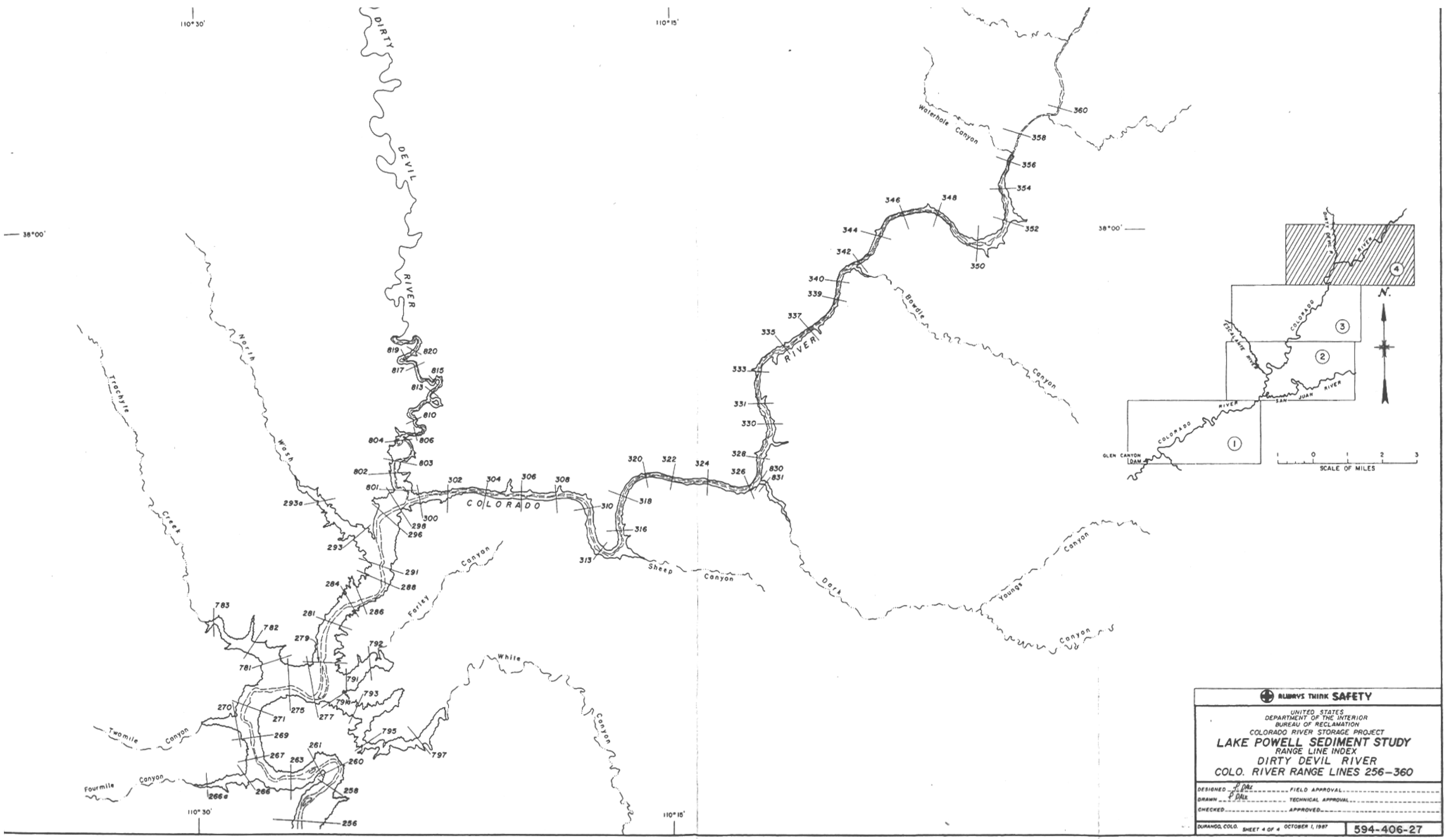
UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
COLORADO RIVER STORAGE PROJECT
LAKE POWELL SEDIMENT STUDY
RANGE LINE INDEX
BULLFROG AREA
COLO. RIVER RANGE LINES 191–254
DESIGNED
FIELD APPROVAL
DRAWN
TECHNICAL APPROVAL
CHECKED
APPROVED
DURANGO, COLO.
SHEET 3 OF 4
OCTOBER 1, 1987
594-406-26
COLORADO RIVER
Bullfrog Creek
Hansen Creek
Smith Fork
Halls Creek
Knowles Canyon
Cedar Canyon
Moqui Canyon
Red Canyon
Good Hope Bay
SCALE OF MILES
GLEN CANYON DAM
SAN JUAN RIVER
N.
110°45'
110°30'
37°30'



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UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
COLORADO RIVER STORAGE PROJECT
LAKE POWELL SEDIMENT STUDY
RANGE LINE INDEX
DIRTY DEVIL RIVER
COLO. RIVER RANGE LINES 256–360
DESIGNED
DRAWN
CHECKED
FIELD APPROVAL
TECHNICAL APPROVAL
APPROVED
DURANGO, COLO.
SHEET 4 OF 4
OCTOBER 1, 1987
594-406-27
DIRTY DEVIL RIVER
COLORADO RIVER
Waterhole Canyon
Bowdie Canyon
Dark Canyon
Youngs Canyon
Sheep Canyon
Farley Canyon
White Canyon
North Wash
Trachyte Creek
Twomile Canyon
Fourmile Canyon
110°30'
110°15'
38°00'
GLEN CANYON DAM
SAN JUAN RIVER
ESCALANTE RIVER
SCALE OF MILES
N.