Search for the SS Central America: Mathematical Treasure Hunting

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In 1857, while carrying passengers and gold from California to New York, the *SS Central America* sank in a hurricane, taking gold bars and coins worth an estimated 400 million dollars to the ocean bottom almost 8,000 feet below. Some 425 people, including the captain, lost their lives. In 1989, after three summers of effort at sea, the Columbus-America Discovery Group recovered one ton of gold bars and coins from the wreck. In 1985, I was given the task of developing a probability distribution for the location of the *Central America*. This distribution was used to construct the search plan that found the wreck. The methods used to develop the distribution were based on classical OR techniques and included a combination of historical, statistical, analytic, and subjective methods.

In 1857, people traveling from California to New York had three choices. They could travel by land across the continent, enduring a long and arduous journey and braving the dangers of Indians, weather, disease, and exhaustion. They could undertake the long sea journey around Cape Horn, fighting their way through the terrible storms at the southern-most tip of the South American continent. Or, they could travel by steamer from San Francisco to the west coast of Panama, cross the isthmus by train, and take a steamship to New York.

Between 1848 and the completion of the transcontinental railroad in 1869, the

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steamship route via the Isthmus of Panama was the main mode of transportation between California and the east coast of the United States. This route provided a journey of 23 to 26 days for those who could afford it. "In the period between 1848 and the end of June 1869, the total arrivals at San Francisco by Panama amounted to at least 375,000 persons, while in the same years some 225,000 traveled eastbound over the same route. . . . Judges and financiers, generals and naval officers, gamblers and women of bad character traveled by way of the Isthmus because it was the obvious way to go for the person who could afford it" [Kemble 1943, pp 206–207]. During this period the steamers on the Panama route transported more than 2.9 million pounds of California gold.

The *Central America* (Figure 1) was one of the steamships operating on the Atlantic side of the Panama route. In a work commissioned by the Columbus-America Discovery Group, Judy Conrad [1988] tells the story of the loss of the *Central America* through the accounts of survivors. Most of the historical information and quotes that I present in this section are taken from her book.

On the 20th of August 1857, the mail steamer *Sonora* left San Francisco carrying about 600 passengers and crew and three tons of gold bound for New York. The

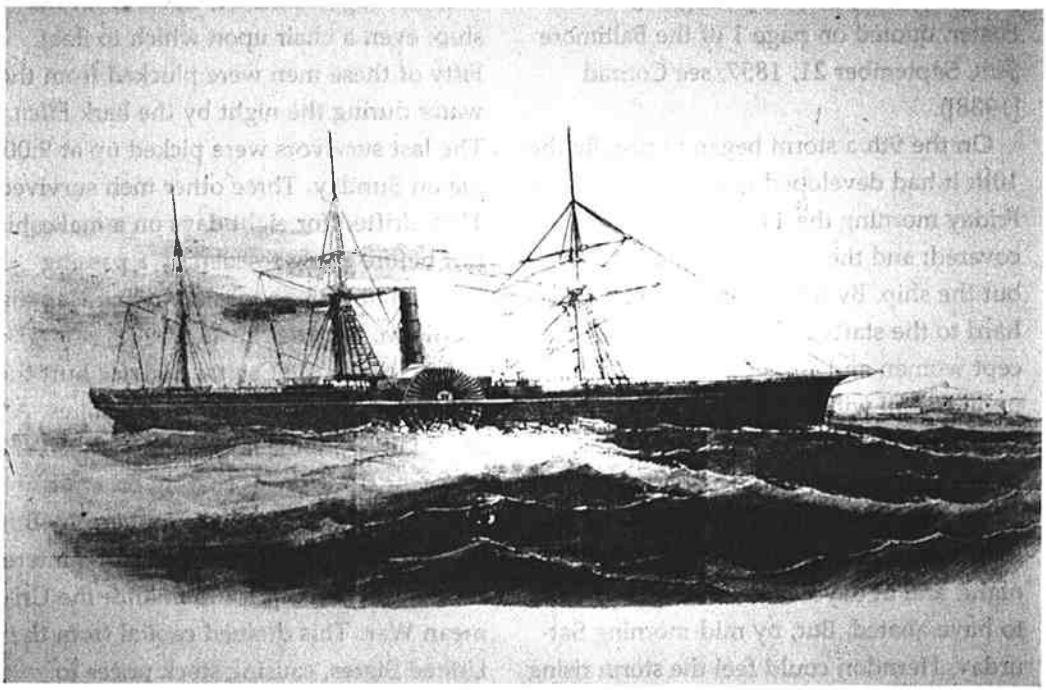

Figure 1: The side-wheel steamer *SS Central America* is shown in this lithograph from Frank Leslie's *Illustrated Newspaper,* October 3, 1857. The *Central America* operated on the Atlantic side of the Panama route taking passengers and gold from California to New York. She sank 200 miles off the coast of South Carolina in a hurricane on September 12, 1857 taking gold bars and coins worth an estimated 400 million dollars to the ocean bottom almost 8,000 feet below. Some 425 people including the captain lost their lives.

voyage to the Isthmus was "one long delight, with smooth waters, sunny skies, and a joyous congenial company" [Lincoln 1911, p. 11]. At the Pacific coast of Panama, the travelers were met by a train which took them to the Atlantic coast to board the mail steamer *Central America.* The *Central America* was a wooden hulled steamship with two large iron-side wheels. The mail steamers were required by law to be captained by a US Naval officer. The captain of the *Central America* was Commander William Lewis Herndon. The ship left Panama on September 3rd, landed in Havana on September 7th, and resumed its trip to New York on the morning of the 8th ". . . with clear weather and every prospect of a pleasant passage" (J. A. Foster, quoted on page 1 of the Baltimore Sun, September 21, 1857, see Conrad [1988]).

On the 9th a storm began to rise. By the 10th it had developed into a hurricane. On Friday morning the 11th, a leak was discovered; and the crew attempted to bail out the ship. By noon, the ship was listing hard to the starboard, and all hands (except women and children) were called upon to bail with buckets and ropes. By 2:00 PM the water covered the coal and smothered the fire in the main boilers. The auxiliary engines could not be started. Passengers and crew bailed heroically all night, and at daybreak the storm appeared to have abated. But, by mid-morning Saturday, Herndon could feel the storm rising again and realized that the ship must go down. At noon he signaled the brig *Marine* to rescue passengers from the *Central America.* Fifty-nine women and children plus 41 male passengers and crew made it to the *Marine* before evening when darkness and distance prevented further rescue efforts.

At 6:30 PM the schooner *El Dorado* approached the *Central America.* Captain Herndon relayed his last estimated position to the captain of the *El Dorado.* He then waved the *El Dorado* away from the sinking ship and asked it to stand by until morning. The *El Dorado* drifted away in the storm. A few minutes before 8:00 PM, Herndon fired the rockets signaling that the ship was sinking. Just after 8:00 PM the ship sank, stern first.

When the ship went down, many men were dragged down by the undertow. Those that survived grabbed pieces of wooden superstructure, doors from the ship, even a chair upon which to float. Fifty of these men were plucked from the water during the night by the bark *Ellen.* The last survivors were picked up at 9:00 AM on Sunday. Three other men survived. They drifted for eight days on a makeshift raft before being rescued by a passing ship. Some 425 people, including Captain Herndon, lost their lives.

The loss of the *Central America* hurt the financial markets in the United States. A speculative bubble in the summer of 1857 had sent stock prices soaring on Wall Street. At the end of the summer, the British and French governments raised interest rates in their countries to finance the Crimean War. This drained capital from the United States, causing stock prices to plunge and a financial panic to occur on Wall Street. Bank reserves were reduced to a perilous state, and financiers were awaiting the shipment of gold on the *Central America* to shore them up. When the first survivors of the *Central America* reached shore, news of the loss was quickly spread throughout the eastern half of the country by the new telegraph system. This news contributed to the collapse of many already weakened banks. By mid-October, all but a handful of the country's banks had suspended specie payments (payments of gold for paper money). Hundreds of thousands of people lost their jobs, and in 1857 the federal treasury ran a deficit for the first time in a decade.

The *Central America* was the most famous shipwreck of its time, comparable to the loss of the *Titanic* in this century. A committee, appointed by the companies that insured some of the gold carried by the *Central America*, investigated the loss and recommended that new ships be built with iron hulls and water-tight compartments. (The *Titanic* was so equipped.) A monument was erected in honor of Herndon at the US Naval Academy, and a town in Virginia was named after him.

The Civil War that followed so quickly after the loss of the *Central America* overshadowed this tragedy and dimmed it in our historical memory. The discovery of the wreck of the *Central America* and the recovery of historical and archaeological artifacts along with gold bars and coins furnishes us with the opportunity to reacquaint ourselves with this important event in our history.

Columbus-America Discovery Group

The Columbus-America Discovery Group was formed in 1985 to conduct multi-disciplinary research, to develop sophisticated deep-ocean technology, and to locate, explore, and recover the remains of the *SS Central America.*

Thomas G. Thompson, director and founder of the *Central America* Project, received a BS in mechanical engineering from the Ohio State University. He followed his strong interest in ocean engineering and exploration by serving as chief engineer aboard research vessels operating in the Caribbean and Pacific Oceans. He designed, constructed, and maintained underwater search and recovery equipment. From 1980 to 1987 he worked as a research scientist with the Battelle Memorial Institute studying, among other things, the feasibility of mining polymetallic sulfides from the deep ocean.

In 1975, Thompson took up lost shipwrecks as a hobby and began to collect in-

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formation on shipwrecks around the world. In the early '80s new technologies were developed for sonar search and for remotely operated recovery vehicles. Newly developed sonars could scan large swaths of the ocean bottom with high resolution. Advances in robotics, fiber optics, and computers made it possible to build remotely operated underwater vehicles capable of performing a full range of archaeological recovery tasks. This technology eliminated the need for manned submersibles, which are expensive and dangerous to operate in the deep ocean. These developments made it economically feasible for a small, independent entrepreneur to search for and recover objects on the deep-ocean floor.

Bob Evans, one of the project directors, joined Tom Thompson in 1982 and began researching the *Central America* and other historic wrecks. Evans holds a BS degree in geology from the Ohio State University and has worked as a geological consultant and field scientist.

In the late '70s, the *Central America* emerged as a prime candidate for recovery. Several factors influenced this decision. The *Central America* is located on the Blake Plateau, some 200 miles east of Charleston and 1.5 miles below the ocean surface, in an area with a flat bottom and little current. Because of the great depth, the ship was safe from damage by storms and hurricanes as well as from casual exploration by SCUBA divers or treasure hunters. The flat bottom and lack of current allowed for the efficient use of wide-scan sonar for the search. The ship was known to be carrying large quantities of gold, making its location and recovery economically attractive to investors. There was a great deal of historical information available about the wreck. Finally, the wreck was located off the coast of the United States so that legal problems could be handled solely through the US courts and law.

In the early '80s Thompson began to assemble a limited partnership of private investors to finance the search and recovery of the *Central America.* He also began to assemble the team of scientists and technicians that would carry the project to its successful conclusion. In 1985, Barry Schatz, a high school friend of Tom Thompson, joined the effort as the third project director.

The Problem

The *Central America* Project had the following goals: locate the wreck of the *Central America* and recover gold and historical artifacts in a responsible manner; develop new technology for deep ocean exploration; add to the historical knowledge of the *Central America* and its times; and increase the scientific understanding of the deep ocean environment and its inhabitants.

The problems that the *Central America* Project faced were financial, technical, operational, and legal.

The financial problem was to raise the money needed to fund the search and recovery effort. This was done by forming a limited partnership with investors providing about 10 million dollars in capital to fund the effort.

The technical problems were numerous. Among them were the following:

— To choose a wide-swath, high-resolution sonar and develop an improved image processing system using microcomputer technology and optical storage devices;

— To construct a probability map estimating the location of the wreck and develop a search plan to yield a high probability of success; and

— To design and build a remotely controlled underwater vehicle capable of performing the tasks of recovering gold, delicate archaeological artifacts, and marine life at depths of 10,000 feet.

The operational problems included

— Leasing a ship capable of carrying and supporting the necessary men and equipment;

— Hiring and training a crew of people to perform the sonar search and to maintain and use the recovery and com-

puter equipment; and
- Imbuing the scientists and technicians doing the work with the patience and determination necessary to complete a multi-year project with an uncertain result.

The legal problems included protecting the wreck from pirate salvors intent on taking advantage of the work done by the Columbus-America Discovery Group and fending off claims by insurance companies and others to ownership of the gold after it was recovered.

In the summer of 1985, I was given the task of developing a probability map (that is, distribution) for the location of the *Central America* from the historical information provided by Evans. The objective was to use the map to design an efficient search plan that would produce a high probability of finding the target. It would provide specific directions for performing a search and serve as a basis for estimating the amount of time, effort, and money necessary to assure a high probability of success. This information is important for obtaining sufficient monetary support from investors and for preparing the investors, scientists, and technicians for the length of time and amount of effort required for a successful operation.

The Search Problem

The first part of the search problem was to produce an estimate of the location of the target, in this case the wreck of the *Central America*. Following the paradigm developed by Bernard Koopman [1946] and his colleagues in the Navy's Operations Evaluation Group during World War II, we stated this estimate in terms of a two dimensional probability distribution on the location of the wreck. To develop this distribution, we made use of the following information:

Historical:
- Herndon's last reported position as passed to the schooner *El Dorado;*
- Sighting of the *Central America* by the brig *Marine;*
- Recovery of survivors by the bark *Ellen;*
- An estimate of the wreck's location by Captain Badger, a passenger on the *Central America;*
- The drift of the survivors on the raft; and
- Estimates of wind speed and direction recorded during the hurricane.

Statistical:
- Historical distribution of winds and currents in the area.

Analytical:
- Estimates of the uncertainty in celestial navigation;
- Estimates of the effect of wind on the drift of the *Central America;* and
- Estimates of the wind-driven current.

Subjective:
- Weights representing the quality of the information used to estimate the wreck's location.

The methodology for combining these diverse types of information had its start with work done by Richardson [1967] during the 1964 search for an H-Bomb lost off the Mediterranean coast of Spain. In many search problems the information about the target's location comes from a variety of sources and is often inconsistent. The information does tend to cluster into self-consistent sets, each of which tells a "story" about the location of the target.

These clusters are called scenarios. Because of the inconsistencies among the scenarios, one cannot combine them in a standard statistical fashion as though they were independent and unbiased estimates of the target's location.

I followed the approach taken by Richardson and used each scenario to produce an estimate of the target's location in terms of a probability distribution. The scenarios were weighted in a subjective fashion, and a composite probability distribution was obtained by averaging the scenario distributions according to the scenario weights. This composite distribution formed the estimate of the target's location used to plan the search. This weighted scenario approach was originated by John P. Craven [Richardson 1967].

In 1968, this search methodology was further developed by Richardson [Richardson and Stone 1971] to produce probability maps for the successful search for the remains of the US nuclear submarine, *Scorpion*. The technology reached an advanced state of maturity in the computer-assisted search planning program (CASP) developed for the US Coast Guard by Richardson and Discenza [1980] with assistance from me and others. I used a modified version of the CASP software to produce the probability maps for the *Central America*.

Approach to Estimating the Location of the Wreck

Here are the basic steps of the approach:

(1) Gather all relevant information about the loss.

(2) Organize the information into self-consistent clusters, each of which becomes a scenario that can be used to provide an estimate of the location of the wreck.

(3) Quantify the uncertainties in the information in each scenario in terms of probability distributions.

(4) Using these probability distributions, run a Monte Carlo simulation to compute a probability map as the estimate of the location of the wreck resulting from each scenario.

(5) Assign subjective probabilities or credences to each scenario and produce a composite probability map that is the weighted sum of the probability maps for each scenario.

(6) Perform a sensitivity analysis to determine the critical input parameters.

The first step of the approach is to gather all of the information available about the wreck. This was done primarily by Evans. He obtained information from newspaper accounts, many of which were given by survivors of the wreck, from ships' logs, from books written by the survivors, from the report to the Secretary of the Navy made by Lt. Matthew F. Maury, Superintendent, US National Observatory (who was married to Herndon's sister), and from testimony given to the committee that investigated the loss. From the Webb Institute and the Smithsonian, Evans obtained copies of the blueprints used in constructing the *Central America*. (A scale model of the *Central America*, constructed from Smithsonian blueprints, is on display today in the Herndon Depot Museum in Herndon, Virginia.) Evans studied the stories of the people on the *Central America*, became knowledgeable about the design and construction of wooden-hulled steamships, and investigated the methods used for navigation in the 1850s. He reviewed the efforts of other groups that had tried to locate the *Central America.*

Evans organized this information into a correlation matrix. A row in the matrix corresponded to a single account of the loss. The columns designated times. An entry at a given row and column gave a summary of what was happening at that time according to the account represented by the row. The matrix made it easy to cross check the numerous accounts and obtain information about what happened at a specific time.

Figure 2 shows a map of the general area of the *Central America* loss and indicates some of the important positions used in constructing the probability map. A glance at the positions in Figure 2 shows the amount of variation in the information. For example, the distance between the Herndon position and the *Ellen* position is about 60 miles. The information appeared to cluster into three self-consistent scenarios. The first scenario was based on the position given verbally by Herndon to G. Sherlock, the first mate of the schooner *El Dorado.* The second was based on the reckoning by Captain Burt of the position of the *Marine* when it sighted the *Central*

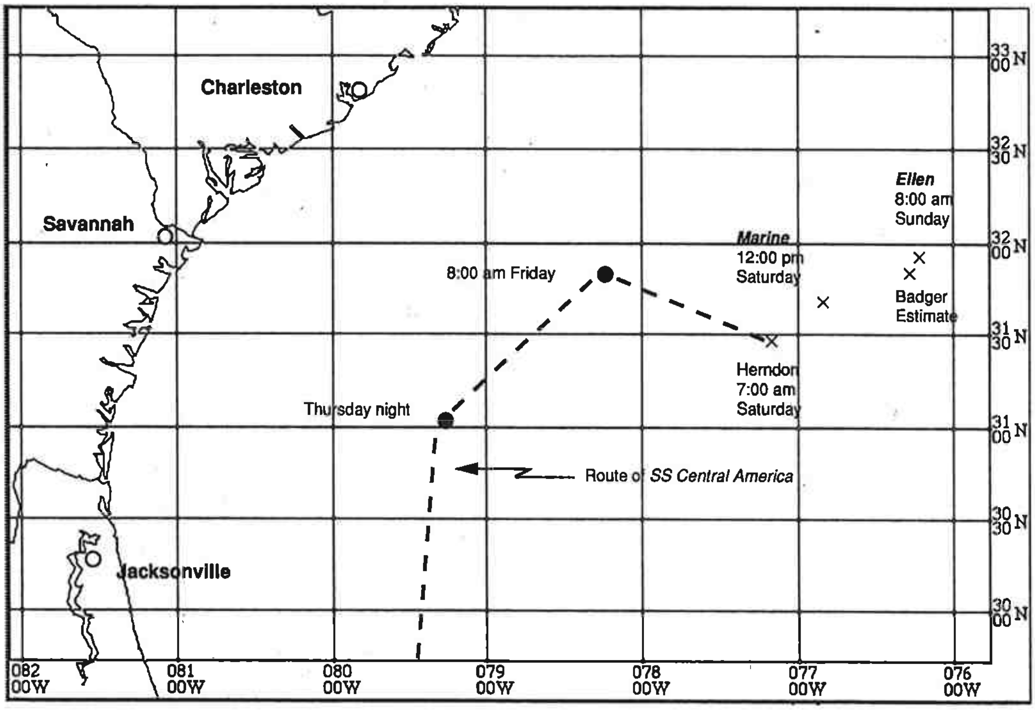

Figure 2: The dashed line shows the route of the *Central America* during its last voyage. The line terminates at the position relayed by Captain Herndon to the schooner, *El Dorado,* one-and-one-half hours before the *Central America* sank. Also shown are the estimated positions of the *Marine* when she sighted the *Central America* at noon on the day of the loss and the *Ellen* at 8:00 AM the next morning as she was recovering survivors. Near the *Ellen* position is the location of the wreck as estimated by Captain Badger, a passenger on the *Central America* who was rescued by the *Ellen.*

America at about noon on Saturday. The third is based on the celestial fix taken by the *Ellen* at 8:00 AM on Sunday as she was recovering the last of the survivors from the *Central America*.

***Central America* Scenario**

The primary piece of information in the *Central America* scenario is the position of the *Central America* passed by Captain Herndon to the *El Dorado*. The position was passed in the midst of the storm just an hour and a half before the ship sank. This raises the immediate question of when and how this position was taken. The only methods for estimating one's position at sea were to obtain a celestial fix or to dead reckon from the last fix. By studying the accounts of the disaster, Evans determined that there was a clearing in the storm on Saturday morning around 7:00 AM at the time of a lunar meridian, the high point of the moon above the horizon for that day. Evans also determined that Herndon returned his navigational instruments to the cabin of Judge Monson, a passenger on the *Central America*, at 8:00 AM on Saturday morning. On the basis of this evidence we surmised that Herndon had taken a celestial fix at 7:00 AM on Saturday morning and that the position relayed to the *El Dorado*, 31°25'N, 77°10'W, was this fix.

How accurate was this fix?

How accurate was this fix, and what does it tell us about the location of the *Central America* when it sank 13 hours later? To answer these questions, we first examined the method by which the celestial fix was taken. We assumed that a sextant was used to determine the altitude, h, of the meridian of the moon measured in degrees from the horizon, and that a chronometer was used to estimate the Greenwich mean time (GMT) at which the meridian occurred. From standard navigational tables one obtains the declination, d, of the moon at this time. The declination is the angular height of the moon's meridian measured from the equator. The latitude, L, of the observer is calculated by

$$L = d + 90 - h.$$

Using these same tables, one determines the Greenwich hour angle (GHA) of the moon at this time. The GHA is equal to the longitude of the observer.

To determine the accuracy of the fix, Belkin [1986] analyzed the errors in this navigational method. Characterizing the uncertainties in the estimation of latitude and longitude as normally distributed with mean zero, he obtained the following estimates of the standard deviations, σ_{lat} and σ_{lon}, of these uncertainties expressed in nautical miles (nm):

$$\sigma_{\text{lat}} = 0.9 \text{ nm and } \sigma_{\text{lon}} = 3.9 \text{ nm.} \tag{1}$$

The uncertainty in longitude is more than four times greater than the uncertainty in latitude. The reason for this is that estimation of the longitude requires determination of the time of the meridian. The observed path of the moon had a rather broad apex making it difficult to determine the exact point at which the meridian occurred when using a sextant. This, rather than the error in the chronometer, proved to be the dominating factor in the longitude uncertainty. Determination of latitude requires only an accurate estimate of the altitude of the moon at the meridian and does not require knowledge of the time of meridian. As a result there is less error in determining latitude.

On the basis of this analysis, we modeled the uncertainty or error in the fix as having a bivariate normal distribution with mean (0, 0) and standard deviations along the north and east axes as given by (1).

Of course the *Central America* did not stay stationary during the time between the celestial fix at 7:00 AM and when she sank at 8:00 PM that evening. During this time we know that her engines were disabled and that she had no sails hoisted. She was at the mercy of the winds and currents. In order to account for her movement during this time we estimated her drift. There are two components of drift:

—Drift due to the ocean current.

—Drift due to the effects of wind on the ship (leeway).

As one would expect, no one recorded the ocean current during the storm, so we had to estimate it indirectly. The ocean current is the sum of the geostrophic and the wind-driven current. One can think of the geostrophic current as the current that would be present if there were no wind. In order to estimate the geostrophic current, we used historical data obtained from the Naval Oceanographic Data Center (NODC). This data consisted of all ocean current readings in their data base that were taken in the month of September in the region from 30°N to 32°N and 76°W to 78°W. The data in the NODC files spans the period from the early 1850s to 1974 and were obtained from many countries. This region was broken into sixteen 30-minute by 30-minute rectangles. Within each rectangle, we computed the mean and empirical covariance for the data. We then modeled the current in the rectangle as having a bivariate normal distribution with mean and covariance equal to the computed values.

> No one recorded the ocean current during the storm.

The initial computations showed very small mean values for the current. This implies that, averaged over time, there was no consistent direction for the current in this area. In order to determine if there was a direction to the current at the time of the loss, we reviewed the path of the three men who drifted for eight days on a raft before being picked up by a passing ship. This evidence indicated a generally northeasterly direction to the current at the time. With this in mind we returned to the data from NODC and computed the mean and covariance of the data points lying in the northeast quadrant. This produced bivariate normal distributions with mean vectors having a speed of 1.0 to 1.5 nautical miles per hour (kts) in the northeast direction [Stone 1986]. We took these bivariate normal distributions as our best estimate of the distribution of the geostrophic current during the loss of the *Central America*.

Wind acting on the ocean surface produces a surface current which contributes to a ship's drift. To estimate the winds, Evans returned to ships' logs and survivors' accounts to find estimates of wind speed and direction during the two days preceding the loss of the *Central America.* To account for the uncertainty in these estimates, we modeled the winds as having a bivariate normal distribution with mean equal to the value obtained by Evans and a covariance matrix that allows the wind to vary by as much as 45 degrees from its mean.

Roland W. Garwood of the Naval Postgraduate School used his computer model of wind-driven current to estimate the current that would have been produced by the winds as estimated by Evans. Garwood produced estimates for each six-hour period from 7:00 AM on Saturday to 1:00 PM on Sunday. The resulting currents had speeds ranging from 0.2 to 0.4 knots. The uncertainty in these estimates was represented by a bivariate normal distribution with a standard deviation of 0.1 knots in each direction.

To obtain the distribution of the total ocean current, we computed the distribution of the vector sum of the geostrophic and wind-driven current. Note that the geostrophic-current distribution is space dependent while the wind-current distribution is time dependent. The distribution of the sum of the two currents is both space and time dependent.

The direct action of wind on a ship also contributes to drift. This component of drift is called *leeway.* To estimate this component, we need to know the leeway factor, f, for the *Central America.* The leeway factor is the fraction of the wind velocity that is converted to drift as a result of the wind acting on the area of a ship that is above water. If the wind velocity is W, then the leeway (or drift) produced by the wind is fW. (Here, we assume that the ship drifts in the same direction as the wind is blowing. This is not always true.) Tsung-chow Joe Su of the Department of Ocean Engineering of Florida Atlantic University used a leeway model that he had developed to estimate the factor f for the *Central America.* To specify the parameters needed by this model, we used measurements obtained from blueprints of the *Central America.* The resulting estimate was $f = 3\%$.

Generating the Probability Map

The method we used to generate the probability map for the *Central America* is based on simulation. It begins by drawing 4,000 points to represent the possible positions of the *Central America* at 7:00 AM on Saturday when Captain Herndon took his celestial fix. These points were obtained by making 4,000 independent draws from the bivariate normal distribution representing the error in this fix and adding this error to the reported position. For each of these points the simulation proceeds as follows. It makes an independent draw from the total ocean current distribution to obtain V, the total ocean current vector, and an independent draw from the wind distribution to obtain a value for the wind vector, W. The simulation uses a time interval h specified by the user. We chose six hours. The simulation computes the total displacement D for the increment by

$$D = (V + fW)h. \tag{2}$$

This displacement is added to the initial position, and the process is repeated (with new draws for V and W at each time increment) until the time at which the *Central America* sank is reached. (We assumed that as the ship sank it went essentially straight to the bottom.) The final position of each

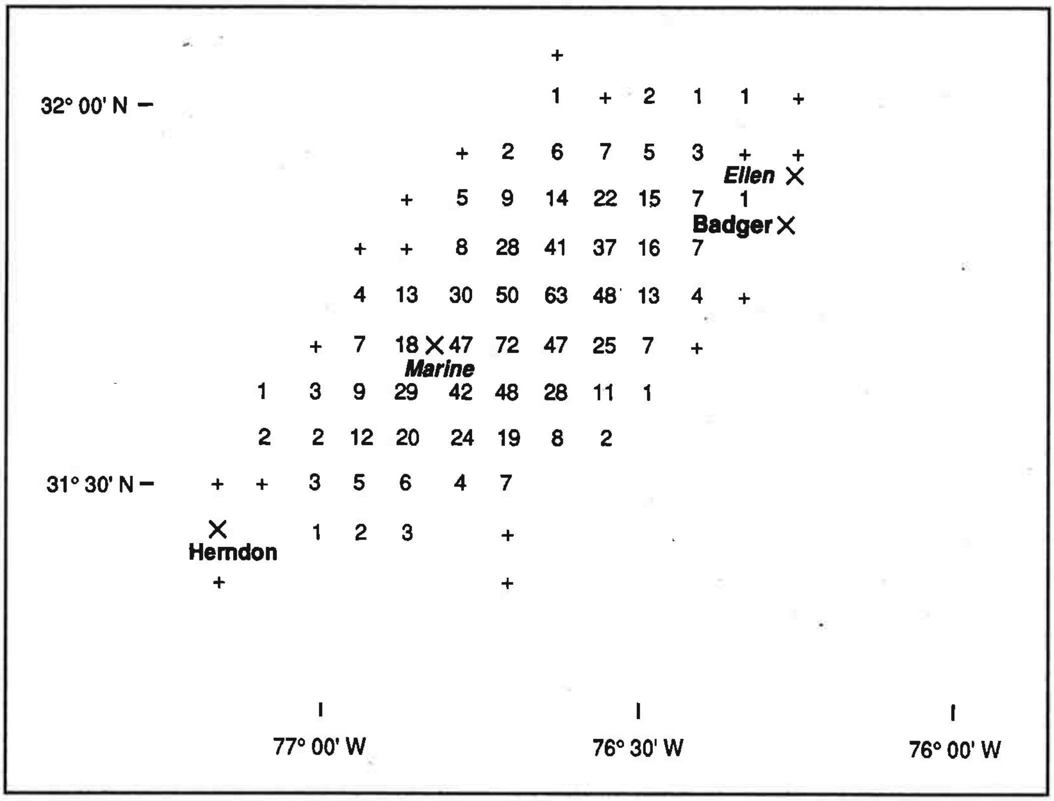

Figure 3: The probability map for the *Central America* scenario is based on the position Captain Herndon relayed to the schooner *El Dorado* one-and-one-half hours before the *Central America* sank. The number in a cell is the probability that the wreck is in that cell multiplied by 1,000. The Xs indicate the positions given by Herndon, *Marine, Ellen,* and Badger that are identified in Figure 2.

point is recorded.

We imposed two grids on the ocean bottom. One grid consisted of four nm by four nm cells and the other of two nm by two nm cells. We used the grid of four-mile cells for determining the general size of the search area and comparing the consistency of the maps produced by the different scenarios. We used the grid of two-mile cells for detailed planning. We computed the number N of points falling into each cell and assigned the probability,

$p = N/4000,$

to that cell. Figure 3 shows the resulting map of cells with their probabilities. This is the probability map for the *Central America* scenario. We also computed probability maps for two other scenarios, the *Ellen* and the *Marine.*

Ellen Scenario

For the *Ellen* scenario, we used the position of the *Ellen* at 8:00 AM on Sunday when she was recovering survivors from the *Central America.* The approach was to drift the survivor backward to the time of the sinking of the *Central America* to obtain an estimate of the position of the wreck.

At 8:00 AM on Sunday, the captain of the *Ellen* took a celestial fix using a meridian of the moon. The recorded position was 31°55'N, 76°13'W. For the uncertainty in this position we used the analysis in Belkin [1986] which yielded

$$\sigma_{lat} = 0.9 \text{ nm and } \sigma_{lon} = 5.4 \text{ nm.} \qquad (3)$$

To obtain the probability map for this scenario, the simulation started by making 4,000 draws from the bivariate normal distribution representing the *Ellen's* position at 8:00 AM on Sunday. A person in the water has no leeway, so his drift is determined solely by the ocean current. To produce this backward drift, we set the leeway factor to zero and multiplied the mean vectors for ocean current by minus one. Each point was drifted backward this way to 8:00 PM on Saturday when the *Central America* sank. The resulting probability map is shown in Figure 4.

***Marine* Scenario**

At 12:45 PM on Saturday, the *Marine* sighted the *Central America*. Captain Burt of the *Marine* reckoned his position to be 31°40'N, 76°50'W. Our best estimate of the last time that Burt made a celestial fix was at 6:00 AM on Friday. For most of the time between this fix and the sighting of the *Central America*, the *Marine* was being driven by the storm with little or no sail on. We estimated the leeway of the *Marine* at four percent and applied the wind ve-

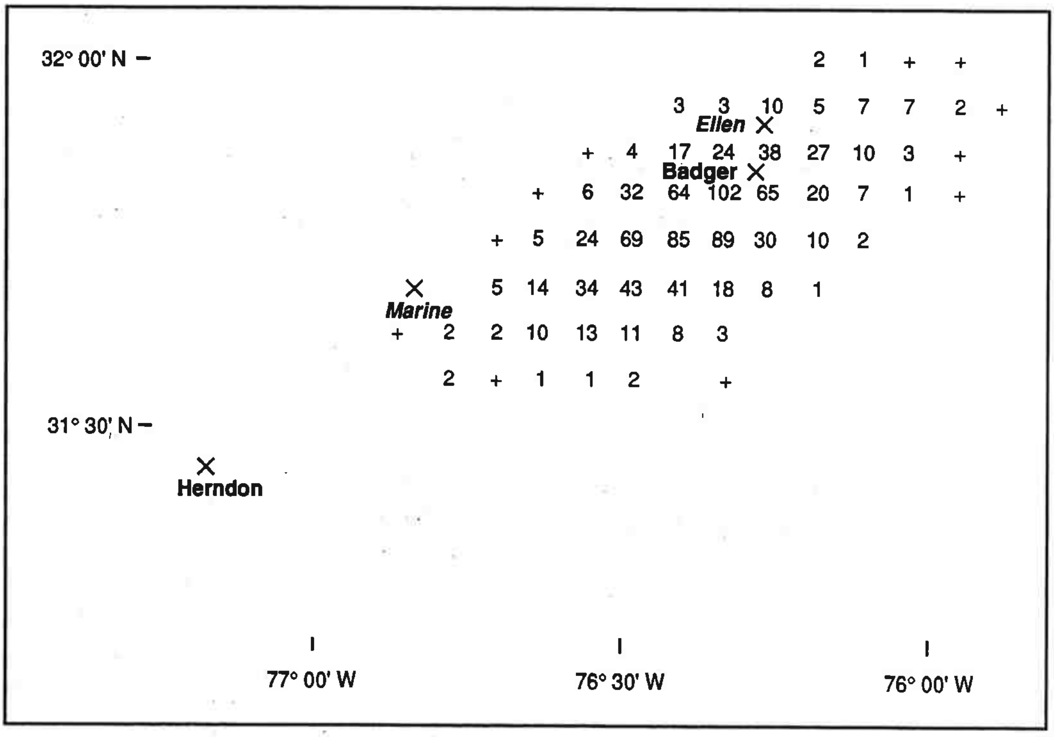

Figure 4: The probability map for the *Ellen* scenario is based on the reported position of the *Ellen* at 8:00 AM the morning after the loss as she was recovering survivors. The number in a cell is the probability that the wreck is in that cell multiplied by 1,000. The Xs indicate the positions given by Herndon, *Marine*, *Ellen*, and Badger that are identified in Figure 2.

locities for that period of time to estimate that the *Marine* traveled 77 nm since the last fix. We assumed that the error in dead reckoning a position is no more than 25 percent of the distance traveled since the last fix. This resulted in an uncertainty that was circular normal with standard deviation of nine nm in each direction.

As well as accounting for the uncertainty in Burt's reckoned position, we also accounted for the distance of the *Marine* from the *Central America* at the time of the sighting. The *Marine* heaved to near the *Central America* at 1:30 PM, 45 minutes after the sighting. Assuming that the maximum speed of the *Marine* was eight knots, we calculated that the *Central America* could not have been farther than six miles from the *Marine* at the time of the sighting. We assumed that the minimum sighting distance was one mile.

The *Central America* was sighted off the lee bow of the *Marine*. The *Marine* was reported to be running before the wind which was from the SW at this time. As a consequence we estimated the *Marine* to be heading NE and the lee direction off the bow to be ENE = 67.5°. We added an uncertainty of ±60° about this direction.

The simulation is similar to those above. First, 4,000 points were drawn from the bivariate normal distribution representing the position of the *Marine* at the time of the sighting. For each point independent draws were made for the offset distance, s, (in nautical miles) and direction, θ. The value of s was drawn from a uniform distribution on [1, 6], and θ was drawn from a uniform distribution on [7.5°, 127.5°]. The position of the point was then displaced a distance s in the direction θ to obtain the position of the *Central America* at 12:45 PM. When this process was completed, the file of points was drifted to the time of the sinking by the method described above. Figure 5 shows the resulting probability map.

Composite Probability Map

We combined the three separate probability maps in a subjective fashion to produce the composite probability map used for planning the search. We gave each scenario a weight that represented an estimate of the strength and credibility of the information used to generate the scenario. Thompson, Evans, and I determined these subjective weights on the basis of a number of hours of discussion. During these discussions, we reviewed the information that formed the basis for the scenarios and assessed the reliability of each piece of information. We looked at each scenario as a whole to determine if there was corroborating evidence that strengthened the credibility of that scenario. As an example, the position estimated by Captain Badger, a passenger on the *Central America*, was very consistent with the *Ellen* scenario. Lieutenant Matthew Maury made an estimate of the location of the wreck based on the information that he had collected in his report to the Secretary of the Navy. This position also supported the *Ellen* scenario. The celestial fix on which the *Ellen* scenario was based was taken after the storm had passed on a ship that was in no danger of sinking. This position was written in the ship's log. By contrast, Herndon's position, on which the *Central America* scenario was based, was passed verbally to the *El Dorado* in the middle of a storm just one and one half hours before the *Central*

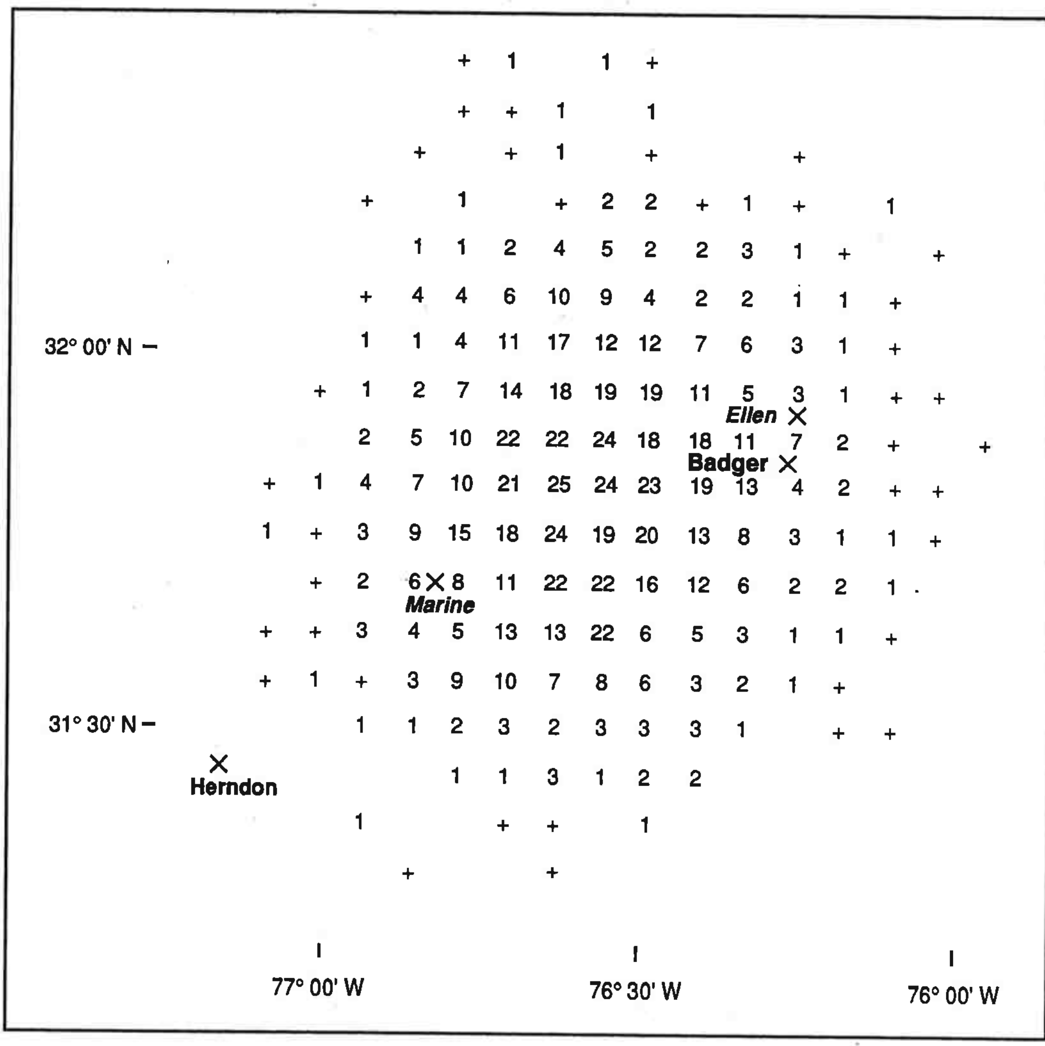

Figure 5: The probability map for the *Marine* scenario is based on the estimated position of the *Marine* when she sighted the *Central America* at noon on the day of the loss. The number in a cell is the probability that the wreck is in that cell multiplied by 1,000. The Xs indicate the positions given by Herndon, *Marine, Ellen,* and Badger that are identified in Figure 2.

America sank.

At the end of the discussion, we each assigned a percentage to the three scenarios. The percentages represented the relative credibility of the scenarios and were required to add to 100. We averaged the three sets of percentages to produce the scenario weights. The results were

Central America 23%,
Ellen 72%, and
Marine 5%.

The *Ellen* received the highest weight or credibility for the reasons discussed above. The information in the *Marine* scenario was so uncertain that we gave it a very

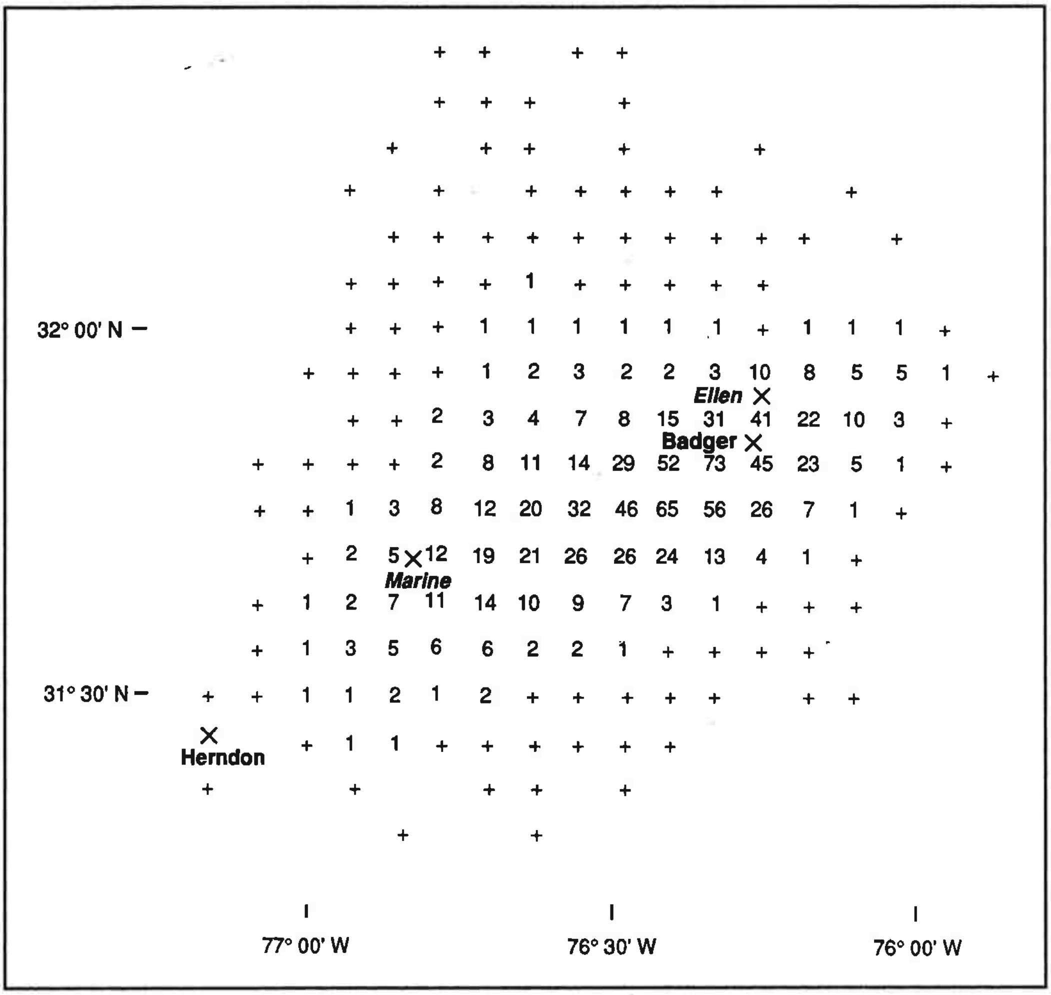

Figure 6: The composite probability map for the location of the *Central America* is the weighted average of the maps for the *Central America, Ellen,* and *Marine* scenarios. The number in a cell is the probability that the wreck is in that cell multiplied by 1,000. The Xs indicate the positions given by Herndon, *Marine, Ellen,* and Badger that are identified in Figure 2.

low weight but did not discard it entirely. The composite probability map shown in Figure 6 is the weighted average of the scenario maps. In particular, the probability in a cell in the composite map is the weighted average of the probabilities in that cell in the scenario maps.

The Search Plan

Fred Newton [1986] of Triton Technology developed the search plan (Figure 7). He designed it to produce a high probability of detecting the *Central America* with the sonar search. The side scan sonar used was the SeaMarc IA. This sensor has three ranges, long, medium, and short. The shorter the range, the higher the resolution. The long range covers a swath of 2,500 meters on each side. For the long-range setting, Newton estimated the probability of the sonar detecting the *Central*

America as a function of the range of the sonar from the target. More precisely, consider a sensor following a long straight path while passing a stationary target. The distance of the sensor at the point of closest approach to the target along this path is called the lateral range. Using estimates of the acoustical properties of the water, the target, and the ocean bottom, Newton calculated the signal-to-noise ratio at the sensor as a function of lateral range from the target. He then converted the signal-to-noise ratio to a probability of detection. The result is the lateral range function shown in Figure 8. Over most of the 2,500 meter range, the signal-to-noise ratio (SNR) was calculated to be 20 decibels (db) which produces a detection probability of

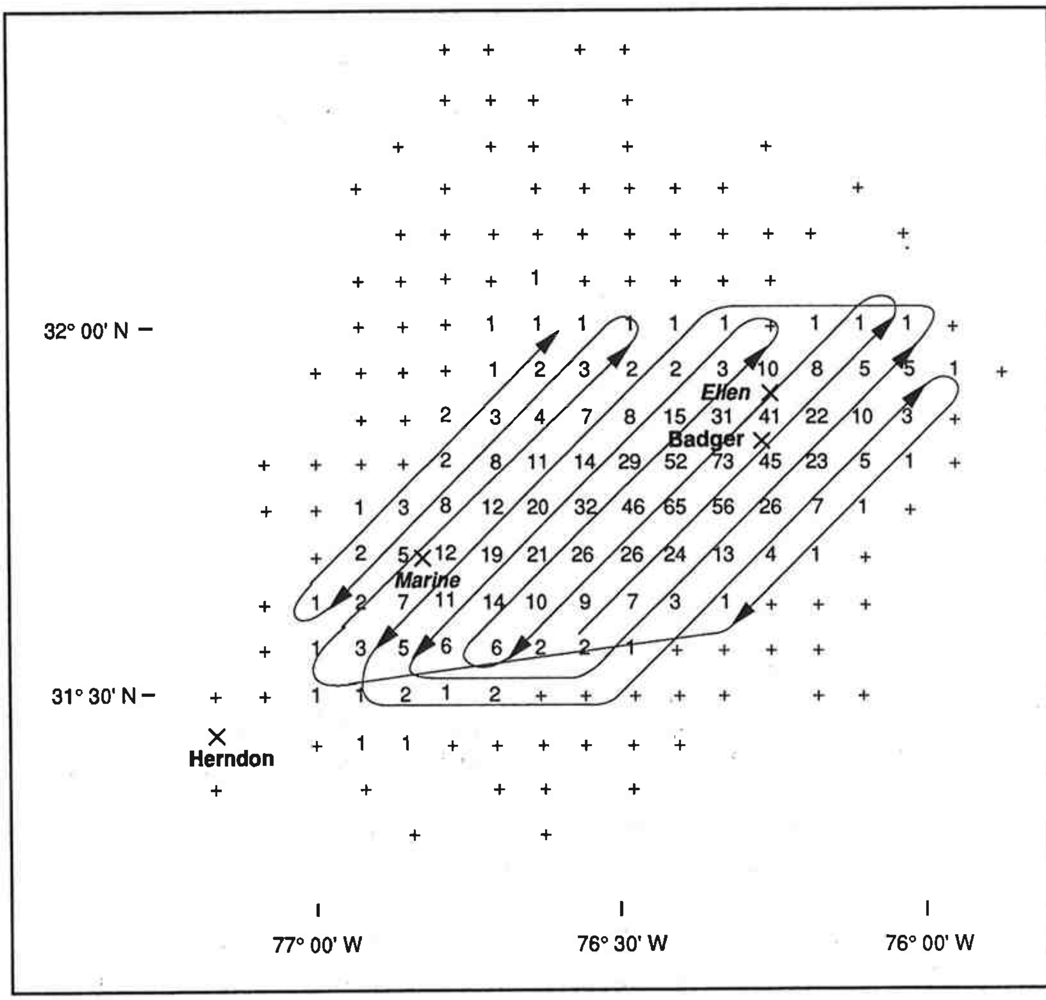

Figure 7: Superimposed on the composite probability map is the search plan that found the *Central America*. The plan consists of long straight paths with arrows indicating the direction of motion. The plan starts near the bottom center of the figure, searches the high probability areas first, and then works its way out to the lower areas. The number in a cell is the probability that the wreck is in that cell multiplied by 1,000. The Xs indicate the positions given by Herndon, *Marine, Ellen,* and Badger that are identified in Figure 2.

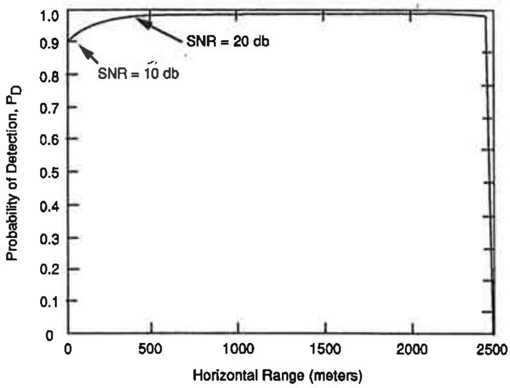

Figure 8: The detection capability of the SeaMarc IA sonar, operating on the five kilometer scale (2.5 kilometers on each side) and searching for the wreckage of the *Central America*, is characterized by the lateral range function. The lateral range function gives the probability of detecting the target as a function of range from the target. Over most of the 2.5 kilometer range, the signal to noise ratio (SNR) at the sensor is 20 decibels (db) producing a 0.99 probability of detection. The detection probability decreases near the sensor because of increased bottom reverberation. Detection probability falls off sharply near the maximum range of the sensor.

0.99. At ranges close to the sensor, increased reverberation from the ocean bottom causes the SNR and the probability of detection to drop. At the outer reaches of the 2,500 meter range, the SNR and probability of detection also drop.

The sonar is operated by towing it from the ship via a long cable. Along with the towing cable, there was a coaxial cable to relay the sensor responses back to the ship where they were recorded on an optical disk and displayed on paper. The responses recorded on disk could be analyzed and displayed in many fashions some of which included color enhancements. This analysis could be performed in real time during the search or pursued in a more leisurely fashion at a later time. This proved to be an important capability. Since the ocean bottom was some 7,000 to 10,000 feet deep in the search area, a long cable had to be played out from the boat to the platform carrying the sonar which was towed 250 feet above the ocean bottom.

When towing a sensor at the end of long cable, it is desirable to minimize the number of course changes required. This suggested a plan with long straight search legs. In addition, to maximize the probability of success if the search has to be curtailed because of weather or equipment problems, one should start by searching the high probability regions first.

Newton considered three plans with these general characteristics. In each plan, the spacing between legs was chosen so that there was a very small probability (0.003) of leaving a gap between swaths. For each of the three plans, he used a computer program to calculate the probability of detecting the target as a function of search time. The computation took account of the lateral range function for the sensor, the probability of gaps between swaths, and the amount of probability covered by the swath of the sensor while following the plan.

Of the three plans, the one shown in Figure 7 produced the highest detection probability at the end of the search and during most of the intermediate search times as well. Figure 9 shows the estimated probability of detection as a function of search time for this plan. The plan accomplishes all the goals. It has long straight legs that cover a parallelogram containing most of the probability in the map. The legs start in the middle of the parallelo-

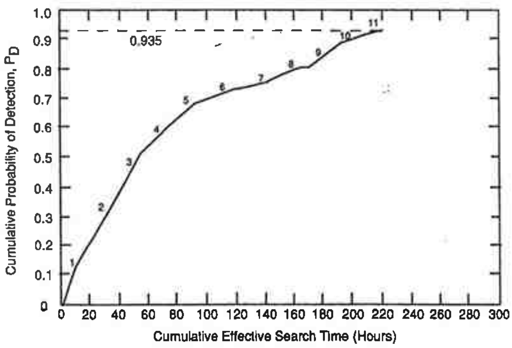

Figure 9: Using the search plan in Figure 7, Newton calculated the probability of detection as a function of effective search time. Effective search time does not include time lost for weather, breakdowns, or other nonproductive time. The calculations assume an average speed of two nautical miles per hour and include the turning time between tracks. The numbers next to the curve segments are the numbers of the line segments in the search plan, numbered in the order in which they are followed.

gram in the high probability area and work their way outward.

As well as providing a plan that yielded a high probability of success, the analysis allowed the Columbus-America Discovery Group to estimate and budget for the amount of sea time necessary to reach this high level of success.

The Search

After preliminary testing of the equipment, the sonar search began in June, 1986. The sonar search was performed by Williamson and Associates. Early in the search, the sonar produced a very promising contact located southwest of the Badger position in the cell having probability 56×10^{-3} of containing the target (Figure 6). The size of the contact appeared about right, the sonar trace showed a mound that resembled a pile of coal, and the contact was in a high probability area. These facts produced a strong feeling that the sonar search phase should end right there, saving the more than one million dollars required to finish the planned search. In spite of this feeling, Thompson decided to press on to complete the sonar survey as planned. The survey took 40 days during the summer and covered approximately 1,400 square miles of ocean floor. The survey produced a number of interesting contacts including the early, very promising contact mentioned above.

The following summer, the Columbus-America Discovery Group returned to search with their underwater vehicle, *Nemo*. *Nemo* is a remote-controlled device, equipped with stereo video, still cameras, and robotic arms. *Nemo* is operated by a crew of five scientists and technicians who control its movements from the ship with the aid of a teleoperational system. The teleoperational system allows a technician on board the ship to move a mechanical arm and cause the arm on *Nemo* to respond accordingly. By watching *Nemo*'s arm movements on a television, a technician is able to perform delicate operations on the ocean floor 10,000 feet below the ship. Using *Nemo*, they performed a visual survey of the contact in the high probability area southwest of the Badger position and found the wreck of a wooden-hulled ship. In early July they recovered a number of artifacts from the wreck. These included lumps of coal, pieces of iron, ceramic dishes and pottery dating from the early 1850s, and articles belonging to women and children. Airlifting some of these artifacts to a court in Norfolk, they obtained an injunction to keep other salvors out of the area of the discovery. This area is the first injunction area shown in Figure 10.

The remainder of the summer was spent exploring this wreck site. Over the winter of '87–'88, the Columbus-America Discovery Group continued to review the computer records of the other contacts using image processing software that they were continually improving. During this review, they discovered that one of the contacts that had been found near the end of the 1986 sonar survey had a look and texture similar to that produced by the coal at the wreck site they had investigated during the summer of 1987. The group decided that this second contact was worth further investigation.

At the beginning of the summer 1988 cruise, the group began by testing its equipment in the area of this second contact. On the first pass of the video cameras

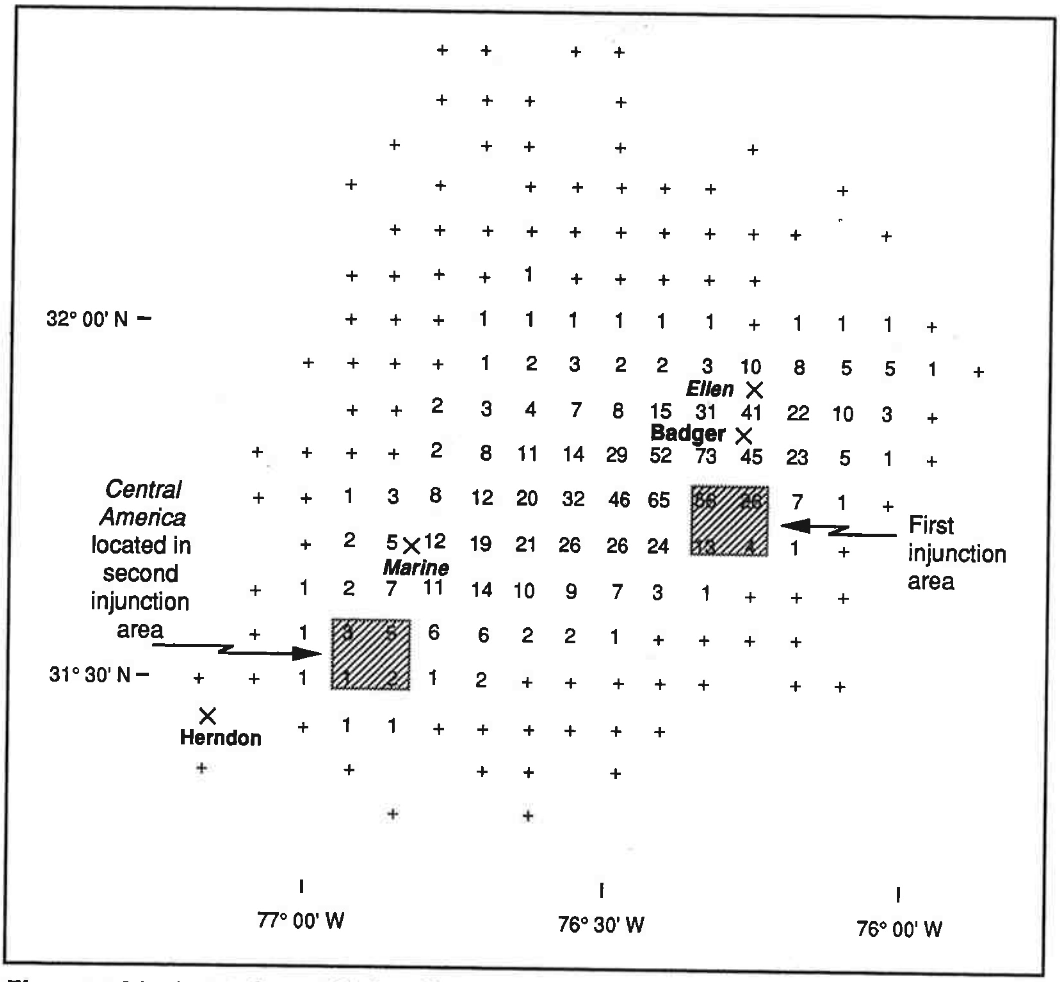

Figure 10: The first and second injunction areas are shown on the composite probability map. The mysterious first wreck was found in the first injunction area and investigated extensively during the summer of 1987. The *Central America* was found in the second injunction area in 1988. In October of 1989, one ton of gold bars and coins from the *Central America* was brought to port in Norfolk, Virginia.

over the contact, two large iron-side wheels were spotted. Later, the bell from the *Central America* was recovered providing conclusive proof that this wreck was the *Central America*. The location of the *Central America* is inside the second injunction area shown in Figure 10.

At the end of this summer, a gold bar and several smaller pieces of gold were recovered providing much needed reassurance to the group. In the summer of 1989, the group recovered one ton of gold bars and gold coins from the wreck. In October 1989, this gold was handed over to the custody of the federal courts in Norfolk, Virginia in a ceremony that received nationwide television coverage. In the same month, 39 insurance companies filed claims to the recovered gold as well as to the two tons of gold remaining on the ocean bottom. In August 1990, the claims were settled in the favor of the Columbus-America Discovery Group, giving them full rights to all items salvaged from the wreck. In 1990 the recovery efforts continued bringing up not only gold but valuable historical artifacts such as the intact trunk of Mr. and Mrs. Ansel Easton, a honeymoon couple who survived the sinking. Recovery operations continued in the summer of 1991.

In the summer of 1989, the group recovered one ton of gold bars and gold coins from the wreck.

The final result of this effort will be a treasure of gold, historic artifacts, and scientific discoveries. The identity of the wreck in the first injuncted area remains a mystery. The mystery is deepened by the unlikely coincidence that the search area should contain two wrecks of wooden hulled ships dating from the 1850s and carrying coal as well as women and children.

Conclusions

It is evident from Figure 10 that the wreck was found in a low probability area that was searched near the end of the plan shown in Figure 7. The storybook result would have been for the *Central America* to have been found in a high probability area near the beginning of the search. In 1987, we thought that was the case. Given the actual result, what can we say about the value of the procedures for developing the search plan?

The most obvious thing to say is that they worked. The second is that very few real operations that involve breaking new ground proceed in an ideal manner. This lesson has been learned many times but still bears repeating for those who have never tried to do the extraordinary. Persistence and careful planning are crucial to success. Problems will occur. Plans will go wrong.

Still the results of this search show the power and utility of the methods used for producing the probability maps. The crucial methods are

(1) The use of the weighted scenario methodology to include all the information about the target location—even inconsistent information; and
(2) The use of probabilities to quantify and express the uncertainties in the estimates.

The weighted scenario method allowed us

to incorporate the information from the *Central America* scenario even though it appeared to be inconsistent with and of lower quality than the information from the *Ellen* scenario. The navigational fix for the *Ellen* was taken after the storm had cleared on a boat that was not in danger of sinking, and the probability map for the *Ellen* scenario is consistent with estimates by Badger and Maury. The probability map for the *Central America* scenario is not. The subjective weights given to the scenarios reflect these considerations, but the philosophy of including all information kept the *Central America* as well as the *Marine* scenario in the map and provided enough probability in the area containing the wreck to require a prudent search to cover that location.

In hindsight, it is apparent that the *Central America* scenario, based on Captain Herndon's position, was the most accurate of the three scenarios. Herndon was highly respected as a careful seaman and an excellent navigator. It appears that he was able to take a more accurate celestial fix on a sinking ship in the middle of a storm than the captain of the *Ellen* did after the storm cleared on a ship that was out of danger.

The philosophy of expressing uncertainties as probabilities leads to probability maps whose extent expresses the uncertainty in the estimate of the target's location. The fact that the target was located in a low probability region only emphasizes the need to account for these uncertainties and to take the resulting probabilities seriously, even the low ones.

The methods prevented us from concentrating solely on the most likely scenario and highest probability area and thereby missing the *Central America*. In order to guarantee a high probability of success, we planned an extensive, 40-day, sonar survey, and we needed it.

Thompson used an analysis of the probability of detection versus search time similar to one shown in Figure 9 to estimate probability of success as a function of funding level. He showed this analysis to investors as a way of quantifying the amount of risk in the operation. The higher the level of funding, the higher the probability of success, and the lower the risk. This allowed Thompson to convince investors to provide funding for a 40-day sonar survey which was designed to yield a high probability of success. He explained that if the investors chose a lower level of funding, the search could still proceed, but the risk of failure would be higher. In hindsight, it is clear that the prudence of Thompson and the investors in providing for an extensive search paid off.

The prudence of Thompson and the investors in providing for an extensive search paid off.

One might ask what would have happened if the Columbus-America Discovery Group had not used search theory to plan this search. Obviously, we can not answer this question precisely, but we have some indications of what might have happened. The first indication is from Tom Thompson and Bob Evans themselves, and the second is from the history of past efforts.

Discussions with Thompson and Evans

indicate that the following is likely to have happened. They would have concentrated on the *Ellen*'s position and the positions estimated by Badger and Maury that are consistent with it. They would not have planned a search extensive enough to have covered the location of the *Central America*. It is likely that the search would have uncovered the still mysterious first wreck with coal and other artifacts from the 1850s and that they would have eventually decided this was the wrong wreck. Finally, they probably would not have been able to return to their investors for more money to continue the search in other areas.

Other groups have tried to search for the *Central America*. In particular, a group from the Lamont-Doherty Geological Institute of Columbia University performed an unsuccessful sonar search. They searched for about two weeks at sea in the early 1980s with a sonar similar to the one used by the Columbus-America Discovery Group and failed to find the wreck. Their failure was at least partially due to the lack of careful analysis and planning that the search theory approach supports. Apparently, they did not use search theory methods for planning their search, and they certainly did not plan for enough effort to guarantee a high probability of success.

Acknowledgments

When I began this work I was senior vice-president at Daniel H. Wagner, Associates. A number of people at Wagner Associates participated in this work. Richard Clark provided computer assistance in estimating the distribution of the ocean currents in the area of the loss and in running the version of CASP that was used to produce the probability maps for the location of the *Central America*. Robert J. Lipshutz provided initial estimates of wind-driven current. These were later superseded by the estimates made by Roland Garwood.

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