

Chapter 8

The Grounding of the *Royal Majesty*

“There are three things which are a wonder to me: The way of an eagle in the air; the way of a serpent upon a rock; the way of a ship in the midst of the sea . . .”

—Proverbs 30: 18-19

With summer winds out of the northeast at 16 knots, any sailing ship would make good headway to the New England coast. But the *Royal Majesty*, a modern cruise ship, did not need sail power to slice the waves—she had two titanic diesel engines with hefty amounts of horsepower to propel her all the way to Boston Harbor. Built at the renowned Finnish shipyard Kvaerner Masa, her slanted foremast and streamlined chimney stack gave her the sleek appearance of a stately cruise liner. Elegant looking and with a high superstructure, this modern leviathan of the sea was almost 600 feet long and 10 decks tall, well-built and powerful. But in her hold, she was hiding an old sea tale with a modern twist.

Only three years in service, she sported the state-of-the-art in navigation equipment: three radars, an integrated bridge system with an autopilot and a radar-map display, a sophisticated speed log, and an accurate gyrocompass. Unlike vessels of the past, which had to rely on hugging the coastline or sighting constellations to find their way, the *Royal Majesty* was equipped with a Global Positioning System (GPS). The GPS is a marvel in the world of navigation. If the invention of the magnetic compass was the first revolution in navigation, and finding longitude with chronometers the second, then the global positioning system with its artificial constellation of orbiting satellites is surely the third; no need to rely on distant stars, sun, moon, and no prayers for



Figure 8.1. The cruise ship *Royal Majesty* (source: National Transportation Safety Board).

a cloudless sky. The GPS displays the latitude and longitude with an accuracy of about 100 yards, anytime, anywhere.

Out to Sea

June 9, 1995, Bermuda. Departure time: 12:00 P.M. As the 1,200 passengers were readying themselves for the last two nights of a seven-day cruise, the officers and staff were also preparing themselves for the return voyage. The navigator, perched up on the bridge an hour before departure, was testing and checking all his navigation systems, the pride of his job. They were in “perfect” condition, no anomalies were detected.

The bridge of the *Royal Majesty* was smart. With its huge front windows and sophisticated equipment, it looked like a set from a science fiction movie. In the front was a large crescent-shaped console planted with several radar screens, navigational displays, and ship alarm indicators. Behind it, separated by a partition, lay the long chart table. Mounted just above the table, within an arm’s reach, were the GPS and the LORAN-C units (see figure 8.2). The LORAN-C is another navigation system, providing reasonably accurate position data by triangulating radio signals from onshore transmitters. Its major drawback is that it deteriorates in accuracy as the distance from shore increases. Naturally, the officers always preferred the more accurate GPS. On this departure, like every other, the navigator selected GPS as the primary source of position data.

While the GPS and LORAN-C display units were inside the bridge, their antennas were mounted on the roof to better facilitate the reception of radio



Figure 8.2. The chart table and the bridge. The left arrow points to the GPS unit, the right arrow points to the LORAN-C unit. Source: National Transportation Safety Board (the photo has been enhanced).

waves. The roof above the bridge of a vessel is called the “flying bridge.” Passengers were never allowed to walk on the roof, and the officers hardly ever used it during a passage, but electricians and technicians would climb up there on a fairly routine basis to check the cables and maintain the GPS and LORAN-C antennas. The *Majesty’s* flying bridge was just like any other—a low railing all around, antennas of all sorts, satellite receiving domes, and bundles of connecting wires—except that the gray coaxial cable coming out from the closed bridge and leading to the antenna of the global positioning system was hanging loose; it wasn’t sufficiently secured or strapped to the flying bridge’s roof.

The departure from Bermuda was normal. On the bridge, the officers were busy bringing all the necessary systems on line, checking their critical functions and alarms, reading the weather charts, setting the watches, and examining the sailing plans and nautical charts. Just before noon, while the buffet lunch was being served in the dining halls, the ship departed the Ordnance Island terminal. The bridge was busy with the captain, harbor pilot, and officers conning the ship, taking orders, and maneuvering the ship in the small harbor. Outside, lookouts on both sides of the bridge were guarding her flanks for any unforeseen or unusual circumstances. Commands and directions were given with authority, and she began to move and turn smoothly with her bow thrusters and main engines. Now, with her stern to the terminal and her bow to the northeast, she slowly glided on her own

power away from the pier and through the breakwaters into the blue Atlantic Ocean.

At 12:05 P.M., she was making 14 knots and every line, cable, flag, and unlash cloth flapped in the wind. 16 knots by 12:20 P.M. A small launch came alongside to pick up the harbor pilot at 12:25 P.M. With engines revving up to cruise speed, the ship was approaching 20 knots. Bermuda was slowly disappearing aft until it was a low coastline behind the ship.

Inside the bridge, the tense port departure activities began to calm down. The focus was now on the 677 nautical miles that lay ahead to Boston Harbor. The ship's position (called a fix) was plotted on the chart and regular reports from the engine room followed. At 12:30 P.M., the navigator walked to the chart table and compared the GPS and LORAN-C positions—one-mile difference. "Not bad," he muttered to himself with pride. The GPS was computing the ship's position by receiving timed transmissions from three or more satellites orbiting the Earth, and then converting time to distance. Then the GPS went on to compute, based on the distance to the three satellites, the location of the ship. The LORAN-C was doing basically the same thing by receiving timed transmissions from three or more land-based transmitters on the East Coast of the United States. The accuracy of the LORAN-C deteriorates with distance, and therefore a mile difference in a location as far off the U.S. mainland as Bermuda was a testimony to the accuracy of the LORAN-C.

Satisfied with the accuracy of the fix he just laid on the map, the navigator walked away and joined the captain, who was standing by the large windows. Above them, on the flying bridge, the loose GPS cable was banging freely in the wind and slapping the flying bridge's deck; the connection between the GPS cable and the antenna was coming apart. At 12:52 P.M., interruptions in the global positioning data began: after a few seconds of no position signal, a one-second alarm chirp sounded, similar to a wristwatch alarm. Nobody heard it; it was barely audible. At 1 P.M., the captain commanded "change course to 336, take us up to Boston." Nine minutes later, the global positioning system signal was back again. But it did not last long, because at 1:10 P.M., the connection between the cable and the antenna broke away for good.

Around 2 P.M., the navigator set the autopilot in navigation (NAV) mode. In this mode, the autopilot would get position data from the GPS and then guide the ship along a pre-programmed route that would take the ship to Boston with little human intervention. On this run there were three legs: 500 miles from St. George, Bermuda to a point just south of Nantucket Island; then skirting the infamous Nantucket Shoals up to the northern part of Cape Cod; and finally around the Cape into Boston Harbor.

Figure 8.3 is a map of the route between Bermuda and Boston. But maps, as we already know, are only an abstraction. In the real ocean, there are winds, currents, tidal streams, and rolling waves. They all combine to push, or offset,

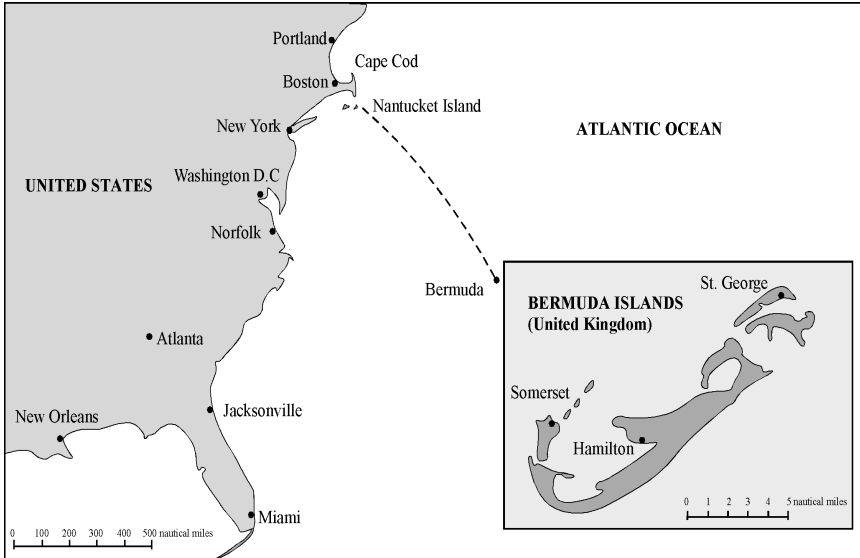


Figure 8.3. From St. George, Bermuda (see inset) to Boston, Massachusetts.

the ship away from its intended route. If the autopilot simply maintains the course plotted on the chart, it will never keep the ship on track. To compensate, the autopilot steers a slightly modified course.

But how does the autopilot know how much to compensate for these effects? Well, the autopilot calculates the difference between its current position and where it is supposed to be. Once you know where you are and how much you have deviated, you can determine what course changes are needed to get back on track. We all do this when we drive along an open road with high winds. We get blown to one side and then steer our way back to the center of the lane. After a few such episodes, we learn to oversteer a bit into the wind to counter its effect on the car. The autopilot does the same thing. But since the autopilot has no eyes to gauge how much to oversteer, it uses GPS position data to do this. Under normal sea conditions, these modified course changes are so little, they are hardly even noticeable—a degree to port here, a degree to starboard there. Yet without these minute course corrections, any vessel will wander off its intended track.

Change of Shift

By late afternoon Bermuda was well beyond the horizon and the passengers were resting after a luxurious lunch buffet, but the routine work in the bridge continued—there were fixes to make, engine room readings to record, information and events to be entered in the ship's log book, communications with

other ships and vessels, and recording of sea and weather information. A decent formality has always been observed aboard ships at sea. Mariners do not think of work in terms of hours, but of watches: At 4 P.M. the chief officer takes the afternoon watch and relieves the navigator; at 8 P.M. the second officer is on duty; at midnight the navigator returns; at 4 P.M. of the next day, the chief officer stands again; second officer at 8 P.M.; navigator noon.

It was now 28 hours since leaving Bermuda and the monotonous work on the bridge continued. Sea duty is like a clock that never stops. Every hour, on the hour, the position of the ship in the midst of the ocean is fixed. There are many ways to do this: in coastal waters, one can find the ship's position by taking compass bearings from two separate landmarks. The intersection of the two lines fixes the position of the ship. Using radar, a fix can be obtained by taking the distance to two objects or three objects (such as radar beacons, buoys, and capes), and then plotting a distance arc around each one. Where the arcs intersect is where the position is fixed. When the vessel is far from shore, the ship's position can be fixed with reference to the stars, the moon, or the sun. And finally, there is also the GPS and the LORAN-C. On the *Royal Majesty*, the captain and officers relied solely on the GPS.

A few minutes before 4 P.M. on that Saturday, the chief officer came to relieve the weary navigator. The lookout was also being relieved by his mate. Shift change on a ship's bridge is a well-choreographed and time-honored ceremony that repeats itself every four hours. A fix is drawn on the map, logbooks are signed, reports are relayed, and relevant information such as changes in wind and current, objects or close-by ships, is exchanged. The chief officer conferred quietly with the navigator over the charts. The ship was about 80 miles away from shore and they were transitioning from deep-ocean navigation into the more hazardous coastal passage where there are many vessels and fishing boats to worry about and, of course, the vicinity of land. The point of transition was just south of Nantucket Island. They were scheduled to dock at Boston in the early morning of Sunday, June 11.

Nantucket, the capital of a nineteenth-century whaling empire that ranged from the Atlantic to the Pacific, is a small crescent-shaped island, actually a sand bank, located about 20 nautical miles south of Cape Cod. Spread around it is Nantucket Shoals—a moving set of shoals that insulted and bedeviled mariners for centuries. Ships of all sizes, some of them Nantucket's own, have grounded and sunk in those treacherous waters. To protect ships from the dangerous shoals and help separate traffic of vessels in and out of Boston Harbor and around Cape Cod, the U.S. Coast Guard created the Boston traffic lanes (figure 8.4). Just like a boulevard with two opposing lanes and a divider in between, there are lanes for northbound and southbound ships. Defining the separation zone is a series of six lighted buoys. The BA buoy marks the southern entrance into the lanes and the buoys that follow—BB, BC, BD, BE,

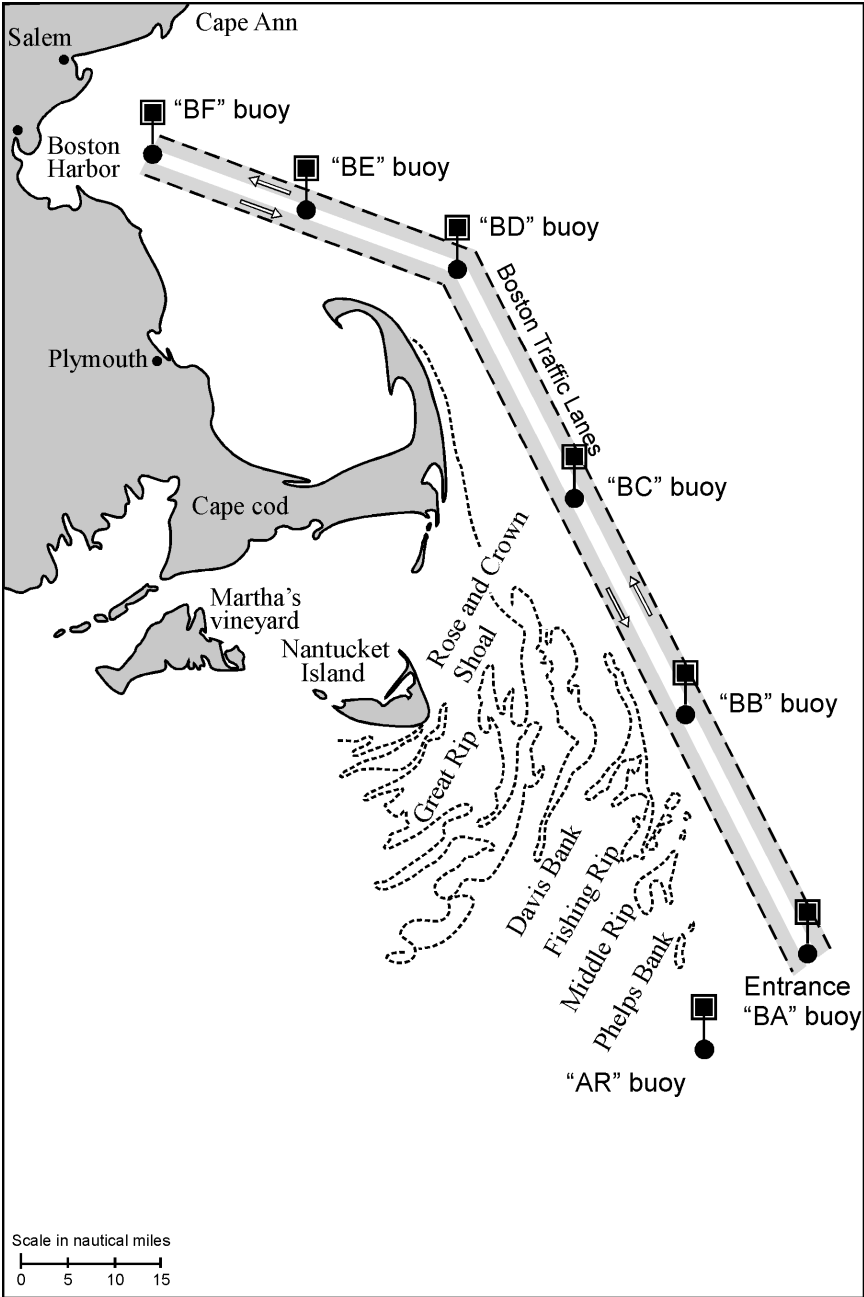


Figure 8.4. The Boston Traffic lanes, Cape Cod, and Boston Harbor.

and BF—mark the way to Boston Harbor. Each buoy has a radar reflector and a unique flashing characteristic.

Twenty minutes after 4 P.M., the captain entered the bridge. He inspected the sophisticated radar display on the spacious console and the logbook. Everything looked fine. Ready to leave, he walked by the chart table, followed by the chief officer. The chart was spread wide open, ready. Poised above the chart table, the GPS displayed in green glowing red alphanumeric digits the latitude and longitude of the ship (see figure 8.5[a]). The two officers looked at the latitude and longitude coordinates on the GPS display and compared it with the small pencil mark on the map.

“Here we are, and here are the traffic lanes,” said the chief officer.

“Excellent,” replied the captain.

But what neither of them noticed was that in addition to the latitude and longitude coordinates and all the usual data, the GPS display showed two small, innocent-looking text symbols—**SOL** and **DR** (figure 8.5[b]). But these two symbols were hardly innocent—they portrayed a serious problem in the GPS. **SOL** stands for **SOLUTION**, indicating that the GPS was *no longer* computing an accurate position solution. Actually, it had not been producing accurate position solutions for quite some time—ever since the connector between the cable and the GPS antenna had given up an hour after departure, the unit was unable to receive any satellite signals and update its true location.

So what information was the GPS displaying for the past 27 hours?

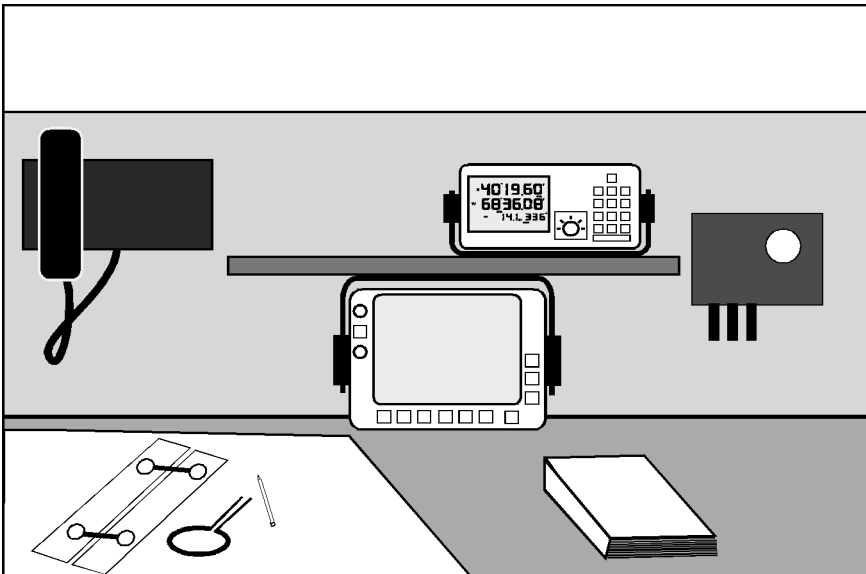


Figure 8.5 (a). The chart table and the GPS unit (top shelf) and LORAN-C unit (bottom of shelf).

Not receiving any satellite signals, unable to determine its position, the GPS defaulted to dead reckoning (DR) mode. Dead reckoning is an old method of navigation dating back to thirteenth-century Mediterranean mariners and the introduction of the magnetic compass. Dead reckoning—which should properly be written *d'ed* reckoning, an abbreviation for deduced reckoning—boils down to laying down a compass course and estimated distance on the chart. The navigator would start from the port of departure, plot the course line on the map, and then mark the distance traveled. With every course change, a new line was drawn and the new distance marked. With this simple geometry, the estimated position of the ship was calculated.

But how does one get the distance traveled? There were no odometers on thirteenth-century ships—but if one knows the speed of the ship one can compute distance. The early method was to throw flotsam in the water, note how long it took to travel from the bow to the stern (a known distance), and convert time and distance to speed. In the age of Spanish caravels and inaccurate hourglasses, sailors would throw the flotsam and sing a fast sea chantey—and when the flotsam reached the stern mark, the pilot would note the last syllable reached in the chant, and convert that syllable into speed. Columbus, they say, was a master in dead reckoning navigation, making amazingly accurate landfalls during his return trips from the New World.

In modern ships, dead reckoning is calculated by obtaining the ship's heading from the gyrocompass and distance traveled from the speed log—a sort of a ship's odometer. Using the same arithmetic as employed by navigators

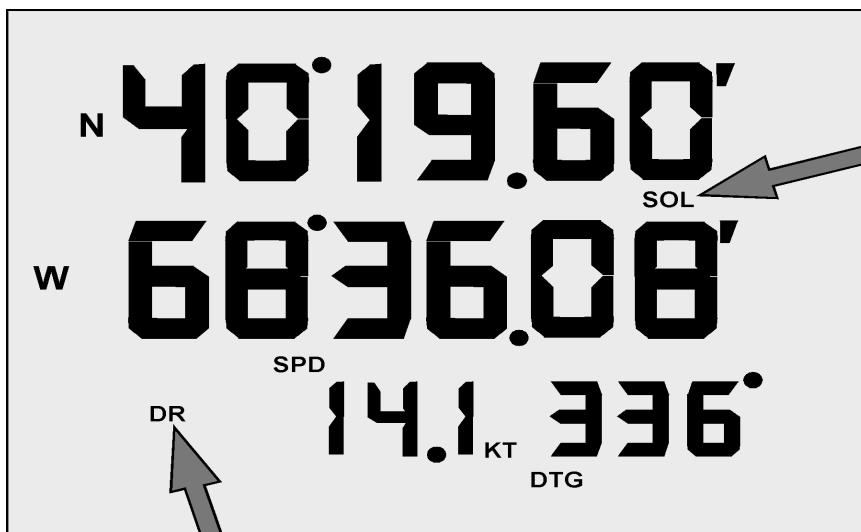


Figure 8.5 (b). GPS display indications at 8 P.M. on the night of the grounding. The arrows show the DR (dead reckoning) and SOL (solution) indications.

in the age of discovery, a fix is calculated. This is exactly what the GPS does in dead reckoning mode. And just like thirteenth-century dead reckoning navigation, it needed a starting point. In the case of the *Majesty*, it was a point some 30 miles northeast of Bermuda, corresponding with the last GPS fix, just before the antenna connector finally broke.

At first, the effects of sea, wind, tidal currents, ocean currents, compass and steering errors were negligible; the *Royal Majesty* was sailing almost parallel to route and the latitude/longitude was only slightly off. But as the hours passed and Bermuda fell behind, slowly and surely the gentle eastward swell rolled her aside and the east-northeast wind buffeted her superstructure leeward. The position data were deteriorating at a rate of a half nautical mile per hour.

Meanwhile, the crew was plotting the ship's position by reading off the latitude and longitude from the GPS display, assuming the position portrayed there was accurate, as always. And since the GPS unit was spitting out dead reckoning positions—completely oblivious to what the sea and wind were doing to the ship—the trail of hourly plotted fixes on the chart showed as if she was exactly on her intended track. Therefore, nothing appeared amiss—the navigation actually looked perfect. And since the time-honored rule of taking a backup fix (from another source, e.g., LORAN-C, radar, or celestial navigation), was not practiced on the *Royal Majesty*, her officers believed that all was well. But at any rate, at 5 P.M. on June 10, after 28 hours in DEAD RECKONING mode, the *Majesty* was 14 miles southwest of her intended route.

Entering the Lanes

“When do you expect to see the first buoy?”

The chief officer, answering the phone, responded quickly to the Captain: “we are about two and a half hours away from the Boston traffic lanes.” Then they went on to discuss how they were going to pass a mile or so to the right of the entrance (BA) buoy, which marks the entrance into the Boston traffic separation lanes (see figure 8.6[a]). The BA buoy, about six feet wide and ten feet tall, had a boxy-looking radar reflector on it—making the small buoy detectable by radar at a range of about 10 nautical miles. But the ship was still 35 miles out, so they could not detect it yet on the radar.

“Call me when you see it,” said the captain as he ended the conversation.

In preparation for entry into the Boston traffic separation lanes, the chief officer lowered the speed to 14 knots. This was good practice in coastal waters where small vessels abound and fog banks appear without notice this time of year. At 5:30 P.M., after tea, the captain was up on the bridge again. He checked the vessel's progress by briefly looking at the chart and then walked forward to examine the radar map. There he could see it all. The radar map not only showed the radar image, but overlaid on top of the radar image was a map-like

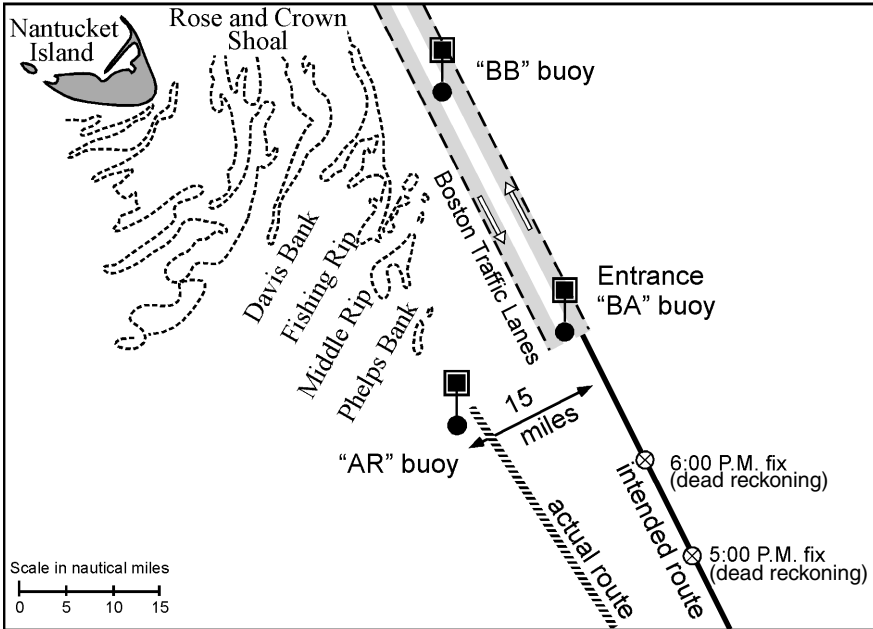


Figure 8.6 (a). Actual and intended route of the *Royal Majesty*.

rendering of the traffic lanes and buoys. On the perimeter of the display there was a plethora of related information such as heading, course, speed, drift, set, autopilot data, and the latitude and longitude of the vessel (see figure 8.6[b]).

At 6 P.M., the radar map showed the vessel sailing on track and heading accurately toward the right side of the traffic lanes. Yet in reality, the *Royal Majesty* was 14.5 miles west of the lanes, close to shore, and heading toward the dangerous Nantucket Shoals (figure 8.6[a]). The radar map deceived the crew—and the reason for this is important for us to understand because it exposes the kind of problems that plague automatic control systems, especially of the navigational kind. You see, the source of ship position for the radar map display was none other than the crippled GPS unit; whatever the GPS said, the radar map displayed. And since the GPS position did not reflect the ongoing and increasing position deviation, it provided information as if the ship was following its pre-programmed route. That's what the radar map displayed—which was, of course, a false description.

The only way for the officers of the *Royal Majesty* to recognize the discrepancy was to compare the information displayed on the radar map with another (independent) source of position data. One such source could have been the radar image, which is part of the radar map display. The radar does not deceive; it cannot tell you where you are, but it always tells you where other buoys and landmarks are, in relation to you. But although the radar was on, the ship was

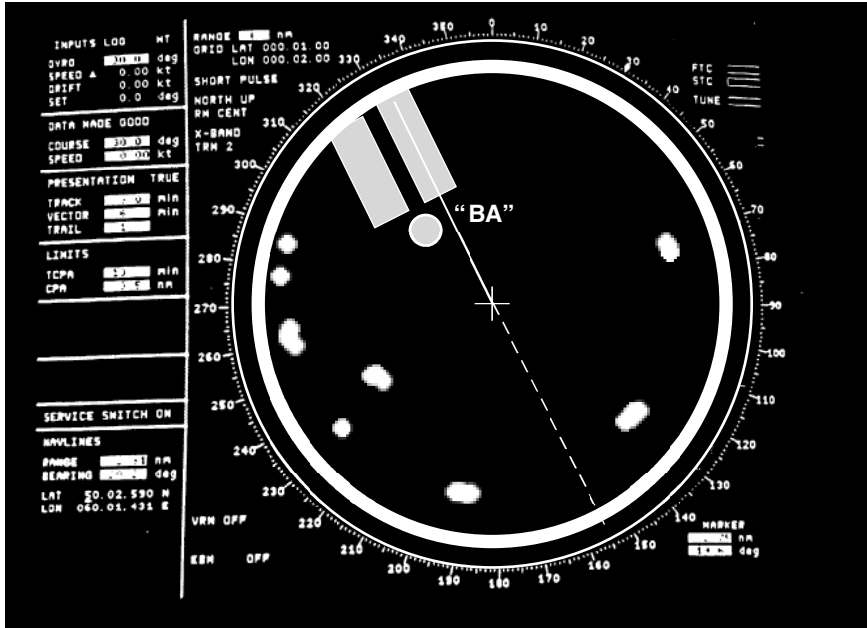


Figure 8.6 (b). The radar map, showing the radar screen and rendering of the traffic lanes and entrance buoy (BA).

more than 15 miles away from the entrance buoy to the Boston traffic lanes, which was too small to be detected. And since the radar's range was set to 24 miles, they did not see land on the radar. As a consequence, the map shift was not detected.

At 6:45 p.m., the chief officer saw a blip on the radar, approximately seven nautical miles away. The little blip was collocated with the rendering of the entrance buoy on the radar map (figure 8.6[c]). Based on the GPS position data, which indicated that the *Royal Majesty* was following its intended track, and on the fact that the blip had been detected on the radar at the time, bearing, and distance that he had anticipated detecting the BA buoy, the chief officer concluded that the radar blip was indeed the BA buoy. But most of all, it was the fact that the blip appearing on the radar coincided with the plotted position of the buoy on the radar map display, which sealed his conviction that this was the BA buoy. There it is, he thought, just where it should be. The chief officer was now certain that the ship was well protected from the dangerous Nantucket Shoals.

Mariners, to this day, are very wary of the entire area. It is considered one of the most treacherous areas to navigate in the entire U.S. coast, and piloting books warn that "the whole area should be avoided by deep draft vessels when possible." The Coast Guard had planted several large buoys to mark the area.

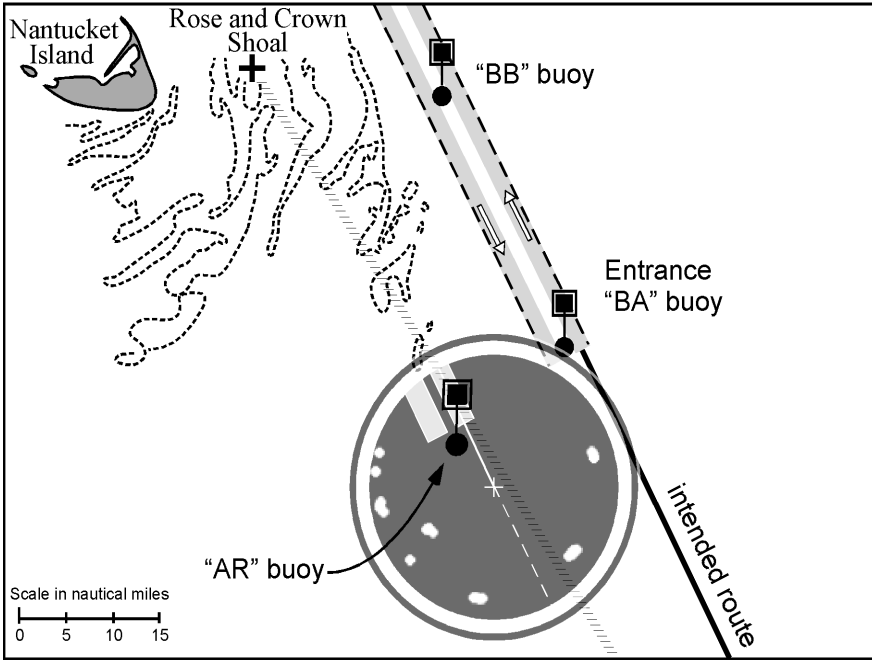


Figure 8.6 (c). Superimposition of the radar map and buoy rendering on top of an actual nautical map. Showing how the actual location of the “AR” buoy matched the expected location of the “BA” (entrance) buoy.

One of them, the Asia Rip buoy, flashing yellow light at a 2.5-second interval, was guarding the southeast tip of the shoal area. Anchored by a long and heavy chain to the wreck of an unfortunate vessel, the Asia Rip buoy was 15 miles to the west of the entrance buoy. And 15 miles is an important number here, because by a rare and unfortunate twist of fate, at that time the *Royal Majesty* was exactly 15 miles off her intended route! And therefore, on the radar map, it was actually the radar return from the Asia Rip buoy that coincided with the rendering of the entrance (BA) buoy (see figure 8.6[c]).

But on the spacious and modern bridge of the *Royal Majesty*, all of this was hidden from view. On the radar screen everything looked picture perfect; the ship was heading toward the rendering of the lanes and the little tick marks on the chart were there to prove it. A feeling of complete security, the most fatal delusion a seaman can entertain, fell upon the bridge. And it is true that the great majority of accidents at sea are not due to the violence of weather or fragility of a ship, but over-confidence as to the ship’s position.

At 7:20 P.M., a large iron buoy, with a light and an awkward-looking boxy radar deflector on its flat top, was passed less than 2 miles off the port side of the ship. The chief officer had been tracking it on the radar for the past half an

hour, assuming it was the genial entrance buoy. Like a disregarded messenger, the Asia Rip buoy bounced in the wake of the *Majesty*, and then quietly faded out of sight.

Several minutes later, the captain telephoned the bridge and asked the chief officer for the third time whether he had seen the BA buoy. “Yes, captain, we just passed it 10 minutes earlier.” The captain then asked whether the chief officer had detected the buoy on radar. “Yes, captain, I did.” The captain was now relieved of his concern. Unfortunately, the chief officer did not tell the captain that he had been unable to visually confirm the identify of the BA buoy, and the captain did not ask whether the buoy had been visually confirmed. And the good ship *Royal Majesty*, blowing white smoke out of her smokestack, continued toward the shoals—leaving a tranquil wake behind.

The 8 P.M. Shift Change

On Saturday evening, June 10, the winds were blowing on the starboard side. The temperature was falling slowly and the gray daylight was fading away. The ocean was running to the shore with increasing force. As the second officer walked to the bridge, lights started to appear on the decks, the smell of burned fuel was in the air, and the ship rolled gently with the three- to four-foot waves. New to this ship, but hardly a novice mariner, he walked briskly up the flight of stairs, opened the large wooden door, and entered the bridge.

Inside, it was already night. An array of digital lights were coming from the displays, and radio calls from the speakers. A ship is like a city that never sleeps. During the change-of-shift briefing, the chief officer informed the second officer that they were well inside the Boston traffic lane. “Course 336, speed 14 knots, wind from the east-northeast at 15 to 20 knots. I already turned on the navigation lights for you.” The second officer went over to the chart table to look at the fix. Meanwhile, two lookouts took their positions on the port and starboard side.

The evening watch slowly transcended into that calm so common on a ship’s bridge during the night. The second officer, now alone on the spacious bridge, was standing by the radar map. Noting several radar returns on the port side, he moved his head up and looked outside. As the night spread over the waters, navigation lights slowly replaced the masts of vessels in the vicinity. Red over white, he noticed; fisherman working along the nutrient-rich Nantucket Shoals. Noting that all the fishing vessels were far away and almost stationary, posing no danger to the *Royal Majesty*, he reduced the radar range to six miles—giving the traffic lanes his full attention.

The lookout on the port side reported a yellow light on his side. “Thank you.” Several minutes later, both lookouts reported seeing red antenna lights on the port side. Then they reported seeing more red flashing lights off on the

horizon. Like a set of city traffic lights, these lights announced the presence of nearby land. The port and starboard lookouts continued to report uncommon sightings to the officer. He acknowledged each with a “roger” but did not take in the significance of these sightings. With his radar scale set on 6 miles, the phosphorous image of Nantucket Island, now 25 miles away and almost dead ahead, was hiding beyond the scale.

Good Neighbors

The Portuguese fishing vessels *Rachel E* and *San Marco* were pulling heavy nets along Nantucket Shoals all day. From inside the salt-sprayed cockpit windows, Antonio Pimental, a fisherman on the *Rachel E*, was looking at the evaporating horizon and checking the sea conditions. The light of day was fading fast and the sea appeared a deep gray, turning black. And then he gasped. He refocused his eyes with amazement. In front of him, less than a mile away, looming like a disoriented leviathan with gloomy green and red eyes, was a huge ship. And there was no question about it—she was heading straight toward the shoals. As he was considering what to do, he heard the following transmission, broadcast in English, on channel 16, the maritime distress radio frequency. (The following are transcripts of marine radio transmissions, recorded on Coast Guard receivers, on the evening of June 10, 1995):

“Fishing vessel, fishing vessel, call cruise boat.”

There was no reply. Antonio waited a minute and then, recognizing the voice, he called his friend Toluis on the *San Marco*. The ensuing conversation was in Portuguese:

“Hey, it’s Antonio Pimental. That guy is bad where he is. Don’t you think that guy is wrong in that area?”

“I just tried to call him,” replied Toluis. *“He didn’t answer back. He is very wrong.”*

Antonio Pimental picked up the microphone and made the following calls (in English):

“Calling cruise ship in the position 41-02 north, 69-24 west.” “Calling cruise ship 41-02 north, 69-24 west.”

No answer.

After several additional attempts, Toluis picked up the radio and commented, in Portuguese: *“Maybe nobody on the bridge is paying attention.” “I don’t know,”* replied Antonio, *“but he is sure not going the right way. . . .”*

Machine-Machine Interfaces

By now the large and ponderous vessel was well inside the treacherous shoals, her 20-foot-deep hull passing over Phelps Bank, Middle Rip, Fishing Rip, and

Davis Bank. The two huge screws were sending commotion to the bottom of the ocean, raising yellow sand, but not touching. And with the depth meter (fathometer) not selected for display, and its alarm set at a meaningless 0 feet, no one on board knew that she was sometimes only 10 feet from running aground. Although a common practice in any ship passing through costal waters, the officers of the *Royal Majesty* failed to turn on the depth meter for display. They did not consult the depth meter nor did they set its alarm properly. Thus they robbed themselves of critical information that would have forewarned them that they were approaching shallow water. The *Royal Majesty* continued her mindless tack toward Nantucket Island, while on the bridge, high above the waterline, the second officer was observing his progress along what he thought was the Boston traffic lane. As the gray sky turned black veil, the phosphorus-lit radar map with its neat lines and digital indications seemed clearer and more inviting than the dark world outside. As part of a sophisticated integrated bridge system, the radar map had everything—from a crisp radar picture, to ship position, buoy renderings, and up to the last bit of data anyone could want—until it seemed that the entire world lived and moved, transparently, inside that little green screen. Using this compelling display, the second officer was piloting a phantom ship on an electronic lie, and nobody called the bluff.

Why?

Although both the autopilot and radar map had a variety of internal tests to check for erroneous data, all of them failed to warn the crew. To understand this matter, we need to plumb the depths of the machine-machine interfaces involved here. It turns out that there were serious design problems in the communications between the GPS unit, the autopilot, and radar map display that circumvented every attempt to warn the ship's officers about the increasing deviation between the ship and her intended track. Here is why: the GPS sends its position data to the autopilot and radar map display by spitting out a sequence of sentences. Just like the transcript of a theatrical play, each sentence starts with the name of the machine sending the information—followed by the time, the latitude and longitude, and other information. The GPS sentence normally ends with the word “valid.”

The GPS sentences sent out to the autopilot and radar map while the ship was heading out of the harbor (before the cable broke) looked like this:

GPS, 12:10:34, latitude, longitude, valid.

GPS, 12:11:51, latitude, longitude, valid.

GPS, 12:13:01, latitude, longitude, valid.

When the antenna cable broke, the GPS defaulted to **DEAD RECKONING** mode as it was designed to do. It continued sending latitude and longitude, only this

time the values were based on approximated dead reckoning computation. At the time these integrated marine electronic systems on board the *Majesty* were designed, there was no industry standard as to how the GPS unit indicated that the data it is sending was based on dead reckoning calculations (and not on the precise satellite-based GPS solution). To deal with this lack of standards, the designers of this particular GPS unit found a simple and labor-free solution: they used the last word of the sentence as a means of “flagging,” or indicating, that the data was inaccurate, while retaining the entire structure of the sentence as shown above. The last word in the sentence would say *invalid*. Therefore, after the cable broke and the GPS defaulted to **DEAD RECKONING** mode, the sentences read:

GPS, 1:11:46, latitude, longitude, invalid.

GPS, 1:12: 09, latitude, longitude, invalid.

GPS, 1:12: 51, latitude, longitude, invalid.

The only problem was that the autopilot and radar map system were not programmed to look at the last word of the GPS data sentence. Therefore, the *valid* or the *invalid* statements were completely ignored. You see, the designers of the autopilot and radar map system (which is built by another maritime electronics vendor) never expected, even in their wildest dreams, that a device that identifies itself as a GPS would send anything other than accurate satellite-based data. (What was common among other manufacturers of GPSs was to send a null position data such as 00-00 north, 00-00 south, or to send a unique sentence saying that the GPS has failed, or to halt sending GPS sentences altogether.)

But were there other internal checks on the accuracy of the position data? Actually, yes. The autopilot was designed to constantly calculate its own independent dead reckoning position and compare it with the GPS position data. If the difference between the two positions was within tolerance, the autopilot considered the input from the GPS as “good,” accepted the data, and steered the ship according to the GPS data. If the difference was too large, it signaled and warned the crew about the anomaly. That kind of a check should detect a 15-mile offset, right? Not in this particular design. Since both the GPS and the autopilot used the same gyrocompass and speed inputs to compute the dead reckoning information, the two calculations were actually the same and therefore always in agreement, which, of course, eliminated the built-in redundancy and rendered this entire check futile.

One after the other, internal checks that were in place to protect and warn against flawed and erroneous data collapsed like a line of dominos.

In the same way that there is an interface between the user and the machine, there are similar interfaces between machines. Through these interfaces

machines exchange data. There was an interface between the GPS unit and the autopilot and radar map. Through this interface, the GPS unit provided multitudes of information. The autopilot and radar map, on the other side of the interface, accepted some information, and, as we now know, ignored some. The main issue here, just as in interface design, is about abstraction. Here, also, we want a machine-machine interface that is *correct* insofar as it does not *hide* critical information, nor does it *lie* about the actual state (or mode) of the machine.

The interface between the GPS unit and the autopilot/radar map *lied*, because although the GPS was sending dead reckoning data, the interface passed along the data as valid satellite-based data. The GPS was in **DEAD RECKONING** mode and the interface took the information as if it was in **SATELLITE** mode; we therefore must conclude that this machine-machine interface was *incorrect*. (Later in this book, we will be discussing verification and abstraction techniques for designing correct and succinct user-machine interfaces; it turns out that the same concepts can be extended to the analysis and design of machine-machine interfaces.)

The Grounding

By now, the rift between the radar map and the actual ship position had increased to 16 miles, and the ship was coming closer and closer to shore. With an incorrect interface, all internal checks failing, and the officers of the watch not corroborating the accuracy of the position data by any other independent source—the ship was quickly approaching its destiny on Nantucket’s inner shoals as so many other ships had done in the past. With his trust in technological marvels, man tends to lose the sense that the ocean is still something to reckon with. And the cruise ship *Royal Majesty*, now fully confused and disoriented, was scudding towards disaster.

At 10 P.M. the captain came to visit the bridge. The second officer told him that they were inside the traffic lanes, but failed to mention that he actually did not spot the second (BB) buoy on the radar. Satisfied that the positions marked on the chart and the position on the radar map matched and showed the vessel on its intended route along the Boston traffic lanes, the captain left the darkened bridge and walked slowly down the lighted corridor to his office. He felt the deliberate and assuring throb of the engines, as if signaling everything was fair.

Outside, however, things were not all right and starting to deteriorate at a rapid pace: “Blue and white water dead ahead,” shouted the port lookout as he noted the change of ocean color, indicating very shallow waters and breaking

waves. “Thank you” replied the second officer and continued his fixation on the green radar map. Normally, the sight and sound of breaking water would raise the hackles of any mariner, as this is an unmistakable indication of shallow water, but the lookout’s warning went unheeded by the second officer.

Seconds later, the entire ship was jerked to the left as if shoved by a giant hand, with all her 32,000 tons taking the unexpected side blow. The bow shook first. And then another grinding sound from the side. Vibrations raced along her keel, from compartment to compartment, all the way to the stern. Many of the passengers in the lower decks woke up in fright. Like a massive pendulum, the ship swung from side to side, heaving to the right and then to the left, but still moving forward at 14 knots. The second officer was confused and thunderstruck; the captain, working at his desk, sprang up and ran like a madman through the long white corridor back to the bridge. When he got there, the second officer was already steering the clobbered ship manually. The captain dashed to the radar map, kicked it open to 24 miles—and saw an unmistakable crescent-shaped mass of land: Nantucket Island. Looking ahead in dismay he shouted.

“Hard right, Hard right, haaard righttttt!”

But it was too late. A deep guttural quiver came from below as the ocean-going vessel plowed into the shoals. The ship was slowing down. A sense of helplessness descended on the bridge. And then, with cavernous pulsations, as the hull carved through the cruel underwater shoal, the ship came to a grinding halt. They all noticed the awkward stillness of the situation. She was not moving, but her propellers were still lumbering forward. “Engines to idle,” he shouted to the engine room. The engines stopped. Only the comforting sound of the generators and the blowing of the wind broke the unfamiliar silence. The captain quietly ordered, “engines to reverse.” Nothing moved. The propellers were turning backwards but the ship was not moving with them. The heavy propellers were beating the water, but to no avail. The ship was hard aground.

The captain called the engine room for an immediate hull inspection. He couldn’t fathom how the ocean had betrayed him; how his elegant and highly maneuverable ship all of a sudden had become paralyzed and immobilized. With these thoughts and feelings screaming through his body he ran to the chart table to check the GPS and LORAN-C positions. It was then that he realized, for the first time, that the GPS was in error by 17 miles! When he plotted the LORAN-C position on the chart, he had to dismiss the dozens of explanations and speculations that chiseled through his head. The inescapable and humiliating realization of a gross navigational error descended upon him like a dark cloud: his proud ship was aground on the Rose and Crown Shoal, only 10 miles from Nantucket Island. The calm silence was broken with shouts, orders, curses and accusations. At 10:25 P.M., she was stranded on the



Figure 8.7. The *Royal Majesty*, grounded on Rose and Crown Shoal and surrounded by two tugs and a Coast Guard cutter (source: National Transportation Safety Board).

shoal, resting on her right side, showing her dark red bottom, like a matronly aunt caught with her pants down (figure 8.7).

End of Story

All attempts to pull back from the hold of the shoal failed. By midnight, the captain gave up on his efforts to free the ship by using the engines' forward and reverse thrust. Ironically enough, it was a passenger with a cell phone that alerted the United States Coast Guard to the *Royal Majesty's* grounding. Upon the Coast Guard's radio call, the captain confirmed his situation and requested assistance. At noon the next day, two ferryboats that were chartered by the shipping company arrived on the scene. But the plan to off-load the passengers into the ferries was canceled because the sea conditions were too hazardous. In the late afternoon, five large tugboats arrived. At 10 P.M., 24 hours after the grounding, the *Royal Majesty* was finally pulled out. Her double bottom hull saved her. She did not take on any water, did not leak fuel, and fortunately, nobody was hurt. After a thorough inspection she was permitted to travel to Boston Harbor to disembark the passengers and undergo a more thorough examination and Coast Guard inquiry. Several days later she left for a shipyard in Baltimore, Maryland, where she was dry-docked and repaired. Total structural damage was estimated at \$2 million. On June 24, the vessel was declared safe and resumed regular passenger service.

But something else was definitely *not* safe—and it was not just the failure of the GPS antenna, the internal checks inside the autopilot and radar map, or the

so-called navigation error and glaring “human error” that were immediately broadcast on every media channel. The real problem, of course, lay in the interaction between humans, on the one hand, and automated control and navigation systems on the other.

The fact that three officers and the captain did not notice the small **DR** and **SOL** symbols on the GPS display may suggest a breakdown in bridge-keeping practices and poor interface design on behalf of the GPS manufacturer. The symbols were very small (about 1/8 of an inch), inconspicuous, and somewhat misleading (**SOL**). Furthermore, the GPS alarm was not connected to the general alarm system in the bridge, so that when the cable broke and the alarm sounded, only someone who was standing by the unit would hear the one-second beep, which was barely audible to begin with for such a critical failure. Finally, as mentioned earlier, the interface between the GPS unit and the autopilot and radar map was incorrect.

It is also clear that the crew of the *Royal Majesty* over-relied on her automated system. They conducted no cross-checking of navigational data by means of other independent sources such as the LORAN-C navigation, celestial, radar, or compass bearings, to corroborate the GPS fixes. The depth meter data was not used and the depth alarm was set to 0. The second officer was so sure of his track position that he ignored any clue that suggested otherwise. Furthermore, the captain and bridge officers, like most of us, did not fully understand the internal workings of the automated systems under their command; nor did they fully understand how the GPS and autopilot reacted under deteriorating conditions. But how could they? There was no training, whatsoever, provided to the officers about the working of the GPS, autopilot, and radar map.

Mariners have always learned seamanship the old way, the hard way, and for a long time the only way—in the school of hard knocks and on-the-job training. But this ancient tradition no longer holds when it comes to automated systems such as the highly automated bridge of the *Royal Majesty*. The GPS, autopilot, and radar map are complex systems that exchange information, conduct internal checks, employ default modes and settings, and display considerable amounts of information. Understanding how these automated machines behave is a requisite nowadays for knowing “the way of a ship in the midst of the sea.”

Vicente in his book *The Human Factor: Revolutionizing the Way People Live with Technology* (Knopf Canada, 2003; see the auto-clock story in chapter 7).

Chapter 8

Sailors are a superstitious lot, and so are executives of cruise lines. The reputation of a grounded ship does not sail very far. And hence the good ship *Royal Majesty*, once the jewel of the fleet, was eventually sold to Norwegian Cruise Lines, where she began sailing under the name *Norwegian Majesty*. In 1999 she voyaged to Bremerhaven, Germany, where she was hauled up and sliced in the middle. A 112-foot midsection was inserted, giving her an overall length of 680 feet and erasing all physical signs of her embarrassing grounding.

In August of 2001, the Asia Rip (AR) buoy (which was confused by the crew of the *Royal Majesty* with the entrance buoy to the Boston traffic lanes), was “decommissioned” and removed from location. The long and heavy chain that connected her to the wreck below was cut, and the buoy was towed back to shore. Notices to Mariners, issued by the U.S. Coast Guard and dated August 28, 2001, instructs mariners and navigators to cross out Asia Rip from all charts and piloting books.

The factual account for this chapter came primarily from a 1997 National Transportation Safety Board (NTSB) report about the accident and a variety of maritime publications. (The full report, titled *The Grounding of the Panamanian Passenger Ship Royal Majesty on Rose and Crown Shoal near Nantucket, Massachusetts on June 10, 1995*, can be obtained from the NTSB or downloaded from their web site.) The sequence of events and interactions between the bridge officers and the captain is based on the crews’ testimonies following the accident. The description of the routine sea duties and some of the non-technical aspects of this story come from my own experiences as a bridge officer on naval and commercial vessels.

The Global Positioning System is a constellation of 24 satellites orbiting the Earth. The GPS unit obtains its distance from at least three satellites, and then triangulates its exact position on the Earth. Nevertheless, a three-satellite fix can only work if the GPS unit is synchronized with the atomic clocks onboard the satellites. Since it is impractical to install an atomic clock in every GPS unit (it would drive the cost of every unit to above \$50,000), the designers of the GPS used an ingenious idea to correct for any timing errors between the (regular) clock in the GPS unit and the atomic clocks of the satellites: the distance to a fourth satellite is sought and a little trick of geometry (and algebra) is used to calculate the fix as well as to synchronize the GPS’s internal clock with the atomic clocks in the satellites. The implication is that every GPS unit (yes, even your \$100 hand-held unit) is also an atomic-accuracy clock. As mentioned earlier in the notes of chapter 4, one of the reasons for making the GPS system, which was developed and maintained by the U.S. military, accessible to commercial operators, was the navigation error that led to the downing of KAL 007. There are many similarities between the two accidents, which suggest that these navigational snafus are not only about the accuracy of the data, but also about user interaction with automated devices.

Chapter 9

Walk-in interfaces are pervasive and widespread. They are encountered on a daily basis by all of us wherever we turn, and not just by avid Internet surfers. We all use the telephone to call our bank, our doctor’s office, the nearby box-office, or our insurance agent. We no longer