PAN

Ninety years ago, the United States built the Panama Canal by combining innovative engineering strategies with state-of-the-art technology. Now the time has come to create a modern navigation system for the canal, and this time the Volpe Center is providing the know-how.

AMA CANAL

A New Course for the Canal

The lesson of the Panama Canal is a cornerstone of grammar school geography, where students learn the significance of the canal by tracing on a globe the alternate route, all the way around South America, past treacherous Cape Horn, and north again—thousands of miles each way, saved by a 45 mile canal that crosses a tiny spit of land. This lesson is borne out by the 13,000 oceangoing vessels that cross the Panamanian isthmus every year. Even in our "information age," livelihoods around the globe depend on the intercontinental movement of real goods like sugar, steel, oil, and ores. Fortunes rest on the time it takes for wheat to get from Baton Rouge to Vladivostok, or automobiles from Tokyo to Boston, or kiwi fruit from New Zealand to London.

While the Panama Canal provides significant time savings, passage through this narrow waterway presents a host of challenges, especially for the "Panamax" ships, which, at 970 feet long and 105 feet wide, are the largest vessels that can pass through the canal. These oceangoing behemoths are designed for sailing thousands of miles over the open ocean, not for negotiating a shallow channel, maneuvering around oncoming vessels, or squeezing into a lock with only a few feet of leeway on either side. Canal navigation is such a complex affair that every vessel transiting the waterway (even a U.S. nuclear submarine) is directed by a canal pilot who boards the ship soon after it enters canal waters, and who is responsible for the vessel's movements until the far ocean is reached. Like river pilots on the Mississippi, these canal pilots have an intimate knowledge of the canal and its changing restrictions as water levels fluctuate and dredges operate within the channel. As pilots direct ships past landslides, around corners, and over submerged rocks, they navigate by a system of buoys and land-based range markers, originally constructed before World War II.

Dreams of a Passageway

THERE IS NO HUMAINE POWER ABLE TO BEAT AND BREAK DOWN THESE STRONG AND IMPENETRABLE MOUNTAINS....THOSE WHO SEEK TO BUILD A CANAL SHOULD FEAR PUNISHMENT FROM HEAVEN, IN SEEKING TO CORRECT THE WORKES, WHICH THE CREATOR BY HIS GREAT PROVIDENCE HATH ORDAINED.

Jesuit scholar Josephus Acostus, 1625

Ever since Balboa crossed the Central American isthmus and named the Pacific Ocean in 1513, the world's seafaring countries have dreamed of a passage that would broach the thin isthmus that separates the two great oceans. Engineers soon began to explore the challenge. Where to build such a canal? How shall it be excavated? What shall be done with the rock? They returned to these questions again and again over the next 250 years, developing plans that relied on the power of new technologies such as the steam shovel. During the 1880s, following completion of the 105-mile Suez Canal, French entrepreneur Ferdinand DeLesseps poured billions of francs and 25,000 lives into an unsuccessful attempt to build a sea-level canal through Panama. The French effort was thwarted by plagues, unreliable machinery, and almost a billion cubic yards of rock that stood in the way.

The American construction effort, which began shortly after the turn of the century, used the most modern technology in unique and innovative ways to make construction of the canal possible. The first order of business was to eliminate the malaria, yellow fever, and typhoid that made the isthmus unsuitable for human habitation. Unlike his French predecessors, Army Doctor William Gorgas knew that the troublesome diseases were transmitted by mosquitoes. Using techniques he had developed in Cuba after the Spanish-American War, he ordered houses fumigated and screened, swamps and marshes drained, sewers installed, and streets paved.

While mosquito hunters roamed the isthmus, U.S. engineers worked to develop a feasible canal design. The French plan for a sea-level canal was fraught with problems, the most significant of which was the one billion cubic yards of excavation required to reach sea-level at the Continental Divide. The French route also included fourteen crossings of the Chagres River. During storms, this muddy channel swelled to a raging torrent, drowning excavation sites and destroying machinery. The U.S. design overcame both the flooding and excavation problems. During construction, a temporary earthen dike across the upstream section of the Chagres River controlled flood flows into the work area. A larger, permanent dam at the mouth of the Chagres produced Gatun Lake, with a surface elevation of approximately 85 feet; using this impounded water, enormous locks lift vessels up to the level of the lake. This design, which significantly reduced the amount of excavation required along the entire length of the canal, is uniquely suited to Panama, which receives 180 inches of rainfall annually, enough to keep Gatun Lake filled as water flows out through the locks.

Chief Engineer John Stevens, a veteran of railroad construction in the Rocky Mountains, recognized that the challenge of the canal was simultaneously one of excavation and transportation. Rock had to be moved from the mountains, where it blocked the canal, to the river delta, where it formed the core of the new Gatun Dam. The mainstay of the construction effort was the 95-ton, track-mounted, Bucyrus steam shovel. Six million pounds of dynamite per year blasted the hundreds of feet of basalt that blocked the route. At the peak of the construction effort, 25,000 men removed a million cubic yards of material every day. This massive excavation capability was balanced with dumping capacity, using a complex rail system of one-sided flatcars that hauled away 200 trainloads of excavated material daily. As the digging progressed, enormous track shifters moved the rail lines to the main areas of excavation.

For nearly ten years, the focus of the excavation effort was Gaillard Cut, where the canal passes through nine miles of craggy hills. Slopes in the cut are very unstable, and work was hampered by constant slides that buried machinery, increased the volume of excavation, and extended construction by almost two years. These slides and the limitations they impose on the width of the channel are major constraints of the Canal. While the width of the original 300-foot channel has been doubled, the cut remains too narrow for large ships to pass one another.

Since its completion in 1914, the canal has stood as a monument to human ingenuity and perseverance. Although the need for the canal was obvious 400 years before, the task eluded the grasp of the world's finest engineers until the technology existed. It was completed as a result of the confluence of ideas and technology, after yellow fever had been conquered in Havana, after the transcontinental railroad boom had provided the heavy machinery requisite for the work, and after U.S. engineers had devised a canal with locks.

Based on cues from these targets, a pilot aligns the ship within the channel and recognizes when the ship must change course to embark on a new section of channel, or reach. Unfortunately, when rain or fog obscures these visual navigation aids, a pilot may be unable to determine if the ship is within its channel, drifting perilously close to the bank, or floundering in the path of an oncoming vessel.

The canal's navigation difficulties are closely tied to the impediments that hindered its creation. During construction, the area's fractured geology caused recurring landslides that severely hampered excavation; today, unstable slopes hinder efforts to widen the channel, and massive dredges and cranes with names like *Titan* and *Hercules* are constantly at work, clearing the channel of rocks and mud forced upwards by the pressure of the water. Torrential tropical rainstorms previously flooded the Chagres River, sweeping away construction equipment and laborers; now the river is tamed by two dams, but daily downpours can render radar receivers 'blind' when pilots most need the information they provide. The fog that develops almost every evening was once thought to be the precursor of malarial fever and sickness; now sailors know that malaria is transmitted by mosquitoes, and that the real danger of the fog is the speed with which it descends into the canal, and the thoroughness with which it obscures visible navigation aids.

Soon all canal pilots will have a new tool in their efforts to safely guide vessels through this difficult canal: a Communications, Traffic Management, and Navigation system designed by the Volpe Center. This new CTAN system, developed for the Panama Canal Commission by Volpe Center staff in the Center for Navigation, makes the canal safer and more efficient by using satellite data to create a real-time display that shows the location of every vessel in the canal. This space-age, bird's-eye view gives canal pilots and traffic control staff an entirely new perspective from which to view the complex choreography of 50,000-ton vessels slipping into narrow locks and scooting past one another around tight corners, even if the view from the bridge is obscured by fog or rain.

Keeping a Canal Up-to-Date

Since its inauguration on August 15, 1914, the canal has seen the transit of over 700,000 vessels. The canal is operated by the Panama Canal Commission (PCC), a binational entity organized after approval of the Panama Canal Treaties in 1979. Those treaties called for the disestablishment of both the U.S.-run Panama Canal Company and the 10-mile wide canal Zone, which has been under U.S. jurisdiction since 1908; the treaties also called for the final transfer of canal ownership and administration to Panama on December 31 of this year.

Recognizing the canal's role as a key link in the world's economy, the Panama Canal Commission continuously seeks ways to make the canal more efficient and safer. As the volume of ship traffic approaches the capacity of the canal, more efficient scheduling and traffic control are key elements of the proposed improvements. Currently, most vessels pass through the canal with a twenty-minute headway between one boat and another. Even slight complications can be compounded to cause significant delays; the master schedule for canal traffic is redrawn numerous times over the course of a day. Canal authorities installed closed-circuit television cameras at strategic vistas along the canal to monitor traffic, but these cameras are limited in their usefulness, are not helpful to canal pilots on board ships, and can only provide a view of one section of the canal at a time.

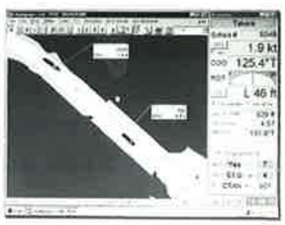
How the Locks Work

Key features of the canal are the monumental locks at both ends. In order to accommodate two-way traffic, each lock has two lanes. Each individual chamber is 1000-feet long and 110-feet wide, large enough to hold the *Titanic*, had it ever reached the isthmus. Vessels must pass through three such chambers in order to reach the elevation of the lake. The locks work like giant water elevators, raising or lowering ships

approximately 28 feet at a time by allowing water to flow into the chamber from the lake or allowing water in the lock to flow out to the ocean. All water moves by gravity; no pumps are used. The huge gates at either end of the chambers are 65-feet wide, 7-feet thick, and between 50 and 80-feet high. They weigh 700 tons but can be swung with just a 40 horsepower motor because they become buoyant when the locks are filled with water.

With the click of a mouse, the pilot can change magnification an

In 1995, the Panama Canal Commission contracted the Volpe Center for Navigation, a known leader in radio navigation systems, to develop a system that would track the location of transiting boats and Canal Commission "floating resources" such as tugboats and dredges. The Volpe Center was the logical choice to develop such a system. The Center for Navigation had already proven its ability with a similar navigation system it developed for the St. Lawrence Seaway Development Corporation. That system was based around a half-dozen portable units that used the Global Positioning System, or GPS, to determine their location. The portable units then transmitted that information to the shore-based control center responsible for scheduling ships waiting to pass through the locks.



Two southbound vessels entering Pedro Miguel locks.

While the Center for Navigation's experience in the St. Lawrence Seaway was important, the requirements for the Panama system presented many new challenges. To begin with, the scale of the project was considerably larger – the Canal Commission requested 120 mobile units. In order to keep costs down and ensure on-time delivery, the Center was committed to building the system from components that could be purchased "off-the-shelf," rather than developing custom-built components. The new system was also to incorporate a key feature that could correct variations in the GPS signal to produce even more accurate location data. This feature, known as Differential GPS (DGPS), had never been applied to vessel navigation systems on such a large scale.

Gatun Locks: Atlantic entrance and exit to canal. There are three chambers in this lock system.

In order to develop the system, Dr. James Carroll, the project engineer, drew on a variety of strengths within the Center for Navigation. Programming specialists Giau Nim and Mac Craven developed the unique communications software that underlies the system. Engineers Jon Pietrak and Ted Papadopoulos built the mobile units, while others focused on the hardware of the radio relay stations and other ground-based components of the system. While each team member had a specialty, each participated in almost every aspect of the system. This spirit of collaboration extended beyond the Volpe Center to include the staff of the Canal Commission. Kam Chin, Pete Kennett, and Henry Wychorski, who set up the DGPS station and the radio network that relays information to the mobile units, consulted with Canal Commission engineers to get their advice and ensure that the new system would be compatible with existing radio hardware. While developing the user interface, Dave Phinney and Kam Chin worked extensively with canal pilots to ensure that the units displayed the most important information in a format that was easy to use. In some cases, this collaboration prompted the development of new features that were not envisioned when the system was first planned.

While participation in the project occasionally gave Volpe Center staff a chance to escape from wintry Massachusetts to sunny Panama, the field work involved many hurdles that do not occur on projects in, say, Iowa. The humidity in Panama can be so overwhelming that, even in air-conditioned offices, metal paper clips leave rust marks on papers in a matter of hours. Field work scheduling had to allow for the interminable customs delays that slow the delivery of material to Panama.

This CTAN system, developed for the Panama Canal Comission by members of the Volpe Center's Center for Navigation, uses satellite data to create a real-time display that shows the location of every vessel in the canal.

The result of all this effort is a coordinated system of 120 mobile units that communicate with a control center via a shore-based communications network. The mobile units consist of a GPS receiver and antenna, a laptop computer, and another radio antenna for communications with the control center. Roughly half of the mobile units are permanently installed on floating resources such as tugboats and dredges. The remaining units are carried by canal pilots onto transiting vessels.

The Global Positioning System is a worldwide navigational aid based on a constellation of 24 orbiting satellites. GPS units receive transmissions from these satellites and calculate their own location based on the geometry of the received signals. Since each satellite provides one measurement from which the receiver's position can be triangulated, transmissions from more satellites provide more accurate locations. GPS units in Panama can receive up to ten satellite signals, resulting in robust geometry and extremely accurate location data. Due to national security concerns, the transmissions from all GPS satellites include a fluctuating inaccuracy that varies with time but is consistent within a broad geographic area. To overcome this inaccuracy, the CTAN GPS units receive correction signals from a GPS unit permanently installed at a fixed, surveyed location on the shore. This reference station, whose transmitter was provided by the U.S. Coast Guard, constantly measures the variation of the GPS signal and transmits this information to the mobile unit so it can combine this differential with the signal it receives. Using this correction, the CTAN GPS units can determine their location to within one meter (three feet) and can provide remarkably accurate speed measurements. This type of GPS system, where a fixed unit transmits corrections to one or more mobile units, is known as Differential GPS.

Once the mobile GPS unit has determined its location, it transmits this information to the shore-based control center via a 9600-baud transmitter operating near 500MHz. Six Ultra High Frequency (UHF) radio data link stations provide complete coverage of the canal, even within the deepest parts of the Gaillard Cut. The control center receives this data, compiles it with data from all the other mobile units and retransmits the entire picture back to the mobile unit via the same UHF data links. This way, each unit will transmit its own location and receive the locations of all other ships in the canal. The full information is updated every few seconds.

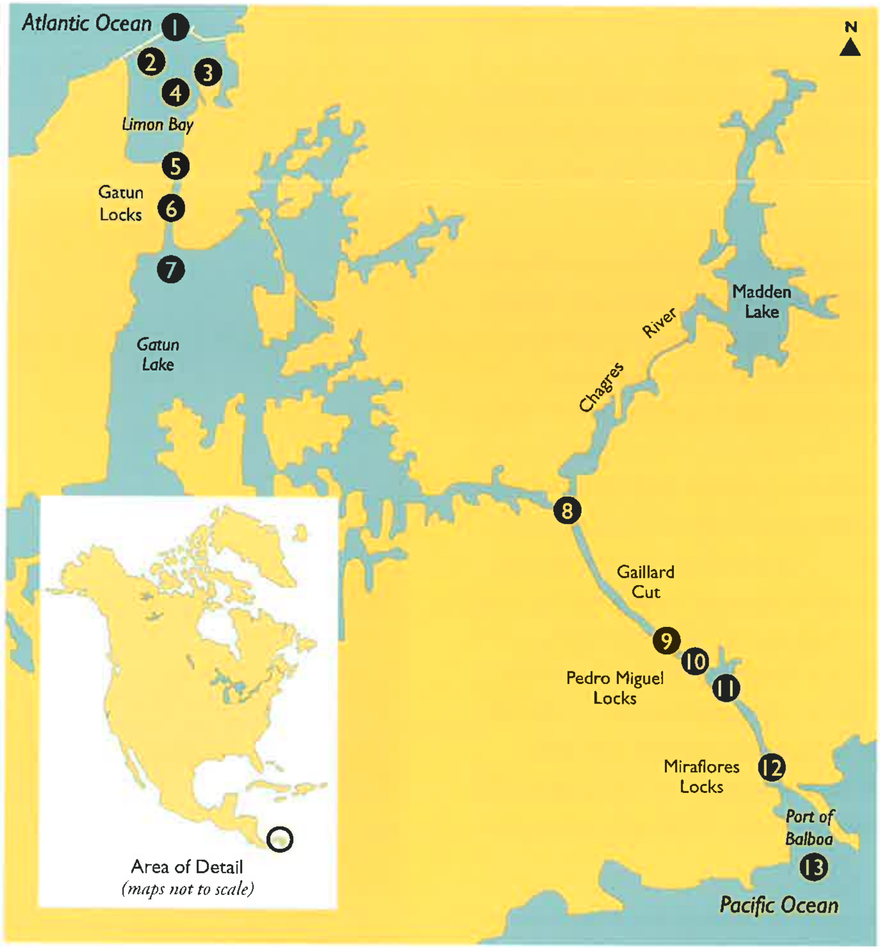
Top photo: A northbound container vessel exits the Gaillard Cut into Gatun Lake; in the background, the Trans-Isthmian Railroad crosses the Chagres River.

Lower photo: The Marine Traffic Control Center, where an array of monitors displays the status of every vessel in the canal.

The system display is compatible with a regular Microsoft Windows environment. During the design phase of the project, Volpe Center staff worked closely with canal pilots in order to ensure that the pilots could efficiently access the information most important to them. With the click of a mouse, a pilot can change magnification or access the name, size, tonnage, country, heading, and speed of any other ship in the canal. The system also incorporates data from the harbor radar, so boats that have not yet been boarded by canal pilots will be visible on the display.

The extensive collaboration between canal pilots and Volpe staff led to a very effective new feature. Volpe staff expanded the computer program to calculate the location where two vessels in the same section of canal will pass each other, and programmed the display

TIMELINE of a TRANSIT



1 5:00 pm: A vessel notifies the Port Captain's Office that it is entering canal waters in Limon Bay on the Caribbean. Scheduling is a difficult procedure that must address the number of boats, their type and size, their cargo, the location and availability of canal resources such as tugboats, and the availability of canal pilots.

2 7:30 pm: Canal Commission boarding officers come on board the ship to inspect the vessel's papers. If the ship has not transited the canal before, PCC personnel perform a process called *admeasurement*, during which they collect detailed measurements of the ship's length, width, draft, and shape.

3 8:30 pm: The Port Captain's office calculates the toll charges, which are based on a unit called the Panama Canal Universal Measurement System (UMS) Net Ton. Panamax-size vessels routinely pay from $80,000 to $100,000 in tolls; the highest tolls are levied on the Queen Elizabeth II, which requires special treatment and must pay approximately $150,000 for each transit.

4 5:30 am: A canal pilot boards the ship and sets up the mobile GPS unit. Panamax vessels are commonly boarded by up to three pilots.

5 6:10 am: The ship begins to enter Gatun Locks. As the bow of the ship approaches the locks, line handlers tie lines from the bow of the boat to 170-horsepower locomotives on both sides of the lock. These locomotives operate on a track and cog railway and apply gentle tension to the bowlines in order to keep the boat properly positioned within the lock. Another pair of locomotives are tied to the sternlines when the rear of the boat comes near the lock.

6 6:30 am: The ship is completely within the locks. Lock gates are operated by the original electromechanical control system designed in 1915; the mechanical aspects of this control system render it nearly fool-proof. For example, controls prevent the lock gates from opening until the water level on either side has equalized. Approximately 26 million gallons of water flow though the locks to raise or lower a ship the full 85 feet to or from the level of the lake.

7 7:30 am: The ship is released from the third lock, into Gatun Lake. In 1915, this was the largest manmade lake in the world. Lake levels are maintained partially by releases from Madden Lake, upstream of the canal on the Chagres River. The route through Gatun Lake is marked by buoys on either side of the channel.

8 11:20 am: The vessel enters the Gaillard Cut, the narrowest and shallowest section of canal outside the locks. The Cut is approximately 8.5 miles long and crosses the continental divide. The speed limit for large vessels within the cut is 6 knots. With as little as 150 feet between the vessel and the near shore, the thrust of the ship's propellors can create countercurrents or "bank suction" that can pull the stern towards shore; a gentle push from a tugboat is usually enough to correct this drift.

9 1:00 pm: The vessel approaches Pedro Miguel Locks. The steep bank on the right hand side of the cut prevents pilots from seeing the locks until the vessel is nearly upon them.

10 2:30 pm: The vessel enters Pedro Miguel Locks, where one chamber lowers the ship approximately 30 feet.

11 3:10 pm: The vessel exits Pedro Miguel Locks into Miraflores Lake.

12 3:30 pm: The vessel enters Miraflores Locks and will be lowered 55 feet by two chambers.

13 4:10 pm: The ship exits Miraflores Locks and enters the Port of Balboa. It continues approximately 7.5 miles, underneath the Bridge of the Americas, which carries the Trans-American Highway, the only fixed road over the canal. Once the vessel passes the last set of buoys at the end of the causeway, it is out of canal waters; after pausing to discharge the canal pilot, the vessel continues on its way to San Francisco, Tokyo, Hong Kong, Sidney, Bombay, or any number of cities made thousands of miles closer by this 45-mile canal.

to highlight this location and indicate the estimated time to that meeting. Using this information, pilots can modify their speed in measured ways, so as to adjust the intercept point to a safe location (e.g., not at a bend). The canal pilots have already made it known how useful this feature is. This type of collaboration was vital to ensuring the buy-in of the pilots. Their job is so complex that they must have complete confidence in the tools they use. If, without that input, Volpe staff had tried to "go ahead and design it, and to tell them what they want," says Jim Carroll of the Volpe Center, "they probably would have taken the unit and thrown it into the water with the case open." By working together, they developed a tool that exceeds expectations.

In August of last year, the new system proved its worth by preventing a potentially serious accident. A 740-foot long bulk carrier in Gatun Lake, transiting north from the Pacific to the Atlantic, was making a transition from Bohio reach to Buena Vista reach during a heavy rainstorm. When the rudder was straightened, the ship continued to turn, and eventually stopped crosswise in the channel. Meanwhile, a 600-foot car carrier was traveling in the opposite direction in Buena Vista reach. Although his radar was 'blind' due to the heavy rain, the pilot of the car carrier looked at the CTAN screen in time to see that the bulk carrier was directly in front of his vessel and across its path. The car carrier's pilot directed his ship to stop on the west side of the channel so the bulk carrier could get straightened out. Both pilots stated that without the aid of the CTAN unit, they would not have had the information necessary to prevent a collision between the two vessels, and a Commission employee noted that, based on the approach angle, "the results would not have been pretty."

While the CTAN system has already demonstrated its usefulness, it also incorporates one key feature that will prove even more useful in the future: flexibility. Volpe staff designed the system to be amenable to enhancements. Already, a new DGPS reference station is under construction on the Atlantic side of the canal. This new station, eight times more powerful than the existing prototype station, will provide a stronger signal and continued accurate location data. In addition, the mobile unit may someday include a second GPS receiver antenna. By integrating the corrected GPS signal from two antennae, the expanded system will be able to calculate with great accuracy the heading and rate of turn of the vessel. This detailed navigation information will prove invaluable in low visibility conditions, during precision operations, and when ships are entering the locks or passing one another.

Because this adaptability is such an integral part of the new CTAN system, it is a tool that will be useful to canal pilots for years into the future. Even if the Gaillard Cut is again widened, and even if a third, larger set of locks is constructed, one thing is sure: the Panama Canal will continue to present challenges. It baffled engineering minds for centuries, ruined one of the world's foremost entrepreneurs, and killed thousands of laborers. Its construction demanded the attention of the United States for almost ten years; eighty years later, it continues to give heartburn to seasoned canal pilots. Since the sixteenth century, great minds have turned their attention to the canal; when the time is right, as it was in 1908, the confluence of innovation and technology can yield remarkable results. Now, the Volpe staff members who worked on this project have added their names to the list of great engineers, technicians, and laborers who have tackled this endless parade of challenges. As they combined their own ideas with the available technology, they developed a tool that reinvents the experience of navigating a vessel through the canal. Like all the workers who planned the canal, drove the steam shovels, poured the concrete, designed the lock gates, and dredged the channel, they have made a new Panama Canal.

Top: The Bridge of the Americas, located near the Port of Balboa, carries the TransAmerican Highway, the only fixed road over the canal.

Left to right: Volpe team members, Peter Kennett, Dr. James V. Carroll, Henry Wychorski, Jr., Theofilos Papadopoulos, Giau Nim

Photographs courtesy of the Panama Canal Commission