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The Lady Be Good: A Case Study in Radio Frequency Direction Finders, with Supplemental Material for On-Line Appendix

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The *Lady Be Good*: A Case Study in Radio Frequency Direction Finders

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Over the past several years, we have contributed articles to *TPT* that focus on a forensics-style reexamination of significant historical events.[1-6] The purpose of these articles is to afford students the opportunity to apply basic principles of physics to unsolved mysteries and potentially settle the historical debate. We assembled the lessons learned and best practices of our activities into a formalized pedagogy for teaching topics in physics, engineering, problem solving, critical thinking, and ethics.[7]

Adding to our repertoire of case studies, we now present the tragic story of the *Lady Be Good,* a World War II B-24 bomber that mysteriously disappeared in 1943. The case presents several teaching opportunities for instructors of introductory-level courses in physics and engineering. The goal of this article is to showcase classroom and laboratory exercises that we piloted with a cohort of undergraduate students enrolled in an interdisciplinary science course. Using our case study approach, students built radio frequency direction finders and used them to navigate from various locations on campus to a "home base."

The mysterious disappearance of the *Lady Be Good*

On April 4, 1943, the B-24 Liberator *Lady Be Good* (*LBG*) took off from Soluch Air Base, located south of Benghazi, Libya. The nine-man crew was under the command of First Lieutenant William J. Hatton, pilot, and embarking on its first combat mission that called for the *LBG*, along with 24 other planes, to bomb the harbors of Naples, Italy, in a two-wave high-altitude attack. After dropping their bombs, the crews were expected to fly their B-24s southeast for a preset amount of time. Based on anticipated wind conditions and agreed-upon flight speeds and altitudes, the planes would arrive northwest of the air base. Here, navigators would locate a radio frequency bearing, originating from Benina Tower 30 miles north of Soluch, to guide the planes home.

Problems plagued the mission from the very beginning, most of them involving weather conditions. Stronger than anticipated headwinds caused the *LBG* to veer east of its intended route and arrive at its target at 7:50 p.m., much later than planned. Unable to see the targets at Naples, the crew dumped its bombs in the Mediterranean to save fuel and headed back to Soluch. Hatton turned the plane along the preplanned southeasterly heading and, because the plane's automatic direction finder (ADF) malfunctioned, relied on his rookie navigator to hone in on the RF beacon to guide the crew home. At 12:12 a.m., Hatton was lost. He radioed Benina and asked for an inbound emergency bearing. The station reported: "Bearing is three-three-zero."[8] Hatton acknowledged the message and signed out.

This would be the last communication received from Hatton—the massive bomber vanished without a trace! The next morning, rescuers conducted an all-out search. Investigators theorized that a German night fighter had picked up Hatton's call for a bearing, honed in on the *LBG*, and shot it down somewhere in the Mediterranean Sea. However, no life rafts nor any other evidence of a water crash were found. The search was abandoned and next of kin notified. On April 5, 1944, a board of officers declared the crew "missing in action and presumed dead." Additional information on the crew and mission can be found in our supplemental online appendix.[9] The fate of the *Lady Be Good* would remain a mystery for almost 16 years.

Radio frequency direction finders

Today, localizing AM and FM sources is a popular sport (called "fox hunting") for amateur radio operators and clubs. During a fox hunt, participants search for the location of a "fox," a handheld RF transmitter or other transmission source, such as a weather station. The sport also provides powerful teaching opportunities for courses in introductory physics. In the classroom, the theory of operation behind radio frequency directional finders (RDFs) is a great way to teach a wide variety of concepts: signal phase, circuit design, spherical trigonometry, latitude/longitude, bearing, the great-circle distance between two points, equirectangular projection, and the distinction between "parallel" and "antiparallel." In the laboratory, building an RDF is a fantastic exercise that allows students to gain hands-on experience with antennas, receivers, and circuit construction. Such a laboratory activity is ideal for an introductory electrical engineering module or soldering exercise in an introductory circuits class.

One popular type of RDF works on the principle of "time difference of arrival" whereby two antennas are alternately connected to the input of a radio receiver. Switching between the two antennas, *at an audio frequency,* allows the user to *hear* any phase errors in the incoming signal. In other words, if one antenna is slightly closer to the transmission source than the other, it receives the wavefront slightly earlier in time than the other. Thus, the RF signal will have a different phase at each antenna. Since the RDF is switching between the two antennas, the switching action imposes phase modulation on the incoming signal. This phase modulation is detected by the receiver and is heard as an audio tone equal to the switching frequency. However, by rotating the RDF's antennas so they are the same distance from the transmission source (i.e., if the plane of the two antennas is perpendicular, or "broadside," to the direction of the signal), the antennas detect the same RF phase, so the audio tone disappears (see Fig. 1). Thus, students can use an RDF to locate the direction of a signal by first tuning the radio receiver to the frequency of the source, then

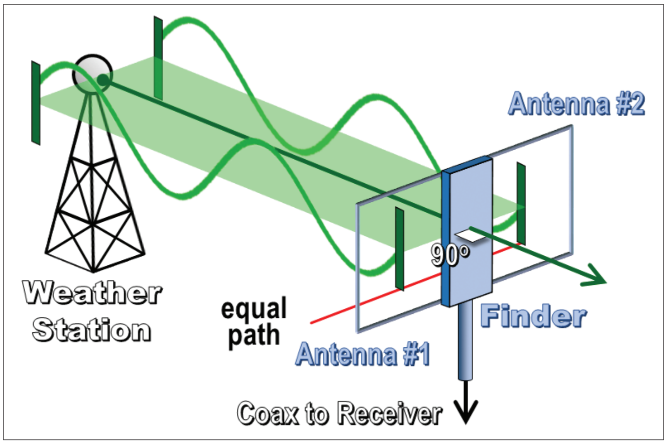

Fig. 1. The theory of operation of an RDF. Both antennas are the same distance from the transmission source; therefore, the signal has the same phase at each antenna. No tone is heard, indicating that the source is on a line perpendicular to the plane of the two antennas.

Fig. 2. An RDF in action. A student uses the "HANDI-Finder®" to pinpoint the direction of a weather station. These finders work best in wide open, flat spaces.

rotating the RDF's antennas until the audio tone disappears —at that instant, the antennas must be perpendicular to the transmitter.

The advantages offered by this type of direction finder are detailed in our supplemental online appendix.[9-11] However, despite their advantages, these finders offer a significant disadvantage in pinpointing the direction of an RF source—they exhibit what is known as a "**180° ambiguity**." In general, bearing lines are inherently ambiguous because an infinite line can indicate two possible directions, 180° apart. Since students hear a null tone when both antennas are oriented 90° with respect to the transmission source, the tone will disappear when the two antennas are parallel or antiparallel to the line of transmission. Thus, students cannot determine if they are pointing toward, or away from, a transmitter! The addition of a "sense" antenna would eliminate the 180° ambiguity, but is intentionally left out of our activity.

Our laboratory activity

We piloted our activity on a cohort of undergraduate students enrolled in an interdisciplinary science course. We divided our activity into three phases labeled: "The Mystery of the *Lady Be Good*," "Constructing Your RDF," and "Navigating Home." The first phase was intended as an anticipatory set to pique students' interests. We presented students with the background information on the disappearance of the *Lady Be Good* that was described at the beginning of this article. We then discussed the theory of operation of an RDF, **but did not discuss the "180° ambiguity" inherent to its design**! In the second phase, teams of students built RDFs over the timespan of two 2-hour laboratory periods (units can also be purchased partially or fully assembled). Most teams required additional time outside of class to complete their RDFs. A number of handheld RDFs are available for purchase as kits. We purchased RALTEC® Electronics' HANDI-Finder® (available for $33.95) since the manufacturer was local and because of the company's excellent reputation for customer service.[12,13] The HANDI-Finder® works from 400 to 1500 Hz and uses two whip antennas made of coat-hanger wire. The whips are folded into U-shapes with their ends mounted to a mechanical anchor point for rigidity. The ends are not connected to any electronics. This compact design is easier to use than other finders that utilize two fully extended vertical whip antennas, mounted 12 to 24 in apart. The electronic switching of a CD4047B CMOS integrated chip alternately connects each antenna to a coax cable down-lead going to the antenna input of an FM receiver (purchased separately) tuned to the frequency of interest. The unit uses low power, is easy to build, and is inexpensive (see Fig. 2). The advantages and sensitivities of different types of antennas are discussed in the literature.[10-12]

In the final phase, students downloaded a compass app to their cell phones. Any app that determines location as a longitude and latitude (φ , λ), as well as bearing (β), will suffice. Many such apps are available as free downloads.[14] Students then walked to several remote locations, chosen by the instructors to cover the full extent of our campus. Once at their locations, students used their RDFs to pinpoint the direction of a radio signal broadcast by a nearby weather station of the National Oceanic and Atmospheric Administration. The Chesterland, OH, antenna (call letters: KHB-59) is 12 miles from campus and broadcasts at 162.550 MHz (as mentioned before, if a weather station is not nearby, low-power transmitters are available for purchase, but these usually require at least an entry-level FCC license to be operated on air). Students were not told the location, or name, of the weather station so as not to bias their search for the signal. Students were only given the station's broadcasting frequency and told that finding the direction of its signal was a "life or death" determination since the bearing would be used to guide them to "home base." While outdoors, students had no difficulty in hearing the nulling of the audio tone, although they experienced difficulty in determining accurate bearings if tall buildings, large objects, and towers were nearby. Our recommendation is for students to take several measurements at different locations, a few feet apart, before settling on a final location and bearing. Using their compass apps, students then recorded their locations ($\varphi_{student}$, $\lambda_{student}$), as well as their determination of the bearing to the station ($\beta_{student}$). Once all the students returned to the classroom, we collectively compared the bearings measured by students vs. the true bearings. Knowing the coordinates of the weather station ($\varphi_{station}$, $\lambda_{station}$), and those of each student, a "true" bearing (β_{true}) can be calculated. The calculations for a spherical Earth are straightforward:

$$\beta_{true} = \text{atan2}(x, y), \text{ where}$$
$$x = \cos(\varphi_{station}) \cdot \sin(\Delta\lambda),$$
$$y = [\cos(\varphi_{student}) \cdot \sin(\varphi_{station})] - [\sin(\varphi_{student}) \cdot \cos(\varphi_{station}) \cdot \cos(\Delta\lambda)], \text{ and}$$
$$\Delta\lambda = \lambda_{station} - \lambda_{student}.$$

A number of sites provide code allowing the user to quickly input coordinates, determine distances and bearings, and display results directly onto a satellite map.[19]

Table I shows a sampling of five (of 40) data points from our activity. Cells highlighted in red indicate that the student faced the weather station. Cells highlighted in yellow indicate that the student faced away from the station. Figure 3 shows a representation of our results on a campus map and also depicts how the instructors chose to send students to locations that covered the full extent of campus. A representation of our results on a regional map is included in the supplemental online appendix.[9] Encouragingly, results demonstrate that all students were capable of locating the direction of the RF signal to within 15° either side of the true bearing. The take-home message here is that the RDFs work … and work well! As expected, many students (25%) fell victim to the 180° ambiguity inherent to the design of these finders. Initially, we expected ~50% of the students to fall victim to the ambiguity since students presumably have a 50% chance of orienting themselves antiparallel to the line of transmission. This discrepancy can be understood by the layout of our campus. As students exit the science center, they naturally face towards the direction of the weather station. Instructors noticed that this layout biased the students to search forward for the transmission signal.

Interestingly, students who performed a more thorough 360° sweep of the campus were more likely to fall victim to the 180° ambiguity.

Table I. Radio Frequency Direction Finder.

Station: *National Oceanic and Atmospheric Administration – Chesterland, OH*	
$\varphi_{station}$	$\lambda_{station}$
D:M:S	**D:M:S**
41:31:21.91	–81:19:42.69

NO.	**MEASUREMENTS BY STUDENTS**			**TRUE**	**DIFFERENCE**
	$\varphi_{student}$	$\lambda_{student}$	$\beta_{student}$	β_{true}	$\beta_{student} - \beta_{true}$
	D:M:S	**D:M:S**	**DEGREES**	**DEGREES**	**DEGREES**
1	41:29:22.87	–81:31:52.49	260	77.6	182
2	41:29:21.77	–81:31:55.72	75	77.6	–3
3	41:29:23.62	–81:31:54.31	270	77.7	192
4	41:29:26.64	–81:31:50.52	90	78.0	12
5	41:29:25.88	–81:31:47.67	66	78.9	–12

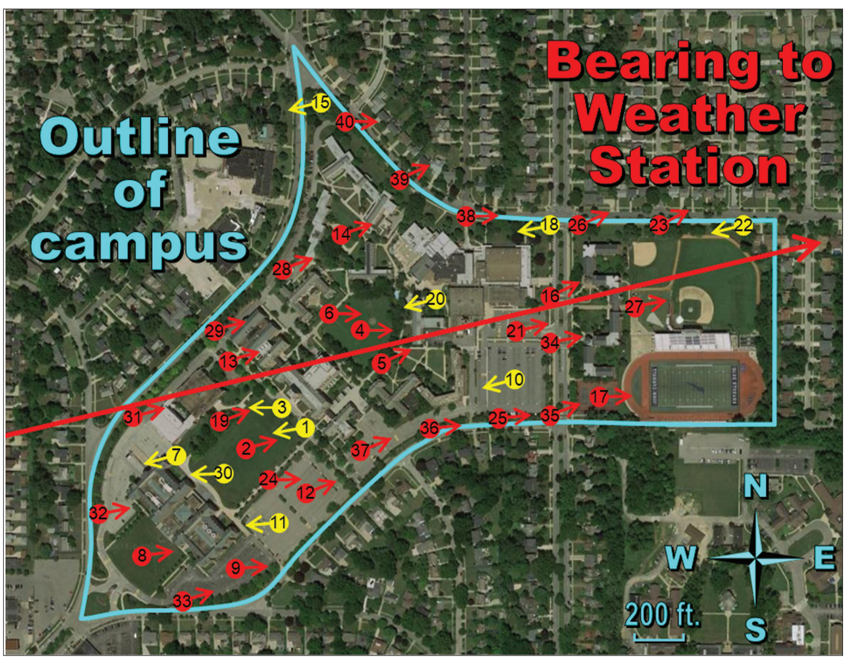

Fig. 3. Campus map. Small arrows indicate the bearing that each student determined. Red arrows face towards the weather station while yellow arrows face away from it.

Mystery solved: The 180° ambiguity

On November 9, 1958, the wreckage of the *Lady Be Good* was located in the Libyan Desert by an oil exploration team. Broken in two, perfectly preserved by the dry desert air, and with no signs of the crew within miles of its crash site, the plane was quickly dubbed "The Ghost Bomber of WWII." Eventually, the remains of eight of the nine crewmen were found 75 to 100 miles northwest of the wreck (see Fig. 4). Somehow, on the return leg of its mission, the crew had missed their home base and flown 440 miles southeast of Soluch, deep into Libya's Kufra district. Low on fuel, the crew parachuted to safety just before the plane crashed into the Calanshio Sand Sea. Diaries recovered from the desert indicate that eight of the nine men survived their jumps (one man's chute failed to open) but were so lost that they initially thought they were bailing out into the Mediterranean Sea. When they landed on the desert floor, they mistakenly thought they were within walking distance of their base, but in reality the plane was in the middle of the Sahara Desert. With only half of a canteen of water and unaware of their location, the survivors agonized in vain for eight days to walk in a northwest direction back to Soluch.[8,20,21] The crew may actually have survived had they instead chosen to walk south to the Oasis of Wadi Zighen. Five of the crew died after walking 75 miles while two crewmen managed to cover an astonishing 100 miles before succumbing to the desert. The remains of the eighth crewman were never found. The diaries of Second Lieutenant Robert Toner,

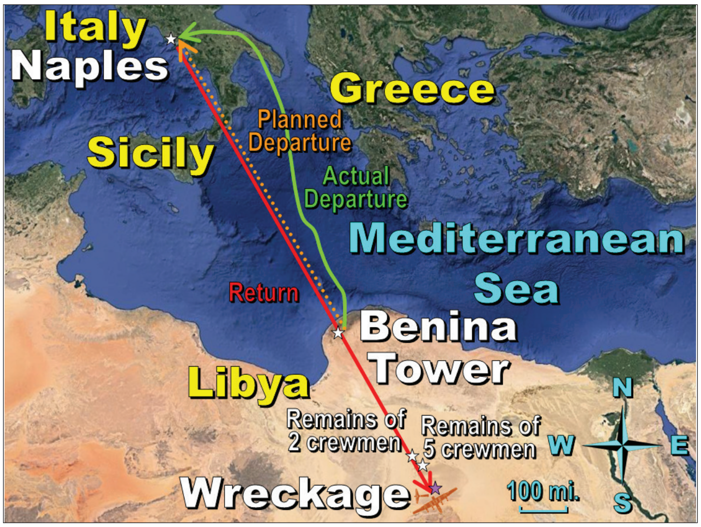

Fig. 4. The actual flight of the *LBG*. Strong headwinds pushed the plane significantly off course during the outbound leg of its journey. After unloading its bombs in the Mediterranean Sea, strong tailwinds pushed the plane past Benina when the crew took a reading off of the back of the tower (called the "reciprocal reading"). Mistakenly thinking they were inbound to Soluch, the plane flew 440 miles into the Libyan Desert. The purple star indicates the location of the remains of Second Lieutenant John S. Woravka, bombardier, who did not survive the bail out. The remains of Staff Sergeant Vernon Moore, waist gunner/radio operator, were never found. Map courtesy of Google Maps.

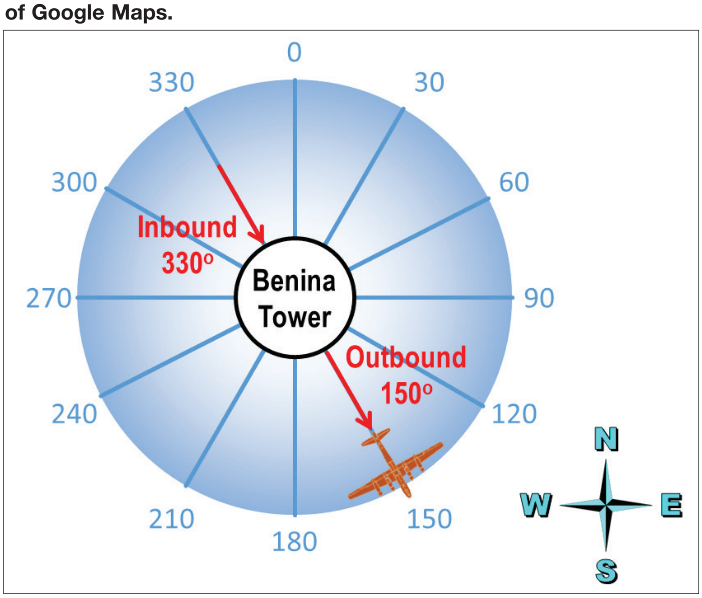

Fig. 5. The 180° ambiguity. When Hatton asked for an *inbound* emergency bearing, the plane had already passed Benina Tower. Thus, the reported bearing of *inbound* 330° was actually *outbound* 150°.

co-pilot, and Technical Sergeant Harold Ripslinger, flight engineer, chronicle the crew's steady decline into mental and physical exhaustion.[22]

The official investigation report cites several contributing factors to the plane's disappearance (see our supplemental appendix[9]). However, the primary cause of the plane's disappearance is listed as the rookie navigator's misinterpretation of the RF directional bearing emitted by Benina Tower. Like our students, the navigator had fallen victim to the 180° ambiguity. As the plane was heading back to Soluch, it had already passed the tower when Hatton radioed for an *inbound* bearing. However, a reading off of the RF front appears identical to a reading off of the RF back (called the "reciprocal reading"). When the navigator detected a bearing of 330°, he assumed the plane was still northwest of Benina Tower and that the plane was *inbound* to Soluch. In reality, the *LBG* was already southeast of Benina and the navigator was reading the reciprocal off of the RF back. Tragically, the navigator's misinterpretation of the reciprocal reading meant that the *LBG*'s *inbound* bearing of 330° *to* the tower was actually an *outbound* bearing of 150° (330°–180° = 150°) away from the tower![23] The navigator became confused and directed the plane deeper and deeper into the desert, albeit along the correct flight path (see Fig. 5). **In short, the navigator made the same mistake that 25% of our students did!**

Student reactions

The HANDI-Finder® used in our activity differs significantly from the rotatable loop antenna used aboard the *LBG*, yet both systems are afflicted by the same inherent ambiguity. The goal of our activity was not in recreating the exact navigational electronics of a WWII B-24 bomber, but in emphasizing to the students that despite the very latest in technological advances and instrumentation, judgments are still a necessary part of scientific endeavors. Our activity is as much a human experiment as it is a technical one. The fate of the *LBG* occurred because seemingly unrelated factors aligned to form a "perfect storm" that led to a catastrophic conclusion. Had any one of these factors been absent or avoided, the plane and its crew would have most likely survived its first combat mission.[24] As mentioned before, we did not tell students about the 180° ambiguity of our RDF's design. Obviously, results would have turned out quite differently if students were aware of the ambiguity because they might have sought additional information to discern the correct bearing (a simple follow-up activity would be for two groups of students to use their bearings to triangulate to the correct location). However, students were surprised to see how easily they fell victim to a somewhat obvious flaw in their RDF's design. Overall, students responded extremely favorably to our activity. The most difficult aspect of the activity was constructing the RDFs. To save time and headaches, we will use partially prebuilt versions in subsequent implementations. However, once the RDFs were built, students enjoyed searching for the direction of the RF signal at different locations on campus. Students were especially intrigued by the historical context of the mysterious disappearance of the *LBG* and to learn how the laboratory activity connected to the plane's final fate. As one student commented in a post-activity survey: "I now see how easy the navigational error was to make. Here we are almost 80 years later making the exact same mistake … and we weren't surrounded by fighter planes, darkness, and unfamiliar surroundings. This gave me a true appreciation for the bravery and heroics of the crew of the *Lady Be Good*."

Acknowledgments

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SUPPLEMENTAL ONLINE APPENDIX

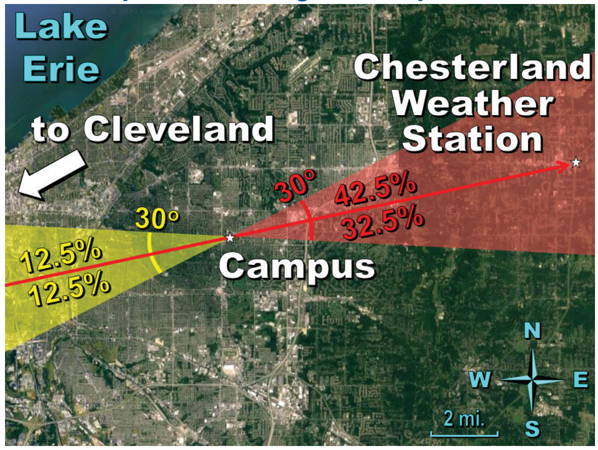
The Lady Be Good

- The *Lady Be Good* was named by the crew who was originally assigned to the plane and who had flown it from the United States to Soluch, not by the crew that flew the plane's first, and last, combat mission.
- The crew who flew the plane's first combat mission consisted of:
  - First Lieutenant William J. Hatton, Pilot
  - Second Lieutenant Robert F. Toner, Co-Pilot
  - Second Lieutenant Dp Hays, Navigator
  - Second Lieutenant John S. Woravka, Bombardier
  - Technical Sergeant Harold S. Ripslinger, Flight Engineer/Gunner
  - Staff Sergeant Robert E. LaMotte, Radio Operator/Gunner
  - Staff Sergeant Samuel E. Adams, Tail Gunner
  - Staff Sergeant Guy E. Shelley Jnr, Waist Gunner/Assistant Engineer
  - Staff Sergeant Vernon L. Moore, Waist Gunner/Assistant Radio Operator
- The new plane had just joined the 376th bomber group on March 25, 1943. The mission of April 4, 1943, was labeled "*Mission 109*." Twelve bombers would form the first wave followed by a second wave of 13. The *LBG* was to be one of the last in formation of the second wave. As the bombers took off, high winds and a sandstorm obscured visibility. Debris from the sandstorm caused several of the bombers in the second wave to quickly abort the mission and return to base. The *LBG* was one of the last B-24s to depart, getting airborne at 2:15 p.m. As one of the last to take off, the *LBG* was far behind the remaining bombers and was unable to join them in formation.
- The *LBG*'s Automatic Direction Finder used a "*loop antenna*" and worked on low frequencies. A loop antenna is one turn, or multiple turns, of a conductor, both ends of which are connected to the receiver antenna inputs. To determine bearing, an operator would turn the loop until a null in the transmission signal was detected, indicating that the loop's axis was aligned with the direction of the signal.

Advantages of the HANDI-Finder®

1. To determine the bearing to a transmission source, students simply rotate the finder and listen for a null in tone, rather than a peak. This null is sharp and much easier to detect than the peak from a directional gain antenna, such as a Yagi.
2. When students null the superimposed audio, they are not nulling the carrier signal. The problem with carrier-null is that as the student tunes closer to the null, the signal he/she is trying to null is getting harder to hear! With this type of direction finder, students can still hear the audio coming from the source as they null the superimposed audio.
3. Since audio is being nulled, students need not watch a dial. Nulling can be done while visually surveying landscape, walking, or taking notes.
4. Since this method uses phase information, it works well with strong signals so no attenuator is required.

Results depicted on a regional map



Regional map. The red arrow indicates the true bearing from our campus to the weather station. Results show that all students were able to pinpoint the correct line of transmission to within 15°. However, 75% of students chose a bearing facing the weather station (as indicated by the red area), while 25% of students fell victim to the "*180°-ambiguity*" and chose a bearing away from the weather station (as indicated by the yellow area).

Contributing factors to the disappearance of the Lady Be Good

Subsequent analysis indicates that the final flight of the *LBG* was plagued by four contributing factors:

1. The crew was inexperienced. Only Hatton had been on a previous mission and that was as a Co-Pilot on an aborted bombing run only two days earlier. At 27 years, Co-Pilot Toner was the oldest man in Hatton's crew.
2. Next, the plane veered significantly off course during the flight from Soluch to Naples because of weather conditions and strong headwinds. The circuitous outbound flight meant that the plane would be returning alone, in the dark, and with a strong accompanying tailwind.
3. The crew jettisoned its 4,500-pounds of bombs over the Mediterranean and Hatton decided to return to base at a higher altitude than planned in an effort to improve his view. The higher altitude, lighter plane, and accompanying tailwind gave the plane a higher ground speed than anticipated. This placed the *LBG* southeast of the Benina Tower, not northwest, when it began searching for the RF signal to guide it home.
4. Finally, the appearances of sand and sea at night are confusingly similar. Thinking they were over the Mediterranean Sea and inbound to North Africa, Pilot and Co-Pilot expected to see, and indeed saw, nothing but darkness below their plane. Low on fuel and thinking they were over water, the crew bailed out of the plane carrying provisions for survival at sea, taking life jackets instead of water and rations.