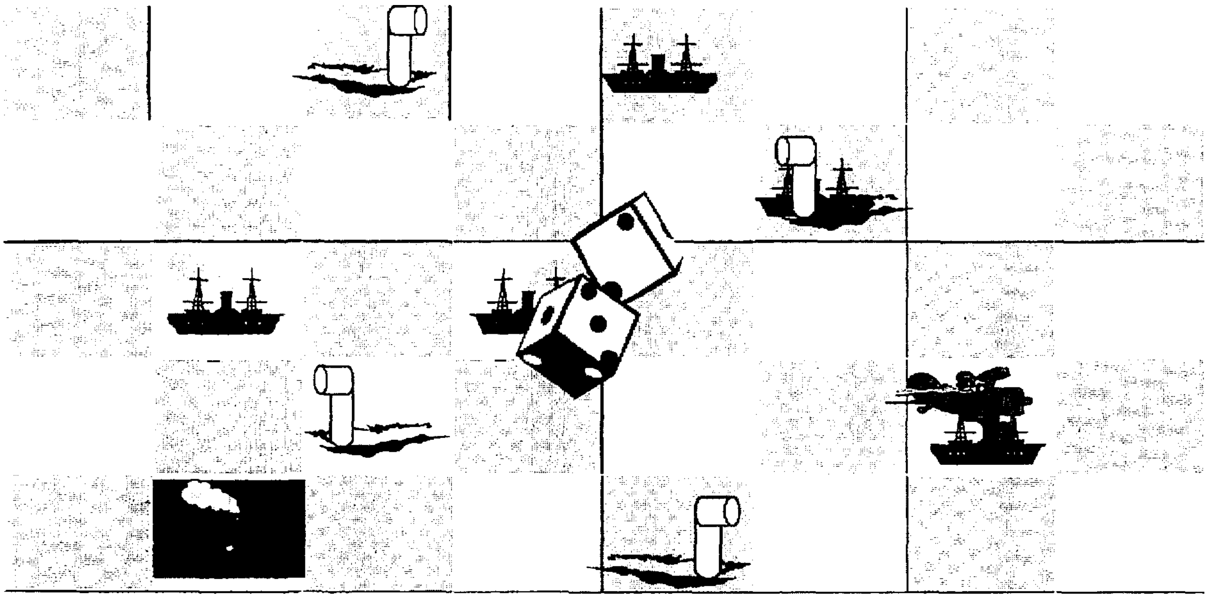
The following paper, "A Chessboard Model of the U-Boat War in the Atlantic With Applications to Signals Intelligence," by Brian McCue, was presented at the Naval Postgraduate School on May 30, 2000, in honor of Wayne Hughes.



# A Chessboard Model of the U-Boat War in the Atlantic With Applications to Signals Intelligence

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Received 26 August 2000; accepted 24 August 2002
DOI. 10.1002/nav.l0071
Published online 27 January 2003 in Wiley InterScien.ee (www.interscience.wiley.com).

**Abstract:** This paper uses a simple Monte Carlo model to analyze the influence of signals intelligence on the Second World War's Battle of the Atlantic. The principle measure of effectiveness is the number of U-boat days of attack to which convoys were subjected. A secondary measure is the number of convoyed ships sunk. The model is validated against historical data and then used to explore the effectiveness of the two sides' signals intelligence. Allied use of signals intelligence is shown to have been capable of completely offsetting German use of signals intelligence, and then some. © 2003 Wiley Periodicals, Inc. Naval Research Logistics 52: 107-136. 2005.

**Keywords:** antisubmarine warfare; signals intelligence; Second World War; Monte Carlo model; measures of effectiveness

## 1. INTRODUCTION

*The question inevitably springs to mind, what would have happened if [Bletchley Park] had failed to crack the German naval ciphers? But what would have been the result if on the German side, the B. Dienst had equally had no success? . . . Such speculation is fascinating.*

—Patrick Beesly [3, pp. 265-266]

In this paper, I will investigate the influence of *signals intelligence* (SIGINT), the knowledge gained from listening to one's enemy's radio emissions, on the Battle of the Atlantic. The battle is a veritable laboratory of signals intelligence, not only because the U-boats' hunt for convoys placed a premium (whose size we are to determine) on each side's knowledge of the location and plans of its adversary, but also because each side used signals intelligence for only a part of the time. Thus, we have a natural "quasiexperiment" [12] in which three out of the possible four possible conditions of signals intelligence (each side having it, or not, in turn, except that for no extended time were both sides bereft) occurred for significant periods [54, p. 39; 9, Vol. II, p. xxvi].

*This paper is not a product of the Center for Naval Analyses.
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Though this topic has been addressed before [54, 55, 56, 61, 62], my approach here is novel; I create and apply a "Monte Carlo"[1] model of the conflict, establish that it reproduces reality well, and then experiment within the model to explore the effects of signals intelligence. Through this method, I can address the kind of "what if" question that historians (who refer to these questions as "counterfactual conditionals") customarily decline to answer. The model creates and tracks U-boats and convoys through many replications of the campaign, or through alternate campaigns in which I have altered the level of SIGINT available to one or both sides. It lets me answer questions historians cannot because it lets me recombine the basic facts of the case (such as the number and speeds of the U-boats and convoys, the size of the region in which the operated, the distance at which a U-boat could detect a convoy) with alternative conditions of SIGINT. Historians can, in contrast, only look at what happened.

This paper will only address the period from July 1942 (when the convoy battle was joined in earnest, after coastwise shipping on the East Coast of the United States ceased to be easy pickings) through May 1943 (after which the Germans responded to their mounting losses of U-boats and

[1] So called because, for purposes such as deciding which U-boats or convoys are to be compromised by SIGINT (given that a certain overall proportion are to be thus compromised), the model makes a random choice.

far worse, U-tankers, by temporarily withdrawing the U-boat force from the Atlantic, and, coincidentally, the Allies changed to a new convoy cipher [66, p. 71 depriving the Germans of their source of SIGINT). Briefly, I show that under the conditions of this period (all other things being equal),

- Both sides benefited from SIGINT, the Germans the more so.
- When it was working. Allied SIGINT more than offset German SIGINT.
- Had there been no SIGINT on either side, fewer merchant vessels would have been sunk.
- Contrary to the conventional wisdom, the German side did not experience a "saturation" in which it had more intelligence than it could use.
- The principle utility of Allied SIGINT, in this context, was its ability to nullify any level of German SIGINT.

The use of a modeling approach will, I hope, have some side effects as well. Modeling skeptics and practitioners alike will have the opportunity to see that a model can reproduce the results of an actual conflict. Each may be surprised at the simplicity of the model: as in cartooning, much can be left out if the important aspects are presented rightly.

On the way to writing the present paper, I wrote:

- A circulation model, much like that in my book, *U-Boats in the Bay of Biscay* [44], in which the U-boats in the Atlantic moved among such states as Searching, Converging, Attacking, and so on
- An operations research-style study that tried to reprise the OEG Reports 66 and 68 [54, 55] using computation-intensive approaches made possible by the advent of computers
- An extensive statistical investigation that considered the sighting of convoys using the well-developed mathematics of mortality calculations [461
- A quick-and-easy regression analysis [47]
- A detailed Monte Carlo model that operated on the individual U-boat level.

Yel, in the end, I found each approach wanting. The circulation model and the in-depth statistical study suffered, *inter alia,* from a lack of "configurai" considerations, those statistical dependencies—spatial and otherwise—whose importance has been highlighted by the work of Timothy J. Horrigan [30]. The Monte Carlo model embodied configuration, but it was hideously complex and difficult to explain. I turned to Epstein and Axtell's terrific *Growing Artificial Societies* [16] to see how such a model can be explained clearly, and saw that their approach was to grow the model as well, first explaining to the reader a simple model, and then expanding the model and the explanation incrementally. I cast about for how to imitate them, and then remembered the wonderfully understandable chessboard model of Schelling's *Micromotives and Macrobehaviors* [63]. My idea was to present such a model first, as a "model of a model," to help the reader understand the real model later. I quickly wrote the chessboard "model of a model," both as a hands-on procedure and as a nearly trivial piece of computer code, and wrote an explanation of it. To introduce the important idea of validating the Monte Carlo model, I went through the steps of validating the chessboard "model of a model." To my amazement, it validated at least as well as the "real" Monte Carlo model, if not better! Al that point I abandoned work on the detailed model, and concentrated on perfecting the chessboard model, and on using it to answer questions regarding the influence of signals intelligence on the Battle of the Atlantic. The result is the present paper.

## 2. BACKGROUND

*. .. the main weight of our attack in the war on shipping [was, starting in July 1942] operations against convoys to and from Britain, in mid-Atlantic, where they were beyond the range of land-based air cover. It was in these areas on the high seas that the U-boats would enjoy their greatest freedom of action, for wolf pack tactics could be employed without enemy interference in all phases of surface operations, and that we could in consequence expect to achieve the maximum possible success.*

—Admiral Karl Dönitz [15, p. 237]

The Second World War's Battle of the Atlantic, in which German submarines (hereinafter, "U-boats") sought to interdict Allied transatlantic shipping, has been termed "the most extensively documented campaign in all history" [70, p. 385]. The huge and growing literature regarding this struggle contains several useful overall descriptions, to which the reader may refer for more details than are given in this brief description of the essentials."

Briefly, Allied merchant vessels crossed the Atlantic from West to East and vice-versa, and the U-boats tried to sink them. In addition to the troops and supplies needed for the eventual invasion and reconquest of Western Europe (to include the substantial bombing campaign conducted from Great Britain), these ships carried civilian supplies necessary (or the very survival of Great Britain's population. The

[5] Many books treat the general topic of the U-boat war: see also the references of this paper. [68] is a good place to start, as is [70]; the latter is more "journalistic." [49]'s account of the German side is unbeatable. [15] is also of interest, and the monumental [5] is refreshingly easy to read.

campaign illustrates the "rive cornerstones" of maritime warfare identified by Wayne Hughes [31, pp. 24-25]:

1. "Men matter most." The German U-bootwaffe and the Allied merchant marine services took frightful casualties (over the course of the war, the former lost about three quarters of its men), with nary a mutiny.
2. "Doctrine is the glue of good tactics." Though the German word *rudeltaktik* leads us to refer to "wolf pack tactics," what Dönitz really advanced was a wolf pack *doctrine,* from which the tactics followed. Conversely, the various interestingly named convoy tactics and "gambits" [21, 50] followed from having a *doctrine* in the first place.
3. "To know tactics, you must know weapons." Though it figures little in the present paper, the study of the evolution of submarine and antisubmarine weapons during the war is fascinating, and has been well addressed in the literature, starting with the classics of operations research [52, 64].
4. "The seat of purpose is on land." The purpose of the convoys was to keep the United Kingdom supplied with food, and to build up Allied forces there to the point that they could mount a cross-channel invasion of the continent.
5. "Attack effectively first." Aside from its implications for search, a major component of the wolf pack doctrine was that a number of U-boats must attack the convoy at once, rather than stabbing at the convoy individually.

### 2.1. Convoys

A convoy is a group of merchant ships sailing in company, usually escorted by armed naval vessels, [n each of the World Wars, the Anglo-American side displayed some initial resistance to convoying, on the intuitive "eggs in one basket" theory, arguing, e.g., that

> A system of several ships sailing in company as a convoy is not recommended in any area where a submarine attack is a possibility. It is evident that the larger the number of ships forming a convoy, the greater the chance of a submarine being able to attack successfully and the greater the difficulty of the escorts in preventing such an attack.
>
> (Quoted in [11], Vol. II, p. 79; see also [24])

Yet this reasoning is fallacious, and not only because of the strength of the escorts. The grouping of the merchant ships in the convoy would be of some benefit even in the absence of the armed escorts. The reason is simple geometry. Each merchant vessel can be seen (or otherwise detected) by a U-boat for a distance of some miles. Let us consider this distance to be equal in all directions from the merchant vessel: A submarine within the circle so defined will be able to detect the merchant vessel. By operating close together, the merchant vessels cause their circles to overlap, diminishing the total area of the vulnerable region. This feature of convoying is only intermittently recognized (see [64], p. 100; [22], p. 70 [66], p. 5, [11], Vol. II, p. 79).

### 2.2. Wolf Packs

The placement of all the "eggs" in a single "basket" is hannful only if multiple attacks can be made as the result of a single sighting. While a single U-boat might be able to do so, the leverage that it would gain by making a number of attacks would probably not repay what it had lost to the convoy's countervailing leverage gained by overlapping the circles of detection. However, the U-boats' side has available to it a counter-countermeasure to the countermeasure of convoying: If the U-boats' operations are coordinated, a single U-boat's sighting can be exploited by many U-boats in the attack. Thus arise the "wolf pack tactics" (*rudeltaktik*) invented—or at least championed—by the German Admiral of Submarines (later Admiral of the Fleet, and still later Führer) Karl Dönitz:

> The disposition of boats at the focal points of the seaways in the Atlantic has to follow these principles: (a) at least three boats form a group. Disposition of the boats in [an area with] a breadth of some 50 and a depth of 100-200 miles; (b) further groups according to the number of operational boats available—dispersed in the direction of the reported steamer track at some 200-300 miles; (c) command of all groups basically through C-in-C U-boats at home; (d) in the case of a sighting by one of the boats in a group, all the others are to attack independently without further orders; (e) direction of other groups on to the enemy through C-in-C U-boats.
>
> (Quoted in [34], p. 224[3])

[3] The fact that the wolf pack constituted an explicit countermeasure to convoying is not always recognized. A good source for this connection is [49] (paragraph 104), which addresses a period prior to that of our study, but is relevant because it shows the early confirmation by the Germans that the pack attack constituted a valid countermeasure against the convoy, an idea developed by Dönitz and/or his colleagues, based on First World War experience, and tested in a series of at-sea experiments in the late 1930s [22, 34, 39].

When a convoy was detected (either by a U-boat's sighting, a radio message decrypted by the German side, or—rarely—sighting by a German reconnaissance aircraft[4]), the U-boats of a pack converged upon it until they could attack it en masse. Once joined, the battle between the U-boats and the convoy's escorts could last for several days (and, more significantly, nights), usually ending when outside assistance came to the convoy's rescue. This assistance could take the form of a roving "Support Group" of naval ships, or land-based naval aviation flying from bases in Iceland and elsewhere. Part of the improvement in Allied capabilities during the campaign was an increase in the range of these aircraft, shrinking and eventually eliminating the mid-Atlantic "black hole" where no land-based aircraft could reach.

The two sides recognized that each merchant vessel represented an ability to carry many cargoes, and for this as well as for other reasons the largely-empty East-West ships were as strongly attacked as the heavily-laden West-East ones [49, paragraph 255]. Admiral Dönitz also believed that a given amount of U-boat attacking power was best applied in a single onslaught—as if following the above-cited maxim of Hughes. "Attack effectively first' (adumbrated by [49], paragraph 9.)

### 2.3. Radio Intelligence

The wolf pack style of operation required considerable radio communication: U-boats were under orders to report in to their land-based commander Admiral Karl Dönitz frequently, and in return Dönitz exerted a high level of day-to-day and sometimes even hour-to-hour control over his U-boats [22, p. 124].

Given the importance of the convoys to the Allies, this large volume of radio traffic became a target for the collectors and producers of intelligence. As is now well known, owing to the series of revelations regarding "the ULTRA secret" that began in the mid-1970s and continues to the present (e.g., [33], [66], [74]. and many others), the Allied side was often able to read German messages enciphers on the supposedly undefeatable Enigma machine. Even when these messages could not be read—such as during most of 1942, following the introduction of an improved version of the machine for naval use—the facts of the transmissions themselves (the locations from which they emanated, the wavelength upon which they were heard, the recognizable "fist" of the telegraph key operator, and even the electrical "fingerprint" of a U-boat's radio set itself) could be mined for considerable information [551. This signals intelligence (SIGINT), and other information, was used by the Allies to create a best-estimate plot of the known or suspected locations of U-boats, and to guide convoys around the regions where U-boats were suspected of lurking.

It is perhaps less well known that the Germans, for their part, similarly used SIGINT to find the location of Allied convoys. The organization responsible for doing so was the B Dienst, in particular the X-B Dienst branch thereof, and the resulting intelligence product is generally referred to accordingly in the post-war literature (to include this paper) simply as "X-B." While the Enigma machine, though ultimately defeatable, was sophisticated and the effort against it required the services of a remarkable team of geniuses at England's Bletchley Park [28] and their counterparts in the Washington, DC area, the convoy cipher was relatively easy to break and the X-B Dienst was, to varying degrees, able to do so throughout the period considered in this paper.

The Germans dismissed their own occasional suspicions that Enigma messages might be read by their enemy [49. paragraph 301]. The Allies eventually realized the vulnerability of the convoy cipher and replaced it [66, p. 7].

The recent literature on the U-boat war includes many excellent sources regarding the role of signals intelligence; some are cited in the References.

### 2.4. Stages of U-Boat Intercept and Attack

In attacking a convoy, the U-boats worked their way through a well-defined sequence of steps: searching, finding a convoy, organizing an attack upon it, and executing the attack. The "finding" step could be accomplished by a single U-boat (sometimes one that was not even searching), but an entire wolf pack was needed for the attack, so an intermediate step of "stalking" the convoy, while massing boats for the attack and getting them into position, was needed. If cued by X-B to the existence of a convoy elsewhere, the U-boats first had to move in on the convoy, a process that I will refer to as "converging" because it usually brought U-boats from a spread-out wolf pack patrol line to a concentrated attack on the convoy. The wartime operations researcher P.M.S. Blackett advanced a similar (albeit slightly more tactically oriented) conceptual breakdown of U-boat activities [4, p. 232], and a modem four-step version has been offered by W.J.R. Gardner in his pathbreaking analysis of the role of signals intelligence in the U-boat war [22, pp. 82ff].

The possible states of convoys and U-boats, shown in Table 1, will play a key role in structuring the model of the

[4] Help from long-range aviation could have helped the U-boat fleet a great deal, as Dönitz recognized at the time. However, in one of the personality-based resource misallocations for which the Third Reich is well-known, Dönitz's requests for aircraft were unsuccessful because of Göring's concern that a separate Naval Aviation force might arise (see, for example, [49], paragraphs 100-103 and elsewhere). Also, the use of maritime patrol aircraft was difficult and initial results were noi promising (see [49], paragraphs 111-114 and 244).

Table 1. Corresponding states of convoys and U-boats.

| Convoys | U-Boats |
|---|---|
| Unsighted | Patrolling |
| Compromised | — |
| Threatened | Converging |
| Sighted | Sighting |
| Shadowed | Shadowing |
| Under attack | Attacking |

U-boat war presented in Section 4. In this typology, *unsighted* convoys correspond to *patrolling* U-boats in the sense that no contact has been made; the convoys are zig-zagging towards their destinations, and the U-boats are looking for them. A *compromised* convoy is one whose course has become known to the U-boats, through X-B signals intelligence. A *threatened* convoy is a compromised one to which U-boats have been assigned; they are *converging* to intercept it based on the information in the signals intelligence. If ULTRA were able to reveal the existence of the converging U-boats, the convoy could alter course and resume being unsighted. At that point, the pursuing U-boats would most accurately be considered *errant,* inasmuch as they are heading for an intercept that is not going to happen, but for simplicity we will simply consider them to have resumed patrolling. A *sighted* convoy is one actually sighted by U-boats; this could occur either because they have converged on a threatened convoy, or because they simply found an unsighted convoy while patrolling. After the initial sighting, there ensues a period of *"shadowing"* (also known as "stalking," or "harrying") while the wolf pack masses in position for the attack. A convoy *under attack* is a sighted convoy that the U-boats have begun *attacking.* As mentioned above, Dönitz believed in the maxim later expressed by Wayne P. Hughes as "attack effectively first!" Therefore, Dönitz would wait until he had massed an entire wolf pack in a position favorable for an attack, and then attack in force. Once under attack, a convoy would not necessarily remain under attack for the balance of its voyage: its escorts might get the upper hand, and help would soon be on the way in the form of land-based naval aviation or additional surface ships. Towards the end of the period under study, airplanes flying from escort carriers could provide relief. Sooner or later, the convoy will be rid of its attackers, and will once again be in the unsighted state or, if it is unlucky, compromised once again by X-B radio intelligence. The U-boats, for their part, have given up and returned to patrolling, looking for other prey, or even the same prey: some convoys were attacked twice.

A reading of Hessler and examination of his diagrams shows that the above taxonomy contains considerable simplification. Some convoys, contrary to Dönitz's precepts, were attacked in dribs and drabs, and others by more than one wolf pack at a time. But the events that can happen in the model replicate the vast majority of the events that occurred in real life.

The timescale on which the convoys and U-boats passed through these states will be of great importance to us later. In taking a broad overview of Hessler's account one can see fairly clearly that attacks seem to average about three days. The conversions of sightings into attacks are harder to quantify from the text, but they, too, seem to average about three days. Arrivai at this figure, however, entails the conceptual difficulty that some sightings were never converted into attacks. The proportion of convoys that were compromised varied widely according to the success of the German X-B Dienst. The rate at which compromised convoys were turned into threatened ones, and the rate at which unsighted convoys were turned into sighted ones, depended upon the total numbers of convoys and U-boats present in the operating area; these, too, varied widely. These numbers, and the proportions of convoys compromised by X-B, are presented in Section 4.

Histories written with cognizance of ULTRA tend to focus on its use in rerouting convoys. In some instances, these convoys were unwittingly heading into a U-boat concentration; ULTRA made the concentration known, and the convoy was rerouted. More commonly, however—if only because of the prevalence of X-B compromises and the result that U-boats acting on X-B information constituted the majority of the risk, if not the majority of the U-boats—ULTRA indicated not only a concentration of U-boats, bat their intent to intercept a particular convoy. In the former case, ULTRA can be seen, in terms of Table 1, as aiding unsighted convoys in avoiding patrolling U-boats; in the latter, it aided threatened convoys in avoiding converging U-boats.

Given this discussion, one may well ask if ULTRA could help convoys once they had been sighted. The literature is fairly clear that once the battle was joined. ULTRA was of little or no *tactical* use. But ULTRA could help in other ways; it could, for example, alert the Allied side to the fact that the convoy had been sighted and the shadowing process had begun [22, p. 201]. Reinforcements could be called in; if they arrived in time, they could perhaps drive off the U-boats before the attack began, if not, they could help shorten the ensuing battle. Another possible use comes to mind, however, one that is not greatly discussed in the literature: the shadowing process was tenuous, and a timely ULTRA-inspired change of course on the part of the convoy, perhaps coordinated with a special attack on the U-boats to get them to submerge at the time of the turn, could conceivably break the shadowing U-boats' contact.

### 2.5. Examples

A few examples will help illustrate the ideas presented above. All are drawn from the period from July 1942 (when

Atlantic convoys became the main target, independent shipping having lessened and coastwise shipping on Ihe Eastern seaboard of the United States having at last been organized into convoys as well, ending the U-boats' "happy time" there), until May 1943, when mounting losses and other factors persuaded Dönitz to withdraw his submarines from North Atlantic waters, at least for a time.

"Happy is the convoy that has no history" (Marc Millner, quoted in [22], p. 185) and by this standard there were many happy convoys, an important fact to keep in mind: from August to December of 1942, only 34% of convoys were intercepted by U-boats at all, declining to 20% in January 1943, and only up to 54% through to the end of our period of study, May 1943. Nearly as happy is the convoy that was sighted by U-boats, but never engaged: Fewer than half of these intercepted convoys were actually attacked [22, p. 187].

The following examples serve to illustrate the kinds of histories that the unhappier convoys could have. For consistency, they are related from the history of the U-boat High Command insofar as possible, though, of course, the truth regarding ULTRA must come from other sources. Convoys designated HX are the main sequence of "homeward," i.e., US-UK convoys; those designated SC are slow US-UK convoys; ON convoys are "outward," i.e., UK-US, with one set of escorts for the whole trip across; ONS convoys are slow ON convoys. Wolf packs were given code names, variously of animals (ranging from Pike to Titmouse), or martial themes.

- Fortuitous sighting, a lengthy period of attack, and then relief:

  ... [5, August, 1942], U-593, at the northern end of the [patrol] line sighted [convoy] SC 94. The remaining boats, 200 to 300 miles astern of her, were ordered to close the convoy. It was hoped that some other boats, approaching the convoy from the northeast, would be able to maintain contact until the whole of [the original pack] arrived. For several days there was almost continuous contact.... On 9th August the convoy received air protection [49, paragraph 219].

- Fortuitous sighting, lengthy convergence, attack, relief, a second sighting, and a second attack:

  [U-164] chanced upon ON 115, 480 miles Southeasi of Cape Farewell [the Southern tip of Greenland], The nearest boats, though 400 miles to the southwest, were ordered to close the target, which they contacted on 30th July [1942]. The convoy's screen drove them off one after another, and one boat was lost. On the morning of 1st August the boats were formed into patrol line *Pirat* ahead of the presumed track of the convoy, but failing to locate it by the evening, they were sent North and South to search. On the following day U-552 sighted the convoy which had evidently made large alterations of course and speed, and other boats were ordered to close. By now we had sunk or damaged three ships out of the convoy, and when it reached the fog belt of Newfoundland Bank, the attack was broken off [49, paragraph 219].

- Attack as the result of X-B compromise:

  On 17th September [1942] we decrypted the noon position on the previous day of SC 100-150 miles Southeast of Cape Race.... It was not until the following day that one or two boats made contact, but the weather prevented any night attacks. On 20th September, [Dönitz] ordered the *Pfeil* boats, then 300 miles to the Southeast, also to close SC 100. ... When a new patrol line (*Blitz*) was being formed, however, U-617 sighted and successfully attacked the convoy,... [49, paragraph 224].

- A convoy, compromised by X-B, escapes unscathed:

  On 10 December [1942] we decrypted a British radio message giving several reference positions for an Eastbound convoy, HX 218. ... At noon on the 13th, the convoy was sighted, as expected, by U-373, and in view of the precise data as to its future movements, the *Ungestüm* group was moved 300 miles westward at high speed. The three boats East of Newfoundland soon lost the convoy, nor did any other boats find it. Believing that the convoy had been diverted to the South, they were told to proceed Southeast at high speed on a new patrol line. But in fact the ships had slipped through without any diversion [49, paragraph 280].

- Two convoys, each sighted by U-boats, drive them off, and eventually escape without having suffered attack:

  [On 14th September 1942], U-440 . . . having made contact [with SC 99), was pursued with Asdics [sonar] and damaged by depth-charges.... On the evening of the 14th the pursuit was abandoned. Fresh boats arriving were formed into Group *Pfeil*, and on the 15th one of these sighted and shadowed ON 129, while the others tried to concentrate. The shadower was frustrated by fog. On the following day two boats sighted the screen, and were lured away from the convoy, which took bold action. The search was given up on 18th September [49, paragraph 223].

- A convoy is sighted by U-boats on their way to intercept a different convoy compromised by X-B, is attacked for some days, and finally rescued:

  On the 25th [October 1942], we had decrypted the exact position of an ONS convoy for the 22nd at 2100.... [A wolf pack] was sent [in that direction] at high speed. In the middle of their line on 26th October instead of the ONS convoy they contacted HX 212. This looked promising and for the next two days the boats succeeded in shadowing this convoy. ... On 28th October the convoy received air escort, but by then we had sunk six ships and damaged another [49, paragraph 260].

- A convoy is compromised by X-B, but rescued by ULTRA, at least temporarily:

  A further convoy, possibly an SC [apparently SC 127], steering a similar course to HX 233, was sighted on 18th April [1943], but not attacked because of poor prospects. On that day we [the land-based U-boat High Command] discovered through a decrypted message why these convoys were using such a Southerly route. The message showed the enemy to be surprisingly well informed as to the number of [boats in the *Meise* wolf pack] and their location, It seemed possible that further convoys would use this Southern route, and hence a new group. *Specht,* was formed on 20th April. . .. These boats were set up in two patrol lines 400 to 600 miles North of the Azores [49, paragraph 321].

- The same convoy, its plans now known to the Germans, is again rescued by ULTRA and a wolf pack is left stranded, waiting for a convoy that never came:

  ... on 23rd April. .. [Dönitz] ordered the *Specht* group, [which] had waited in vain for SC 127, to proceed Northwest at high speed,. . . ([49], paragraph 322; see also [33], Chap. 20).

As some of these examples suggest, to look at examples of particular convoys is to miss an important aspect: The convoys were not tracked, intercepted, attacked, or rescued in isolation. Recent books convey this point regarding key periods such as March [33, 48] or May [211 of 1943; they show the chaos—not only in the everyday use of the term, but I daresay in the mathematical usage as well—that resulted from the passage of multiple convoys in each direction, each subject to varying levels of X-B compromise as well as to varying levels of risk from multiple wolf packs, themselves perhaps subject to varying levels of ULTRA compromise.

## 3. QUESTIONS AND COUNTERFACTLALS

*One cannot write a history of things that do not happen.*

—Admiral Samuel Eliot Morison [51, p. xvi]

Despite the copious data and the considerable amount of attention devoted to the topic, some substantial questions remain. These are worthy of our attention for two reasons.

One is methodology: the U-boat war constitutes a best-case situation for the quantitative analyst of military matters. The facts are available, and enough cases (howsoever defined) occurred that one can hope for usable statistics. In contrast to any study in land warfare, the infinite complexity of terrain is not an issue. Incredibly, morale does not really seem to be either; U-boats and merchant vessels put to sea despite a considerable chance of not coming back, and attacks were generally pressed home in the face of any odds. So the field is clear for quantitative methods, and a large part of my goal is to showcase these, not only to show an instance in which they succeed, but to provide a starting point for a deeper understanding of how they work and what kinds of fruit they can bear.

The other is more practical. Our policymakers operate on the basis of a received view of what has happened already. They use it in ways that do not always appear clearly in the final public record, but in their thoughts and discussions they naturally fall back upon a base of knowledge regarding the past. Some of this is valuable knowledge applied well; some is hazy or misunderstood, and better policy would result from better knowledge. So it is important that the historical record *and its received interpretation* hold water.[5]

### 3.1. How Much Did ULTRA Help?

Historians writing after the revelation of the "ULTRA secret" in the mid-1970s have discussed three specific benefits of ULTRA information in the war against the U-boats. (They have also cited the general benefit of increased Allied knowledge of the U-boats' habits of operation.) Two arguably apply during our period of interest, July 1942-May 1943.[6]

[5] I am indebted to Robert Butterworth for this observation.

[6] The third benefit, the defeat of the "milch-cow" tanker U-boats, occurred just after our period of interest.

The first is the rerouting of convoys so as to evade known U-boat positions. Widespread agreement exists regarding this use of ULTRA during 1941, though historians differ regarding quantitative estimates of how much shipping was saved by this means. Some also cite this benefit of ULTRA during the period of the war considered in this paper (e.g., [70], p. 316), while others consider it to have been of little consequence. There is room for doubt because Allied reading of the Enigma traffic was intermittent during this time, and even when it could be read, there were so many U-boats that it was arguably difficult to evade them all. In any case, the Germans were, for their part, reading the Allied cipher and could—and did—pick up on the rerouting of a convoy and reroute some U-boats to meet it ([33], Chap. 20; [68]. pp. 527-528). Indeed, the British official history of intelligence renders a Scotch verdict:

> . . . the battle which was fought in the Atlantic between December 1942 and May 1943 was the most prolonged and complex battle in the history of naval warfare, and when its outcome clearly hinged on many factors it is not easy to establish the extent to which it was influenced by the Allied decryption of the signals of the U-boat Command.
>
> [27, Vol. II, p. 549]

Rohwer cites another contribution of ULTRA, the ability to deploy aircraft and support groups pro-actively, to "in such a way that convoys in danger could be fought through [by] concentration of forces" [61, p. 89]. He dates this capability from March 1943 onwards, though the Allies had resumed reading Enigma traffic partway through the preceding December.

### 3.2. What about Tactical Use of ULTRA?

There is fairly widespread agreement that ULTRA was of little use once the battle was joined. However, there are reasons to question this view. After all. ULTRA was tactically useful in battles in North Africa, so maybe it could be tactically useful at sea as well. Certainly the U-boats and their High Command communicated by radio while setting up the attack, so the raw material would be present. Maybe ULTRA allowed some convoys to slip away from the harrying U-boats before the attack was joined. Such a use would be tactical in the sense that it happened within sight of the enemy, and would be quite distinct from evading U-boat sighting in the first place.

### 3.3. How Much Did X-B Help?

Historians and others who have recognized the role of the Germans' "X-B" signals intelligence effort at all have generally seen it as making a significant, or even "invaluable," difference in the attack on convoys ([e.g., [61], [66], p. 260, [70], pp. 229-230). Hessler, who was a participant as well as an historian, describes the role of radio intelligence as "great" [49, paragraph 252] as of the early portion of our period of study, and, referring to a time near the end of our period of study, says, "It was almost entirely due to [the] outstanding achievements by our Radio Intelligence Service that the U-boats still succeeded in finding convoys" [49, paragraph 303].

Tantalizingly, Dönitz has been cited as having said that the X-B decrypts were worth an extra 50 boats to him, but we must not make too much of this agreement because the citation may be a misreading of a gloss in the source it cites.[7]

War-era researchers investigated the utility of X-B intelligence using a statistical approach and a staple of operations research, the *operational search rate*, defined in this case as

$$Q_{est} = C/(T\bullet(N/A)) = (CA)/(TN),$$

where $Q_{cst}$ is the estimated operational search rate, $C$ is the number of contacts, $T$ is the amount of time the U-boats spent searching, $N$ is the number of convoys at sea, and $A$ is the area of the region in which they are to be found. Note that the quantity $NIA$ can be construed as the "convoy density"; the identification and use of such "densities" was a standard method during the war [21, 54-56, 71, Chap. 8]. The search rate is the amount of ocean each U-boats would have to inspect each day to result in the given number of convoys sighted, and is thus measured in square miles per day [45, 46, 52, 64].

Researchers found that the search rate of U-boats when looking for convoys compromised by X-B intelligence was about double that of U-boats looking for convoys without the guidance of radio intelligence [56]. In an important conceptual step, they were using the search rate as an indicator; they did not imagine that X-B improved the U-boat skippers' vision. However, their approach did not consider the effect of ULTRA on the search process.

### 3.4. What If There Had Been No Signals Intelligence on Either Side?

Immediately after the war, the Operations Evaluation Group (the OEG; successor to the wartime Anti-Submarine

[7] "Dönitz reported after the war that he considered the [X-B] Dienst to be equal to at least fifty additional U-boats" ([23] (p. 121), citing [3]; but [3] (pp. 54-55), after quoting Dönitz on the X-B Dienst in general, says in his own voice that it "must have been equal to at least an additional fifty U-boats," nor can the reference to fifty be found in [15]).

**Table 2.** Summary of results presented in [54] and [55].

| Dates | U-boat search rate (sq nm/day) | | | ULTRA |
|---|---|---|---|---|
| | No X-B | X-B used | X-B had, not used | |
| 7-12/'42 | 2450 | 8400 | 2600 | None |
| 1-5/'43 | 1400 | 3400 | 1650 | Some |
| 6-8/'43 | | U-boat "retrenchment" | | |
| 9/'43-3/'44 | 1700 | 4050 | | Plenty |

Warfare Operations Research Group, ASWORG, and the Operations Research Group, and predecessor of today's Center for Naval Analyses) sought to investigate the role of both sides' SIGINT efforts in the Battle of the Atlantic [54, 55].

The early post-war analysts, knowing from captured German documents when and where the Germans had and used SIGINT, computed the operational search rate under various conditions of signals intelligence (i.e., the Germans had X-B but the Allies didn't have ULTRA, both sides had their signals intelligence, neither side did, only the Allies did) on a month-by-month basis. They then tried to relate the conditions of SIGINT to the search rates, defined as above. A summary of their results appears in Table 2.

The case in which the Germans had X-B, but did not use it, arises because they sometimes had so much X-B information that there were not enough U-boats to search for and attack all the compromised convoys. Yet sometimes an unsought convoy would be sighted anyway: hence the third data column in the table.

This was a noble effort, but it ran into severe difficulties. The worst of these was that there were really not very many months' worth of comparable data, considering that four different search rates were to be estimated. The analysts counteracted this difficulty by considering the presence or absence of X-B on a convoy-by-convoy basis (there being no pure cases of a full month with neither X-B nor ULTRA), but they erred in their treatment of repeat sightings of the same convoy, counting already-sighted convoys into the density, while giving the U-boats no credit for re-sighting them. Finally, the results are unaccompanied by any statement of the statistical uncertainty surrounding them.

The war-era analysts eventually despaired of reaching a definitive conclusion regarding the influence of signals intelligence on the Battle of the Atlantic, rendering their own Scotch verdict:

> the contact rate might measure the effect of the X-B intelligence of convoy movements, but it is not clear that it would measure the effectiveness of Allied intelligence; that is to say, it is not *a priori* evident that the existence of Allied intelligence would affect the number of contacts made by the U-boats. [...] There is no direct correlation between the contact rate and the volume of promptly decrypted communications. ... This is to be expected since the number of messages transmitted by [the German Commander of Submarines, Admiral Dönitz] fluctuated widely, and depended upon the state of German X-B and on the number of contacts itself.... It is apparent that the great value of decryption intelligence in the defense of convoys cannot be expressed quantitatively by this measure.
>
> [...]
>
> With respect to the defensive use of decryption intelligence by the Allies (to divert and route convoys in order to evade known concentrations of U-boats) it is not possible to express statistically the effect of such intelligence on the ability of convoys to avoid contact by the U-boats. [.. .] A part of [the] collapse of the U-boat effort must be ascribed to the availability of prompt intelligence on the U-boat movements; increased effectiveness of antisubmarine measures, and the failure of the X-B service to provide intelligence on convoys to the U-boats, were responsible for some of it. It is not possible to determine how much credit should be ascribed to each of these factors.
>
> [55, p. 5-2]

In other words, the war-era operations researchers could not see how to untangle the complicated relationships inherent in the data.

The effort could also be criticized on the basis of its results: a search rate of 2400 square miles per day translates (given a U-boat speed of 10 knots[8]) into an inability to detect a convoy that is more than 5 miles away. Other wartime operations researchers had separately estimated the range at which a convoy could be delected and had gotten much larger values: in daylight, a single ship could be sighted at 6 miles, a small 8-ship convoy at 11, and a good-sized 64-ship convoy at 23. Interestingly, the long ranges at which large convoys can be sighted in daylight are attributable to the high probability that at least one of the ships in the convoy will be misburning her fuel, creating a high smoke plume [64, p. 100]. Nor was visual detection the only possible means; U-boats could and did carry their own radio intercept equipment, with which to detect convoys beyond visual range [49. paragraph 278]. Another indication of the U-boats' convoy detection capabilities is pro-

[8] The fact that the convoy is moving as well matters, but this "dynamic enhancement" effect (treated at length in [38]) increases the effective speed of the U-boat, and thus only serves to strengthen the argument advanced here.

vided by the spacing at which they were deployed—10 to 20 miles. At night, when this distance exceeded the sighting range, U-boats dove deep to get a long-range acoustic detection, and fell back in the direction of the anticipated movement of the convoy so as to avoid letting it pass in the night [49, paragraph 255].

Given a ten-knot speed, 2400 square miles per day would seem to be a minimum figure for the U-boat search capability—absent any SIGINT on either side—and a figure of 5000 square nautical miles per day is certainly possible.

However, important difficulties remain, including:

- Dönitz set up his U-boats in patrol lines running north-south, to intercept the convoys moving east-west. Thus the operation was not really one of search, but rather of *screening*, the surveillance of a line that targets (in this case, convoys) must cross. What mattered was not the percentage of the ocean area that the U-boats could search in a given time, but the percentage of the convoy routes that they could, in effect, blockade.
- The operational search rate underlying the OEG approach is a quintessential product of operations research, but the OEG used it as a statistic, and its approach was fundamentally statistical. Therefore, OEG could not capture the effects created by saturation and feedback, especially those created by *saturation* and *feedback*, concepts to which we shall next turn.

These difficulties and others of the statistical approach can be characterized collectively as neglect of *configuration*, the spatial and time-domain statistical inter-dependency of U-boat and convoy positions [30].

### 3.5. Was There "Feedback"?

The radio-orchestrated effort to direct U-boats to an X-B-compromised convoy would itself render the Germans more vulnerable to ULTRA intercepts. Similarly, the redirection of a convoy in response to knowledge of U-boat positions carried the risk that the new orders would be deciphered. Either effect can be termed "feedback."

In the period under study in this paper (July 1942-May 1943), multiple instances of feedback can be found to have befallen either side, e.g., that of SC 127 as recounted above. To my knowledge, though, the effect has not heretofore been noticed as a thing-in-itself, much less assigned a name.

Though they can imagine the process and discern particular cases when it was at work, the involute and self-counteracting nature of any feedback process presents great difficulty to historians and statisticians alike.

### 3.6. Was There "Saturation"?

Another supposed feature of the SIGINT-guided U-boat war has already been identified and named: *saturation*. A present-day person might call it "information overload." The idea is that the Germans could use only so much X-B intelligence at a time, because beyond a certain point they would run out of U-boats with which to prosecute compromised convoys.

The war-era researchers cite saturation:

> In [the period January-May 1943], it is probable that a saturation effect with respect to compromised convoys occurred. That is to say, in some cases [Dönitz] had to choose one convoy among several (that are included as compromised ones in the calculation of *Q*) if he wished to apply the principle of concentration of forces and mass attacks [56].
>
> [Admiral Dönitz] was convinced that it was more profitable to attack a convoy with as many boats as could be homed onto it. Hence it happened frequently that even when he had good X-B on several convoys during a given interval, so many boats were in pursuit of one or even more other convoys that had been contacted, that it was not practicable to allot any boats to search for the remaining ones [55, pp. 3-4-3-5).

The possibility of saturation, i.e., that simply because some X-B intelligence is good does not mean that more would be better, makes analysis of the U-boat war difficult for the historian, the operations researcher, or the statistical analyst. However, it is a key point to get right, because of the precedent it sets for today's discussion of "information warfare." in which the specter of "information overload" is frequently invoked.

### 3.7. What Is the Correct Measure of Effectiveness?

Arguably, the fundamental problem was that the OEG had made an *incorrect choice of measure of effectiveness* (MOE). Their analysis concentrated on estimating the search rate of the individual U-boat, and on how this was raised by X-B and/or lowered by ULTRA. But if configuration matters, then the effectiveness of the U-boat fleet is not the sum of the individual boats' effectivenesses.

Rather than look at U-boat search rates or merchant vessel sinkings, therefore, one can better look at *U-boat attack-days*. A U-boat attack-day is a day spent by a U-boat in attacking a convoy.

One might argue that *merchant vessel sinkings* were the true bottom line, but these depended not only upon the duration of attacks, but also upon changes in tactics and weapons that have nothing to do with search effectiveness or signals intelligence. Thus, while we will consider sinkings from time to time, we can do so only via the number of attack-days, multiplied by the appropriate historical month's ratio of sinkings to attack-days.

### 3.8. How Much Depended on Chance?

A critical shortcoming of the approaches described in this section is their failure to provide any estimate of the natural fluctuation of the result due to the operation of chance. (Even my regression analysis [47], with its "standard error of the estimate" does not do so, because we cannot live up to the requirement that the independent variables be uncorrelated, much less of equal variance.) For unless we subscribe to a determinism of the most radical kind (in which case the study of history would be remarkably dull, bereft of whys and wherefores and in any case fruitless, because our own futures, presumably as prescribed as those of our forebears, could not be improved by studying the mistakes of others), the numbers of U-boats and convoys at sea and the degree to which each side had radio intelligence on the other surely did not combine to create only a single possible value for the resulting number of attack-days. The past might have turned out in different ways, and surely a noble goal is to assess how likely some of those ways were. This assessment is not to be confused with an estimate of the uncertainty of our answer due to uncertainty in the input, or due to imperfections in our method, though there will be some of each of these as well; it is an attempt to address a basic point of curiosity—"did it *have* to turn out that way?"

### 3.9. Counterfactuals

The great goal in the literature of signals intelligence in the U-boat war has been to answer questions such as these, and thereby to assess the contribution of signals intelligence to the efforts of one or the other of the two sides, or both ([22], [33], [61], [62], [66], and many others). This question is often reduced to, "What would have happened had there been no SIGINT?" That is not the only possible formulation, but it runs into the same difficulty as do others (e.g., "What would have happened had the SIGINT been different?"), i.e., that it is a "counterfactual conditional," or "what-if question" [33], Chap. 23], Historians dismiss "counterfactual conditionals" on the grounds of logical principle. Fischer gives a solid accounting of this view, which can be summarized by his introductory comment: "All historical 'evidence' for what might have happened had [John Wilkes] Booth missed his mark is necessarily drawn from a world in which he hit it" [17, p. 16].

As a purely logical stance, this position is unassailable, but it leads to absurdities. Had Booth missed, would Lincoln have lived, at least to see the end of the play? The rigorous logician would insist that this question is as unanswerable as, "had Booth missed, what would have been Lincoln's stance on the Franco-Prussian war of 1870?" But the common-sense answer is that Lincoln died of a bullet to the brain, and that had he not received the bullet, he would not have died, at least not then.

Even with counterfactuals, causality is epistemologically complex: without them, it is completely untenable.[9] Yet historians cite causes constantly, and even go so far as to assert that some causes are "principal" or "important" ones while others are lesser [70, p. xii].

An escape route is offered by *modeling.* Probably almost any account that can sustain meaningful counterfactuals and gradations of causality must depend upon a model: Indeed, it is tempting to *define* a model as, "a means of evaluating the consequences of counterfactuals and the relative importance of facts." One set of facts is most pointedly *not* included in the model: the way the historical battle turned out. Thus, at least in principle, the model comes from a world in which the historical battle had not yet happened and avoids the predicament that all historical "evidence" for what might have happened had signals intelligence been different is necessarily drawn from a world in which it was not.

## 4. A CHESSBOARD MODEL OF THE U-BOAT WAR

*Some vivid dynamics can be generated by any reader with a half-hour to spare, a roll of pennies and a roll of dimes, a tabletop, a large sheet of paper, a spirit of scientific inquiry, or, lacking that spirit, a fondness for games.*

—Thomas C. Schelling [63, p. 147]

Though it lacks the primary requisite of game theorists' games—players—my model of the U-boat war resembles a boardgame in many respects: It has counters, dice, and a board. It also resembles some games (for example, "wargames," as well as many of the games studied by game theorists) in a more profound way: It is a model of reality, with space being represented by the board, time by the turns of the game, and entities by the game pieces.

Search games that actually do involve players can be made quite complex, and in short order they transcend the limits of what most people would consider an acceptable

[9] Fischer explicitly dismisses "Why?" questions on this basis, but admits that among historians his view might make him "a minority of one."

**Table 3.** Basic data on U-boats, SIGINT, convoys, attacks, and sinkings [49, 54, 55].

| Case | U-Boats | XB | ULTRA | Convoys | Attack-Days | Sinkings | Ratio |
|---|---|---|---|---|---|---|---|
| Jul-42 | 17 | 0.39 | 0 | 8 | 59 | 7 | 0.12 |
| Aug-42 | 27 | 0.47 | 0 | 7.3 | 139 | 19 | 0.14 |
| Sep-42 | 39 | 0.37 | 0 | 8.7 | 196 | 20 | 0.10 |
| Oct-42 | 47 | 0.13 | 0 | 7.2 | 202 | 23 | 0.11 |
| Nov-42 | 28 | 0.43 | 0 | 7 | 151 | 28 | 0.19 |
| Dec-42 | 31 | 0.44 | 0 | 8 | 274 | 24 | 0.09 |
| Jan-43 | 41 | 0.63 | 1 | 7.3 | 47 | 7 | 0.15 |
| Feb-43 | 51 | 0.45 | 1 | 6 | 191 | 34 | 0.18 |
| Mar-43 | 58 | 0.88 | 1 | 7.3 | 226 | 48 | 0.21 |
| Apr-43 | 53 | 0.69 | I | 6.5 | 174 | 20 | 0.11 |
| May-43 | 58 | 0.85 | 1 | 8.8 | 300 | 19 | 0.06 |

parlor game.[10] Two exceptions, however, are so important as to demand mention. The first is the computer-and-joystick game created by Washburn to validate theoretical findings in search theory: military officers' performance in this game closely matched the prediction of the theory [72, Section 2.5]. The second, known as *Kriegspiel* (i.e., "'wargame"), can best be described as double blind chess. In it, the players see only their own moves, and the occasional disappearances of their chessmen when captured by the opponent's: The services of a referee are needed to prevent the players from unknowingly making illegal moves, and to effect the captures. A considerable element of search is involved, and the name of the game reflects the perception that ignorance of the enemy forces' locations is a key element of war. In relation to this paper, the game is important because a key element is the ability to hear the referee's statements to the other player, which becomes a form of signals intelligence [41-43]. The game is also important to our topic because several of the postwar American developers of quantitative methods of military analysis were enthusiastic *Kriegspiel* players during their lunch hours at the RAND Corporation [58, p. 38].[11]

The model presented here, however, is quite simple, and the interested reader will have no trouble playing it by hand on a chessboard, as a form of solitaire.

### 4.1. Data

The basic data concerning U-boats and convoys during the period in question appear in Table 3. The numbers of U-boats and convoys are monthly average numbers at sea: The total of individual boats or convoys involved would be greater. The figure for X-B is the proportion of convoys that were compromised in a given month. As to the compromise of U-boats by ULTRA, the figure of 1 message per month is an estimate, based on the intercept data, of the number of messages *revelatory of U-boat plans* that were intercepted per boat per month. (The total number of messages was much greater, but the majority were not directly useful in redirecting convoys.) The table shows the numbers of ships sunk from the convoys in question, and the ratio of sinkings to attack-days, but (as explained above) it is appropriate to think in terms of attack-days.

Multiple regression and its variants are such a staple of present-day analysis that one might ask, especially in view of Table 3, why we cannot simply apply them to the problem at hand and be done. We could, of course, and I have [47]. Some of the results even turn out to be consistent with the method presented later on in this paper. But the regression analysis cannot detect saturation or feedback, and little understanding *of process* is produced: Regression would not help us decide whether or not ULTRA was tactically useful in letting convoys escape once they were sighted.

### 4.2. Setting Up the Chessboard Model

To run this model, you will need a chessboard, a pair of dice, pencil and paper, and some copies of the playing pieces shown in Figures 1 and 2.

On the chessboard, ignore the three rows farthest from you. Thus you are left with a very approximate chart of the North Atlantic region of operations. It will be handy to number the rows and columns. Each "turn" of the game represents a day. Each convoy and each wolf pack of U-boats occupies a square.

To simulate different phases of the battle, different numbers of wolf packs and convoys should be in the game. Table 4 shows how many are appropriate to each month (cf. Table 3; each wolf pack contains a dozen U-boats). For

[10] Some people, however, play relatively complicated search games for fun. See, for example, the products of the now-defunct Avalon Hill Game Company, such as *Jutland, Midway,* and *Bismarck,* all of which represent naval search problems. The solitaire game *Wolfpack,* by the also-defunct Simulations Publications Incorporated, treats the Battle of the Atlantic as considered in this paper. See also [75],

[11] It is regrettable that [58], and at least one derivative work, conflate the chess-variant *Kriegspiel* with more simulative wargames played on maps or sand-tables with pieces representing the capabilities of actual military units.

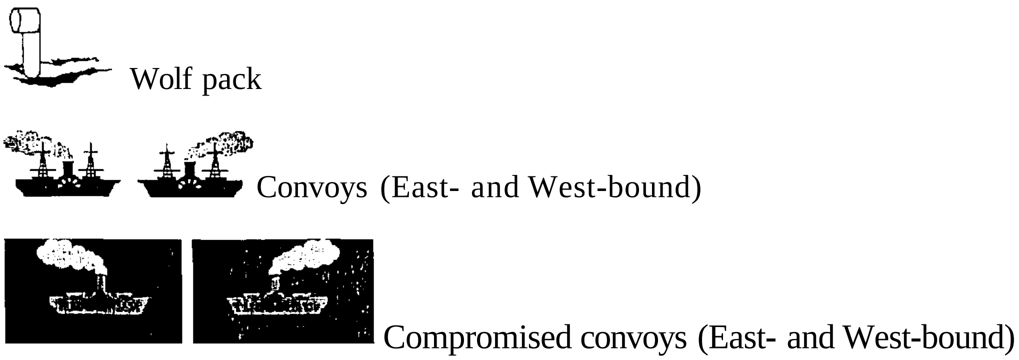


Figure 1. Playing pieces for the chessboard model.

future reference, it also shows the dice results needed to simulate the probabilities of X-B compromise listed in Table 3.

To make the initial setup of the wolf packs, roll a single die for each wolf pack: This is the row number (reroll it if it is a 6). Roll a second die, and add 1: This is the column number. Thus, rolling a I and then a 4 would put the wolf pack on the dark square nearest the middle of the South edge of the board (the square known to chess players as e 1 ). Locate the convoys using dice in the same way, and then flip a coin for each to determine which direction it is going: heads is Eastbound, tails is Westbound.

Note that in this setup procedure, a convoy and a wolf pack can end up the in the same square—if so, the unlucky convoy has just been sighted. (Remember that the war started before our game did—we're coming in on this in the middle.) To see if a convoy is compromised by German X-B SIGINT, roll two dice for it and consult Table 4. (Do this now the beginning of the game, and also anytime a convoy reaches the East or West edge and turns around, in effect becoming a new convoy.) A convoy is compromised if the total showing on the dice is as in the table below. (This table is based on the actual proportions of convoys that were compromised during the various months, as shown in Table 3.)

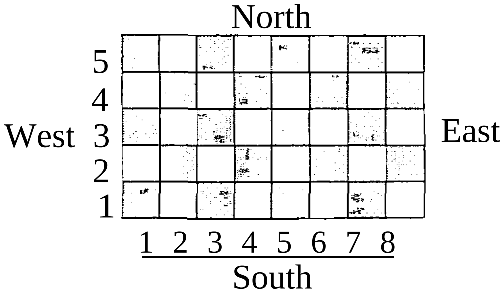


Figure 2. Chessboard "chart" of the North Atlantic.

### 4.3. Running the Chessboard Model

Running the model is accomplished by enacting a number of steps in order. Together, the steps represent the passage of one day. To help understand these steps, the reader may want to review the taxonomy of convoy and U-boat statuses presented in Section 2.

1. The first step is to keep score. On the first day, there isn't any score to keep, but on other days one counts the number of wolf packs that are attacking convoys and adds this number to the U-boats' score for the month.
2. The next step is to see if sightings turn into attacks. For each wolf pack that is in the same square as a nonattacked convoy, roll the die; if the result is a 1 or a 2, the wolf pack takes the convoy under attack and should somehow be marked to denote this fact.
3. Then see about converting sighted convoys, and those under attack, back into unsighted status: roll a die and on a 1 or a 2, the convoy becomes unsighted. The wolf pack attacking such a convoy returns to patrol, and if it just started the attack in

Table 4. Data for the chessboard model [54, 55].

| Month | Wolf packs | Convoys | Dice for X-B compromise |
|---|---|---|---|
| July 42 | 1 | 8 | 3-6 |
| Aug 42 | 2 | 7 | 2-6, 11 |
| Sept 42 | 3 | 9 | 2-5, 10 |
| Oct 42 | 4 | 7 | 6 |
| Nov 42 | 2 | 7 | 2-6 |
| Dec 42 | 3 | 8 | 6-8 |
| Jan 43 | 3 | 7 | 6-10 |
| Feb 43 | 4 | 6 | 6-8 |
| Mar 43 | 5 | 7 | 3,5-12 |
| April 43 | 5 | 7 | 3-8 |
| May 43 | 5 | 8 | 2,5-12 |

the previous step, it does not get credit for it come the next iteration of step 1. This circumstance corresponds to attacks that were repulsed immediately, or broken off because of the timely arrive of reinforcements.

4. This step deals with the effects of X-B and ULTRA, in that order. If there any compromised convoys that are not threatened by wolf packs, turn them into threatened ones by assigning a wolf pack to intercept them. Now the convoy is threatened, and the wolf pack is converging. Use judgement to find the best possible assignments at this time; doing so may entail unassigning a wolf pack that is converging on a distant convoy, if a nearer convoy (or one that is headed towards the wolf pack) becomes compromised, but do not interrupt a wolf pack attack that has already started. Then apply the effects of ULTRA, if it is in use during the month being simulated. Roll a die for each pack that has sighted a convoy or is converging upon one: If the result is a 1 or a 2, the convoy ceases to be threatened or sighted and becomes unsighted, and the pack returns to patrolling. Note that, in the case of a sighted convoy, the pack and the convoy will be temporarily be left in the same square, a situation that will in all likelihood change before the next sightings are made.

5. Move all the convoys. Convoys move only on odd-numbered days, starting with day 1. Convoys are East-bound or West-bound. To move a convoy, roll a single die: If the convoy is East-bound, it moves Northeast on a 1 or a 2, due East on a 3 or a 4, and Southeast on a 5, or a 6. Similarly, if the convoy is West-bound, it moves Northwest on a 1 or a 2, due West on a 3 or a 4, and Southwest on a 5, or a 6. Convoys directed to move off the North or South edges of the board bounce off them like billiard balls, moving South if directed North off the board, or vice versa. It is all right if a convoy moves to a square occupied by another convoy. Sighted convoys and their sighting wolf packs are moved together, but note that just because a convoy and a pack are in the same square does not mean that the pack has sighted the convoy—they may be left over from an unsighting in step 4. in which case the convoy moves without the pack. If the convoy is under attack, do not roll for the North-South movement: zig-zagging at this point is useless, so the convoy heads due East or West.[12] When a convoy moves off the East or West edge of the board, it is replaced by rolling a die and placing a new (and unsighted) convoy in the indicated row (1-5) on the same side (East or West) or, in the event that a 6 is rolled, trying again. New convoys must be checked for X-B compromise, following the same procedure as was used when doing the initial setup.

6. Now move all the wolf packs that do not have convoys in sight,[13] and are not responding to an X-B SIGINT clue. Such wolf pack movement is governed by Table 5. Roll two dice. If the result is 7, the wolf pack remains in the square it occupies: Otherwise, it moves to the neighboring square that corresponds to the number rolled. If there is no such square, because of the edges of the board, then the wolf pack bounces as if it were a billiard ball. For example, if a wolf pack is in the first row and rolls a 12, it moves up instead of down; if it rolls an 11, it takes a glancing bounce off the bottom edge and moves as if it had rolled a 10. In this simple model, wolf packs remain at sea permanently. (In reality, U-boats often had to go and refuel.) It is all right if a wolf pack moves into a square occupied by another wolf pack.

7. Check for new sightings. Convoys in the same square as wolf packs at this time become sighted, and the wolf packs become sighting. It may seem strange to do so at this point, because in some instances the convoy will be one that just became unsighted in the previous step, but there is a reason—to be discussed below—for handling the matter in this way.

**Table 5.** Die rolls for U-boat movement.

| | | |
|---|---|---|
| 10 | 2.6 | 3 |
| 5 | 7 | 9 |
| 11 | 12,8 | 4 |

When these steps are completed, record the passage of a day and begin again ai the first step.

Continue in this fashion, remembering that convoys can only move on odd-numbered days, through all the days of the month. When you are finished, multiply the number of wolf pack attack-days by 12 to get the number of U-boat attack-days, and compare your results to the historical results (above) or mine (below). Your scores for a given month will vary, but the average should be close to the historical values and very close to my results. Notice that

[12] This exception is purely cosmetic, because—unlike in the real world—the diagonal movement is accomplished just as fast as the due East or due West movement.

[13] As above, note that (on an even-numbered day) a pack could be in the same square as a convoy, and not be sighting it; they could have been separated by un-sighting in step 4.

the U-boats progress through the pattern of searching, then possibly converging, stalking sighted convoys, and finally attacking ihe convoys.

### 4.4. Chessboard U-Boat Model Rules Summary

- Ocean is an 8 X 5 "chessboard."
- Squares are 250 nm on a side.
- A 12-boat wolf pack can search a square in a day.
- The steps:
  1. Update the wolf packs' score.
  2. Roll a die for each ongoing sighting, using the appropriate "rule of 1/3" described below, to see if it is converted into an attack.
  3. Roll a die each convoy that is under attack to see if it gets rescued and returns to being unsighted, using Che appropriate "rule of 1/3" described below.
  4. The SIGINT step: Assign a wolf pack to converge upon any compromised convoy that is not yet threatened. Then roll the die for ULTRA, if applicable, using the appropriate "rule of 1/3" described below, to return the convoy to unsighted status and the corresponding pack to patrolling status.
  5. Move the convoys as described below.
  6. Move the packs as described below.
  7. Check for new sightings. Any unsighted or threatened convoy in the same square as a wolf pack becomes sighted, including ones that just became unsighted as a result of ULTRA.

- Packs move randomly, 1 square/day:
  - Pack nearest a compromised convoy heads for it.
  - Pack in a convoy's square stays with it until convoy is rescued.
- Convoys move East or West, randomly zig-zagging, every other day:
  - Convoys under attack don't zig-zag.
- siGiNT rules:
  - Roll dice for each new convoy (each convoy present at the beginning of the game, and each subsequent convoy starting out anew from the East or West edges of the board), consulting the fourth column of Table 4 to see if the convoy is compromised.
  - ULTRA takes a pack off the chase.
- Three "rules of 1/3":
  - A pack in a convoy's square has a 1/3 chance/day of starting to attack (a roll of 1 or 2 on the die).
  - A convoy under attack has a 1/3 chance/day of being rescued (a roll of 1 or 2 on the die).
  - During months with ULTRA, a pack has a 1/3 chance/day of being compromised (a roll of 1 or 2 on the die).

### 4.5. Rationale for the Chessboard Model

This area can be considered to have been 2000 nautical miles East-West and 1300 nautical miles North-South,[14] so on the chessboard it is 2000 by 1250 nautical miles if the squares are each 250 nautical miles on a side. Admiral Dönitz operated his U-boats in packs of about a dozen, and (as explained earlier) each U-boat could search about 5000 square nautical miles per day, so it is not too terrible an approximation to say a wolf pack can search a whole 62,500-square nautical mile square in a day. Nor, given the 10-15 knot speed of surfaced U-boats, is it horribly inaccurate to say that in a day a wolf pack can move from its square to any adjacent square. Convoys were roughly half as fast, and consequently move only on odd-numbered days.

The various statuses of the convoys and wolf packs mirror those of Table 1 and the associated discussion, except that a separate "shadowing" status is not needed because functionally it is only a protraction of the "sighted" status.

Historically, the Allies deciphered a great many messages when ULTRA was "on," but not all of them compromised U-boat plans, Each boat was subject to about one actual compromise per month [55]. Since we are dealing in packs of 12, each pack should be compromised about 12 times per month, or a third of a time per day.

The other rules of 1/3 are based on primarily on a reading of [49]: Conversion of a sighting to an attack, and prosecution of an attack, seem to average about three days.

The sequence of events in the model is at least as important as the numerical values it uses. The sequence has to be such that it will support the observed real-life events cited as examples above. Almost any sequence would have supported the existence of convoys that are never sighted, or that are sighted and undergo prolonged attack and eventual relief. But only by having steps 1-3 (score-keeping, conversion of sightings to attacks, and conversions of attacks back to unsighted convoys and patrolling U-boats) in the order given can we provide for attack that begins and fails immediately. Only by having steps 2-7 (SIGINT, movement of convoys, movement of packs, and checking for new sightings) in the order given can we replicate the instances in which a convoy was sighted and, before coming under

[14] [54. p. 22] describes the region of operations as extending from 40°N to 63°N, and from 10°W to 60°W. described as 4 million square miles, but these must be square *statute* miles; it is 2.6 million square nautical miles, being roughly 1300 miles in extent North-South and 2000 miles in extent East-West. The report says that convoys were to be found fairly uniformly within this region, which a plot of sightings makes plausible. It is also important that we use [54]'s idea of the area operations, because it is the same report on which we have relied for data on convoys' presence in there.

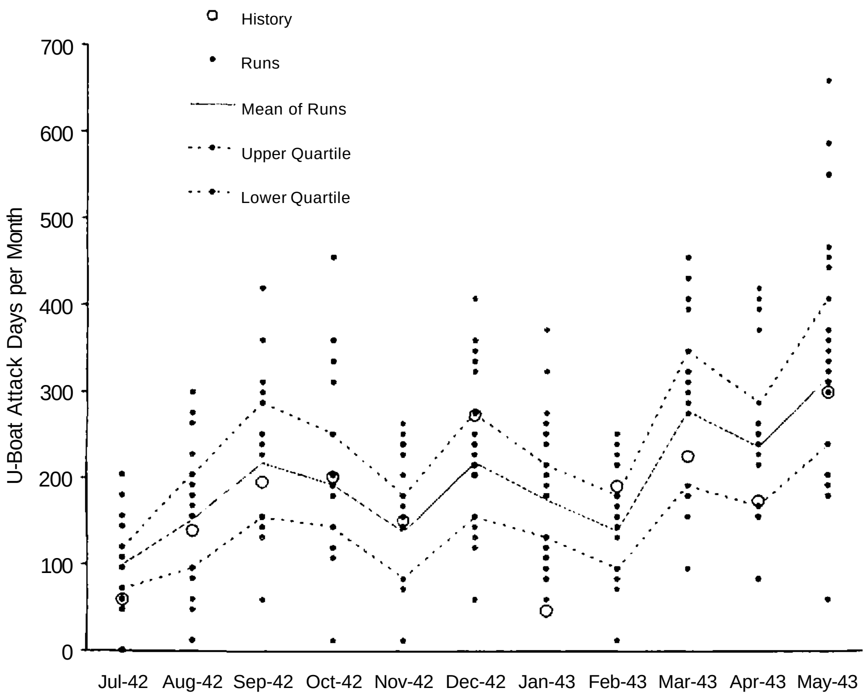


Figure 3. The chessboard model compared to history.

attack, evades the wolf pack, with its chances of doing so increased if it can make use of ULTRA-derived knowledge.

### 4.6. Validating the Chessboard Model

Just because the model has a good rationale doesn't mean that it is valid. Before we can use this model to conclude anything about signals intelligence, we must check that it replicates the results of the actual Battle of the Atlantic. We are fortunate that the historical cases include so wide a variety of input variables: If they were all similar, using them all would not be so very from using any one of them.

Though it can be fun to move the wolf packs and convoys around, it gets boring after a little while. I wrote a short computer program to do the same thing, and ran it 48 times for each month. The results are shown in Figure 3. The only difference between the computer program and the manual model is that the computer program uses the exact historical proportions of X-B compromise as shown in Table 3, not the dice-based equivalents of Table 4.

The model's average results are in many months cases quite close to the historical numbers of attack-days.

The dashed lines contain the middle two quartiles: half the model results lie between these two lines, another quarter above, and the last quarter below. If the random dispersion of the historical results mirrors that of the model, half the historical results, too, will lie between the dashed lines. This is nearly the case—7 of the 11 historical cases are amid the middle two quartiles of their respective months' model results, with another three cases lying just about on the interquartile lines. Nor is the model especially biased—the historical results lie on both sides of the model's median result. With the exception of January, the cases that lie outside the interquartile range do not lie so very far outside, and are not beyond the range delineated by the 48 trials. We may suppose that January can be explained by the paucity of daylight in that month (the variation in daylight being a factor not taken into account by the model), and/or by the severity of the weather (likewise not modeled, and reckoned as a cause of what the participants viewed at the time as a subpar performance by the U-boats [24, p. 91].)

These notions can be formalized statistically. See Table 6, which shows, for each month, the historical number of attack-days, the mean and standard deviation of the 48 runs, the "z-score" of the historical number (the difference between it and the mean, divided by the standard deviation), and the square of the z-score. Assuming (see below) that the results of the runs are normally distributed, the sum of the squares of the z-scores will be chi-squared distributed with 10 degrees of freedom. The chi-square test amounts to noting that the observed sum of the squares is not an improbable result tinder this assumption. In fact, if the distribution of the historical results were distributed identically to the model results (i.e., if the model were perfect, rendering the historical results no different from a 49$^{th}$ run),

**Table 6.** Statistical validation of the chessboard model against the historical cases.

| | Historical attack-days | Modeled | | History's z-score | |
|---|---|---|---|---|---|
| | | Mean | S.D. | z | $z^2$ |
| Jul-42 | 59 | 100 | 45 | -0.90 | 0.80 |
| Aug-42 | 139 | 152 | 76 | -0.17 | 0.03 |
| Sep-42 | 196 | 218 | 77 | -0.29 | 0.08 |
| Oct-42 | 202 | 193 | 87 | 0.11 | 0.01 |
| Nov-42 | 151 | 138 | 63 | 0.21 | 0.04 |
| Dec-42 | 274 | 219 | 80 | 0.70 | 0.49 |
| Jan-43 | 47 | 176 | 66 | -1.95 | 3.81 |
| Feb-43 | 191 | 140 | 56 | 0.92 | 0.84 |
| Mar-43 | 226 | 279 | 93 | -0.57 | 0.32 |
| Apr-43 | 174 | 237 | 83 | -0.76 | 0.57 |
| Mav-43 | 300 | 318 | 124 | -0.14 | 0.02 |
| | | | | Sum | 7.02 |
| | | | | Chi-squared *P*-value | 72% |

then by chance alone the observed sum of the squares of the z-scores would be exceeded some 73% of the time [35].

Comparison to the historical cases is not the only possible form of validation: In the last few years the defense modeling industry has finally begun to take validation seriously, and there is a growing literature on the topic [14, 29]. Other types of validation include confirmation that the input values are correct (we have cited support for them above already) and confirmation that changes in the input values cause the outputs to change in believable ways. We will see in the next section that the latter is the case. Another important form of validation is "face validation," the confirmation that, "on the face of it," the model appears valid to a knowledgeable examiner. The explicit presentation of the model above and the ability to examine the BASIC code itself[15] provide for this form of validation.

Thus we may place the chessboard model of the Battle of the Atlantic in the rather exclusive ranks of combat models that have survived a rigorous validation process. Of particular note is that the validation includes not only a validation of the mean, but also of the variance, of the results. This suggests that the real-world process displays a similar variance.

### 4.7. Observations

After the above validation and either doing some runs by hand or at least watching the graphic display run on the computer screen, we can make a number of observations.

- Simple models can work! One especially surprising aspect of the simplicity of this model (and of some used by the wartime operations researchers), is the "memorylessness" of the "rules of 1/3." Another is that the model's constants have only one significant figure.
- Unlike a regression model, the chessboard model contains no parameters chosen for the sake of a good fit. The search capability of the U-boats, the speeds of the U-boats and convoys, the "rules of 1/3," and so on are all based on facts about the campaign and not all chosen so as to make the attack-days come out right. The number of statistical "degrees of freedom" is *zero*.
- siGiNT comes into play quite a bit. In the next section, we will vary the amount of SIGINT in use, and see how-much difference it makes.
- Running the model, or watching it run on the computer, one may note that wolf packs spend a considerable amount of their time "shadowing" convoys (i.e., after having sighted them, moving along with them, but not yet attacking them); it helps the convoys greatly to be able to shake wolf packs at this stage.
- As Figure 3 makes clear, there is a substantial variation in the outcomes. You can play the same month several times and get very different scores. Because identical outcomes are portrayed by superimposed dots, what Figure 3 cannot show is the relative *absence of central tendency* in the outcomes. Figure 4 shows this dimension for the case of May 1943: While there is undoubtedly a central tendency, there is relatively little, with four values tied for being most frequent, the largest being more than double the smallest, and with the total variation in outcomes spanning more than a factor of ten. Statistically, the mean of the number of attack-days for the month is

[15] Available at http://www.kentaurus.com/mccue/, along with a stand-alone executable program.

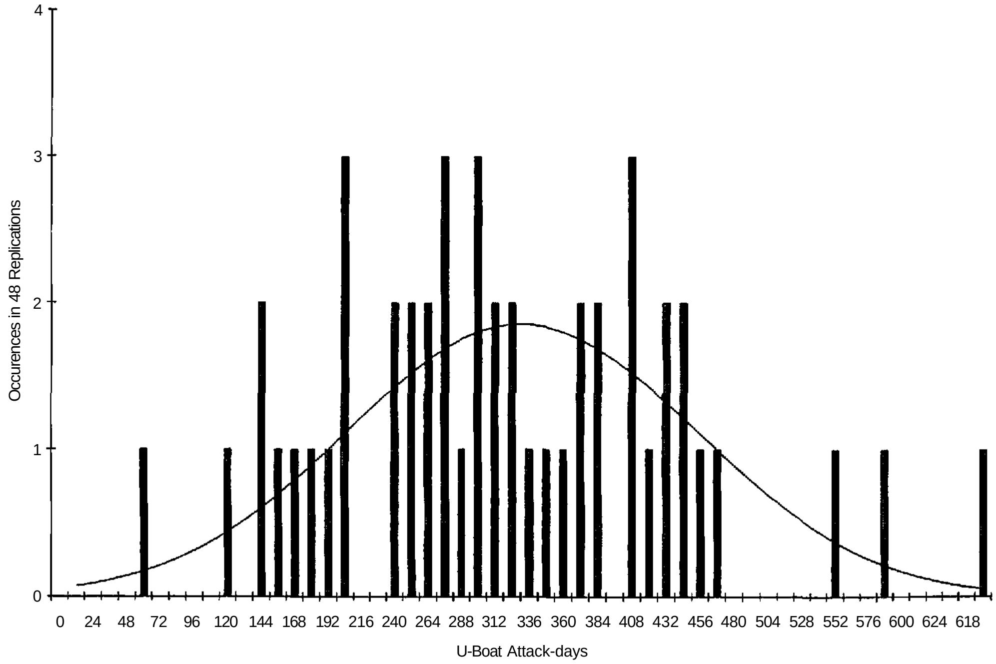


Figure 4. Histogram of modeled number of attack-days in May 1943 and fitted normal curve.

318 and the standard deviation is 124: with these parameters, a normal distribution fits nicely according to the chi-squared test. The large standard deviation indicates a large role for chance in the outcome.

## 5. RESULTS: THE INFLUENCE OF SIGNALS INTELLIGENCE ON THE BATTLE OF THE ATLANTIC

*What can we conclude from an exercise like this? We may at least be able to disprove a few notions that are themselves based on reasoning no more complicated than the checkerboard. Propositions beginning with "It stands to reason that..." can sometimes be discredited by exceedingly simple demonstrations that, though perhaps true, they do not exactly "stand to reason." We can at least persuade ourselves that certain mechanisms could work, and that observable aggregated phenomena could be compatible with types of "molecular movement" that do not closely resemble the aggregate outcomes that they determine.*

—Thomas C. Schilling [63, p. 152]

Having tested the model over a wide range of the possible input variables and found that it seems to be in accord with history, we are now ready to vary the data from their historical values and see what effect signals intelligence had.

### 5.1. Method: Compare "What-If" Results to the Model Base-Case Instead of to Reality

We will assess the effect of particular variables, such as the proportion of convoys compromised by X-B, by comparing the counterfactual cases to modeled cases. A reader might initially look at this comparison askance, wondering why the results of the model are not compared to reality instead of to other results of the model.

The reason is that the results of the model are averages of multiple runs, and therefore—assuming we accept them at all—do not contain the component of randomness inherent in a single historical number. Inasmuch as the runs display considerable variance, we have reason to believe—again, assuming that we accept the validity of the model—that the reality may contain a considerable component of randomness as well. Having made a model-reality comparison for the purpose of validation and having accepted the model (variation and all) as valid, we had best ihen investigate our what-if questions on the basis of model-model comparisons, not more model-reality comparisons [7].

Table 7 shows the historical levels of attack-days and sinkings by month, and the results of the historical base case and the various excursions considered below.

### 5.2. The Influence of X-B

First, we can rerun the model without any X-B compromises. (See Fig. 5, which also shows multiple no-ULTRA conditions,

**Table 7.** Summary of results.

| | U-boat attack-days (average) | | | | | | Historical merchant sinkings per U-boat attack day | Merchant vessel sinkings (average) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Historical | Modeled | No XB | No ULTRA | ULTRA only for evasion | No SIGINT at all | | Historical | Modeled | No XB | No ULTRA | ULTRA only for evasion | No SIGINT at all |
| Jul-42 | 59 | 100 | 44 | 100 | 104 | 44 | 0.12 | 7 | 12 | 5 | 12 | 12 | 5 |
| Aug-42 | 139 | 152 | 91 | 152 | 154 | 91 | 0.14 | 19 | 21 | 12 | 21 | 21 | 12 |
| Sep-42 | 196 | 218 | 142 | 218 | 206 | 142 | 0.10 | 20 | 22 | 14 | 22 | 21 | 14 |
| Oct-42 | 202 | 193 | 164 | 193 | 195 | 164 | 0.11 | 23 | 22 | 19 | 22 | 22 | 19 |
| Nov-42 | 151 | 138 | 100 | 138 | 143 | 100 | 0.19 | 28 | 26 | 19 | 26 | 26 | 19 |
| Dec-42 | 274 | 219 | 135 | 219 | 213 | 135 | 0.09 | 24 | 19 | 12 | 19 | 19 | 12 |
| Jan-43 | 47 | 176 | 97 | 224 | 175 | 132 | 0.15 | 7 | 26 | 14 | 33 | 26 | 20 |
| Feb-43 | 191 | 140 | 124 | 195 | 162 | 139 | 0.18 | 34 | 25 | 22 | 35 | 29 | 25 |
| Mar-43 | 226 | 279 | 172 | 312 | 329 | 221 | 0.21 | 48 | 59 | 36 | 66 | 70 | 47 |
| Apr-43 | 174 | 237 | 178 | 288 | 276 | 208 | 0.11 | 20 | 27 | 20 | 33 | 32 | 24 |
| May-43 | 300 | 318 | 235 | 354 | 335 | 247 | 0.06 | 19 | 20 | 15 | 22 | 21 | 16 |
| TOTAL | 1959 | 2167 | 1481 | 2392 | 2289 | 1623 | | 249 | 279 | 189 | 311 | 299 | 212 |
| Difference | | 0 | -686 | 225 | 122 | -545 | | | 0 | -90 | 32 | 20 | -67 |

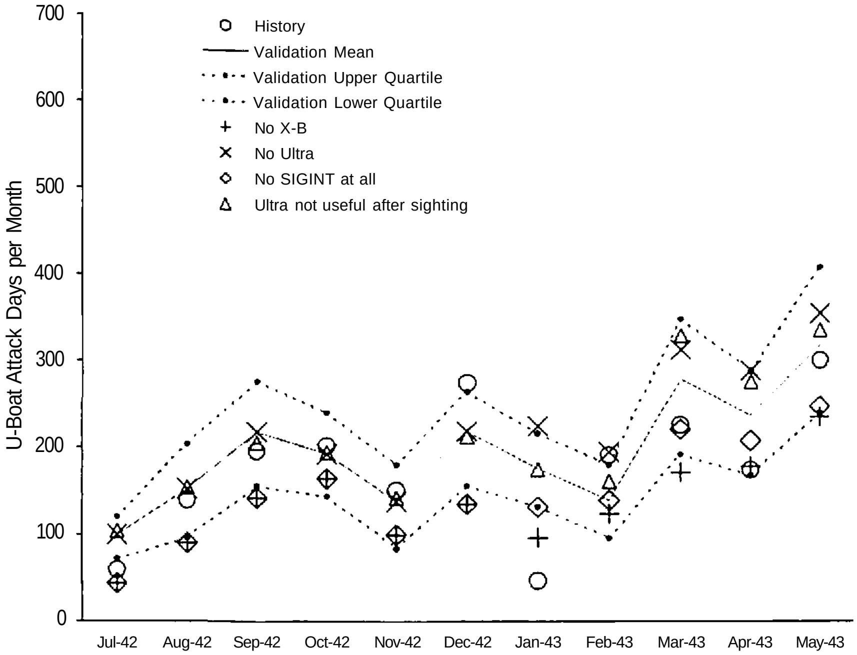


Figure 5. What-if SIGINT cases.

considered below.) Unsurprisingly, the number of attack-days goes down, usually to about a third its average modeled value. Adding the monthly averages and comparing the no-XB case to the historical base case, we find [48] attack-days as compared to 2167, a difference of 686. Taking each pack to be exactly 12 boats (and thus introducing a little round-off error, because the number of packs was found by dividing the historical number of boats by 12), the whole simulated campaign has 444 boat-months, so each boat is responsible for about 5.5 attack-days per month. Thus the extra 686 attack-days conferred by X-B is about 141 boat-months' worth. A given boat might be able to get to sea for 3 or 4 months in this 11-month period, so this is 36-48 boats' worth of help—comparable to the figure of 50 boats mentioned earlier.

Assuming (reasonably) that the monthly ratios of sinkings to attack-days would not be changed from their historical values by a change in X-B—nobody seems to think that X-B was useful to the U-boats in their actual prosecutions of the attack—we can convert the modeled historical case's attack-days into 279 sinkings and the no-X-B case's into 189, a difference of 90.

Temporarily considering the no-XB case to be par, we can make a graph showing the relative improvement conferred by adding the historical levels of X-B SIGINT back in. Figure 6 shows this relationship, with the least-squares trendline passing through the origin because of the truism that had there been no X-B. X-B would not have made a difference. The compromise of all convoys would have led to about a 95% increase over what would have happened with no X-B SIGINT at all, and the observed levels of compromise raised the number of U-boat attack-days by about 50% over what they would have been without any X-B SIGINT. Thus we may say that X-B SIGINT had considerable potential, and that it realized about half of this potential by being responsible for about a third of all attack-days (686 out of 2167) and sinkings (90 out of 279). This evaluation of X-B changes little if we compare the no-ULTRA case to the no-SIGINT case, i.e., if we examine the effect of X-B in the absence of ULTRA.

The regression model valued X-B much less, attributing about 200 attack-days to X-B [47].

But perhaps the most surprising feature of Figure 6 is that is shows no sign of any "saturation" effect: Contrary to the views of all the experts, the benefit conferred by X-B intelligence seems strictly proportional to the amount of X-B intelligence that is available.

In Figure 6, the merchant vessels are receiving the benefit of ULTRA in the historically appropriate months. If we make the same comparison, only without ULTRA (in both the with-X-B and the without-X-B cases), the result is nearly the same, except that X-B makes a little bit more difference. The difference is so slight as not to change the trendline, anchored, as it is, at the origin.

But this analysis is muddied by the fact that the numbers of convoys and wolf packs vary along with the proportion of convoys compromised by X-B. Later we will evaluate the contribution of X-B in another way.

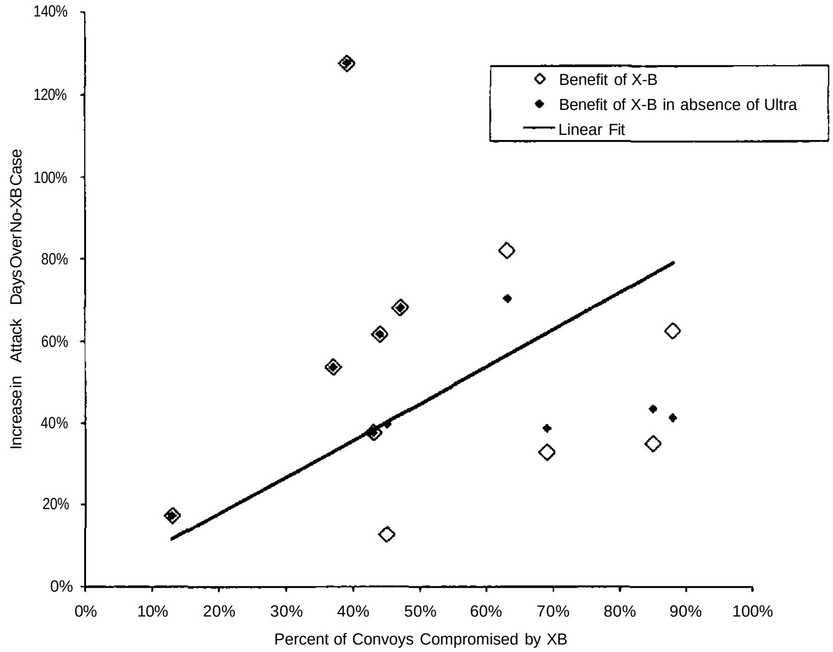


Figure 6. Influence of X-B compromise on attack-days.

### 5.3. The Influence of ULTRA

Running the model without ULTRA, we find that the U-boats gain 225 attack-days, by which they might get 32 extra sinkings. Of course, this all happens in the months in which there was any ULTRA to begin with. Though it is less than the effect of X-B—about 200 attack-days instead of almost 700—one must keep in mind that ULTRA was at work less than half the time.

The regression model credited ULTRA with preventing 425 attack-days [47],

One of our questions concerned the degree to which ULTRA (when available at all) helped by allowing convoys to escape from wolf packs that had sighted them, but not yet attacked. By altering the rules of the model so that ULTRA does not help in this way, we can gauge the contribution of this form of help. Without it, the U-boats score 122 extra attack-days, corresponding to the sinking of 20 extra merchant vessels—a substantial fraction of the overall benefit of ULTRA, but a relatively small change overall.

### 5.4. No sigint at All

Finally, we can consider the case in which there is simply no SKINT at all. This will allow us to investigate the idea of "feedback," namely that ULTRA'S primary utility lay in combating X-B, and/or vice versa. Consistent with what we have seen above, removing SIGINT altogether acts to the detriment of the Germans, costing them 545 attack-days, or 67 merchant vessel sinkings. It is not as drastic for the Germans as the uncompensated loss of X-B would be, of course, because in the no-SIGINT case the Allies are losing the benefits of ULTRA as well, but even in the periods with ULTRA, the net effect of SIGINT is in favor of the Germans.

But these findings are tied to the covarying historical numbers of wolf packs and convoys.

### 5.5. Nonhistorical Cases with and without X-B and ULTRA

So far, we have considered only cases that are, in effect, alternative histories: the historical base case, the no-XB case, the no-ULTRA case, and the no-SIGINT case. These are valuable points of reference, but they do not support an investigation of the role of signals intelligence in a fully satisfactory way because they remain attached to historical accidents such as the amount of X-B available in given months, and the overall trend towards increasing levels of X-B and U-boats at sea.

Therefore, it seems reasonable to work in terms of an "'average month," varying only the SIGINT and keeping the number of wolf packs and convoys fixed at some reasonable level. Four wolf packs and eight convoys is reasonable, and about average. Given these levels, it is easy ro vary the proportion of convoys compromised by X-B across the entire spectrum from zero to unity, with or without ULTRA. Again, I have taken the presence of ULTRA to mean that each wolf pack has a 1/3 chance per day of being compromised (see Figure 7).

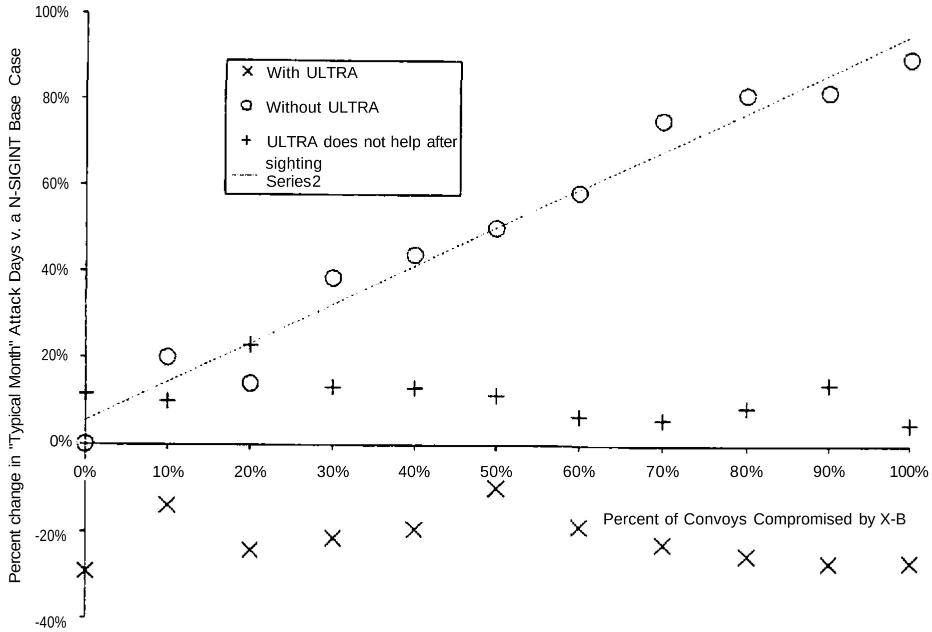


Figure 7. Effect of X-B and ULTRA on attack-days in an "average month."

As was suggested by the historical cases, there is no saturation effect, and complete X-B compromise leads to about a 95% increase in the number of attack-days—but only in a no-ULTRA environment.

ULTRA is able to nullify the effect of *any level* of X-B, as can be seen by the flatness of the graphs of the two with-ULTRA cases. Two cases have to be considered, because of the role of ULTRA in facilitating the escape of convoys once they are sighted. With ULTRA able to do this, it will save some convoys that were sighted without help from X-B. and will therefore reduce the number of attack-days to below the no-X-B level. Just to be sure that nothing untoward is happening, we can temporarily alter the model as mentioned above so that ULTRA does not help sighted convoys to escape. In this mode, ULTRA negates X-B as exactly as can be discerned on the basis of 48 runs. (The fact that the points associated with these runs tend to lie slightly above the horizontal axis is not a cause for alarm; it simply means that the average of the 0% X-B runs—used to position the horizontal axis—came in a little low, as is also suggested by the fact that the trendline's value for 0% X-B is somewhat higher than the 0% X-B point.)

## 6. COMMENTARY: THE EPISTEMOLOGICAL STATUS OF MODEL RESULTS

*War games and war problems have not yet been accepted by some; for some regard them as games pure and simple and as academic, theoretical, and unpractical. It may be admitted that they are academic and theoretical; but so is the science of gunnery, and so is the science of navigation. In some ways, however, the lessons of the game-board are better guides to future work than "practical" and actual happenings of single battles; for in single battles everything is possible, and some things happen that were highly improbable and were really the result of accident. . . . The game calls our attention to the influence of chance in war, and to the desirability of our recognizing that influence and endeavoring to eliminate it, when reasoning out the desirability or undesirability of a certain weapon or a certain method. . . . The partial advantage of the game-board over the occurrences of actual war, for the purpose of studying strategy, lies largely in its ability to permit a [number] of trials very quickly.*

—Rear Admiral Bradley A. Fiske [18, pp. 181-182]

The questions addressed in this paper have been addressed already by historians, whose answers do not all seem to agree. Part of this disagreement is illusory; it results from one historian addressing one portion of the war (e.g., the early period in which the Germans used the three-wheel Enigma machine, which the Allies were able to decipher routinely; the period considered in this paper; or the subsequent period in which the Allies had not only ULTRA but also escort carriers, allowing them to prosecute U-boats—and especially the U-tankers—as never before) while other historians address others. In such cases it is little wonder that different conclusions are reached. But even after paying close attention to such distinctions, controversy remains, and must lead one to wonder about historians' methods: how can practitioners of the same discipline, working from the same vast body of facts, arrive at such different conclusions? Because it is not clear exactly how historians make the link between their data and their conclusions, there is no way to tell how reasonable they are being when they cite X-B has having been of considerable aid to the U-boats, or take one side or the other of the case that ULTRA helped in re-routing convoys.

Apparently, after digesting a sufficient quantity of narrative, the historian feels that he or she has developed an intuitive appreciation of the goals, habits, and capabilities of the participants, and can thereby address collective issues that lie beyond the scope of any single narrative. Apart from its use of intuition, this approach strongly resembles the model-making approach that is the subject of this paper. But where the model-maker assembles facts into an explicit construct, and then undertakes a study of the construct, the traditional historian assembles his or her facts into a mental impression of the whole and then addresses collective issues through consideration of this impression [8].

This approach suffers from several defects: The historian's mental impression is not available for direct examination by others, and the creation and use of the mental impression allows for the intrusion of prejudice and unconscious assumptions,[16] Worst of all, there is considerable evidence that such mental impressions are quite fallible, especially in the very step of moving from the parts to the whole. Schelling [63] shows several examples in which most people's intuition fails them in predicting the society-wide impact of facts about individuals. Schelling's proofs are convincing: Some rely on simple arithmetic, others on simple models that can be worked out by hand on the kitchen table using pennies, dimes, and the like. For example, one of Schelling's models shows that even the weakest fondness for having one's neighbors resemble one's self (in whatever way—Schelling's pennies and dimes could represent any dichotomy of race, ethnicity, language, or denomination) will eventually result in segregated neighborhoods.

The belief that simulations—especially very simple ones—can yield useful discoveries about the real world remains controversial. Fischer, a great authority and a hero for addressing directly the question of the role of logic in historical reasoning, looks askance at the treatment of counterfactual conditionals, but reserves his greatest scorn for the results of wargames [17. pp. 20-21]. Can our chessboard results be meaningful? After all, they were made by playing with dice, and a few markers, or running a computer program—how can they confer any understanding of the U-boat war?

[16] So, too, does the mathematical model, but the avenues of invasion are fewer, and in any case the final product is available tor examination by others, which the mental impression is not.

### 6.1. Understanding the U-Boat War via the Chessboard Model

I maintain that the chessboard game can lead to a good understanding of the U-boat war, better than that obtainable by reading all the U-boat and convoy logs—though of course its creation has required that somebody else do so.

For example, consider the observation that the outcomes for an individual month (and condition of SIGINT) vary widely, i.e., that in any single outcome, luck has played a large role. Historians have difficulty perceiving the role of luck, because for them everything happens only once, and turns out just as it did. Comparing the results of different months (which also vary widely), they might come to suspect that luck plays a large part, but they could not sustain this belief in the face of all the other things that change from month to month, rendering no two alike: the numbers of wolf packs and convoys, the two sides' use of SIGINT, etc. The inevitable result is a tacit conclusion that everything had to turn out exactly as it did. The chessboard model pulls us away from this view of history as a "Just So" story.

To a considerable degree, such illumination arises as a side effect of the process of constructing the model. Koopman identified "mechanitis," defined as

> The occupational disease of one who is so impressed by modern [1956!] computing machinery that he believes that a mathematical problem, which he can neither solve nor even formulate, can readily be answered, once he has access to a sufficiently expensive machine. [37, p. 424].

Yet there are advantages to working with a computer as a colleague. The computer is unrelenting in its demand that details be thought out thoroughly. For example, we have seen the importance of whether or not an ULTRA warning could let a convoy escape U-boats that were already shadowing it. I have to admit that in several years of reading about the U-boat war and writing a book and several papers analyzing it, I had never explicitly considered the idea that ULTRA could cause U-boats to be "shaken" at this stage. Only when I set about writing a computer simulation was *1* forced to consider the processes of the U-boat war at such a detailed level as to bring this point into focus. After that, it was easy to pay attention while the model was running and notice that quite a number of "shakings" were occurring, and then to go back to the historical record and find instances in which this took place,[17] showing that I had made a correct choice in programming it to be possible.

### 6.2. Validity and Omission

Some might wonder how a model that leaves anything out (which is to say, any model at all) can give valid results. The model at hand obviously leaves a great deal out.

As in cartooning, much of the art of making computer models lies in knowing what to omit. In using the model or drawing lessons from it, one must exercise another art: knowing what kind of conclusion the model can support, and which it cannot. As of yet, there exists no mechanistic audit method allowing one to demonstrate that a particular model is fit to answer a particular question, and perhaps none is possible. One should be sought, but in the meantime the ability to discern the applicability of a given model to a given question remains a matter of judgement. It is possible to show rigorously that a given model is *inapplicable* to a given question, and models are accepted largely on the basis of how many such failures they have evaded. For example, if the chessboard model had failed to reproduce with some fidelity the facts of the historical test cases, we would have deemed it inapplicable to answering the what-if questions. One can also assess a model as inapplicable on purely logical, as opposed to empirical grounds. For example, the model at hand would be inapplicable to a study of the perennial question, "Would the earlier introduction of the Type XXI submarine would have materially aided the Germans?" Type XXIs' major advantage was in their submerged speed and the greater *tactical* capability it conferred; tactics are, in this model, totally subsumed into the ratio of attack-days to sinkings, which is an input and not an output of the model. To the degree that Type XXIs could move from place to place on an operational scale faster than could Type VIIs and Type IXs, the model is also inapplicable because of its resolution: The slightly greater speed of the Type XXI would still be rounded off to one square per day, the same as the other U-boats.

[17] On May 3, 1943, the convoy SC 128 eluded the boats of the combined *Specht* and *Star* wolf packs, which were sufficiently nearby that Admiral Dönitz had admonished them, "something can and must be achieved with 31 boats!" [21, pp. 154-155]. Admittedly, it did so on the basis of radio direction finding, not ULTRA, but direction-finding is not broken out as a separate process in this model. (See also the section on "suggestions tor future work.") On the other hand, radio-direction finding was sometimes used as a cover for decryption; On April 11, 1943, the convoy HX 232 altered course to avoid nearby U-boats allegedly revealed by radio-direction finding, but [66, p. 33] this information was in fact "obviously based on the decoded text of the order . . . setting up the patrol line."

### 6.3. Shortcomings Are Survivable

In this model, I have left a great deal out, intending, like a cartoonist, to capture the essentials without representing everything. Aspects of the real world that have been left out of the model include, but are hardly limited to, the following.

- U-boat types. The Germans used two main types of U-boat in this phase of the war, the Type VII and the larger Type IX. Each had multiple variants, but the model treats all U-boats as being exactly alike.
- Convoy types. In a convoy, all ships must move at the speed of the slowest ship. To counteract the inefficiency introduced by this constraint, the Allies organized ships into convoys according to speed, so that there would be fast and slow convoys. This distinction is elided in the model.
- Day, night, weather, seasons, and the Moon. In the model, sightings happen at the same range regardless of the time of day. In real life, more distant sightings could happen during the daytime, and less distant ones might be missed at night. The weather and the moon also influenced sighting and the prosecution of attacks, but are left out of this model. At the latitudes in question, the summer affords about twice as much daylight as does the winter.
- Fluctuation in the numbers of convoys and U-boats in the region of operations. In real life, these (especially the latter) varied a great deal over the course of a month. In the model, they latter vary not at all.

The reader will notice that each of these simplifications has the effect of replacing a variable with a constant. Even if the value of the constant—an average, in some sense, of the distribution of values taken on by the variable—has been chosen correctly, such changes will have the effect of reducing the variability[18] of the results generated by the model. Inasmuch as these already display a considerable amount of variance, it is important to recognize that a more complicated and correct model would display even more variance.

With an explicit model, we can be aware of the model's limitations, and we can be careful not to venture outside of the region in which the model is valid. For example, we know that in our model ULTRA only benefits the convoys by helping them to evade wolf packs and to escape from packs that have sighted them but not yet closed in for the attack, and not by reducing the number of wolf packs at sea. Thus our statements as to the utility of ULTRA related only to its

[18] And, in fact, the variance.

utility in permitting convoys to evade or escape wolf packs, and not to its undoubtedly large utility in limiting the number of wolf packs at sea (by sinking the U-tankers), which I addressed via a different model in *U-Boats in the Bay of Biscay* [44].

The historian runs a great risk of overstepping the bounds of his or her unstated and invisible model when attempting to estimate the importance of some "factor," e.g., signals intelligence, through imagining what would have happened had not the factor been present, and had all other things remained equal ([3], p. 263, and [33], p. 277ff). Typically the historian can make the case that the outcome would have been quite different had the factor not been present, and that therefore it was very important. The trouble with this method is that, applied across the board, it results in the conclusion that everything must have been very important. Nor is the premise that "all other things remain equal" likely to hold in the case of such large departures from the known: Without any X-B intelligence, might not the Germans have stepped up their efforts to spy at Allied ports, or taken more seriously the use of long-range aircraft to provide wide-area search? By drawing our conclusions based on lesser perturbations from the historical case, we are more able to assert that other things would have remained equal.

### 6.4. The Burden of Proof

Many automatically decry any use of modeling in the analysis of military matters, or any use of numbers in considering history. To most of the familiar litany of complaints, e.g.,[19]

- "Who needs these models when we have available to us seasoned military judgement?"'[20]
- "No mere numbers and no computer model can possibly capture the full richness of events"
- "Some people who use numbers have said remarkably stupid things"
- Etc.

one can simply point out that even alleged "seasoned military judgement" is based on some form of model, albeit an unstated and perhaps nonquantitative one, and that words and unstated models share the many of the defects as numbers (they don't capture the full richness of events either, people using them have said stupid things, etc.) and yet there are no complaints lodged against them.

[19] These are all voiced often enough that it would be churlish to identify any of them with any particular source. Such objections and discussions of them are to be found in [1] and [77].

[20] Seldom explicit is the codicil, "... like mine."

The balance of the litany reduces to:

- "Numbers convey a false sense of precision."
- "How can you learn anything from something that didn't really happen?"
- "The model contains some obvious shortcomings."
- "Anyway, you can't get anything out of a model that you didn't put into it."

1 very seriously doubt that anybody has ever actually said, of a model's result, "This answer came out of a computer, so you have to believe it." Yet many a skeptic has nonetheless protested, "Just because this answer came out of a computer, they think I have to believe it." The point on which the skeptics are unconsciously picking up is that the introduction of the model shifts the burden of proof to any who oppose its conclusions. It does so not because it comes out of a computer, or even because it uses numbers, but because it provides a logic trail that leads from the assumptions to the conclusions. The opposition must then either show that the assumptions are flawed or that the logic of the model is wrong, or else accept the result: They cannot in any honesty simply maintain, "we still like our ideas, and we're not interested in you or your model."

### 6.5. Models Codify Their Own Precision

One can point out the discussions of precision and assumptions that accompany this model. Nonnumerical methods lack the self-contained delimitation of their precision provided in the case of numbers by the concept of significant figures, and the lack of obvious shortcomings in the mental processes of historians and purveyors of "seasoned military judgment" is often more attributable to the nonexposure of these workings than to any lack of shortcomings, (e.g., historians' pre-1974 non-discovery of the "ULTRA Secret," or the disastrous military judgment early in the war that convoys were not to be used and instead the Navy should look for U-boats on the high seas with "offensive hunting groups").

As in the present case, models can also give a sense of the possible variation in outcomes, which the historians' "Just So" methods cannot do at all and the purveyors of seasoned military judgement cannot do systematically.

### 6.6. Theories, Models, Computer Programs, and VV&A

Theories, models, and computer programs are three different things, but they are frequently conflated. In the present case, the *model* is the chessboard setup and its rules and the computer program is a set of statements in BASIC. Today's emphasis on Validation, Verification, and Accreditation (VV&A) [14, 29] has in part served to highlight the distinction, inasmuch as Validation supposedly checks the model and Verification checks that the code is faithful to the model. But it is rarely acknowledged ([13] being an important exception) that, for validation to check the model, it will need something, presumably a theory, to check the model *against.*

In the present case, the *theory* is the body of mathematical work regarding searches developed during and shortly after the Second World War in, e.g., the works of Morse and Kimball [52], Sternhell and Thorndike [64], and Koopman [38]. Not much of the theory is used here, but enough: the common-sense notion that U-boats can inspect a region for convoys and find any that are present,[21] and the less intuitive notion that combat processes can, at some level, be represented by "memoryless" processes such as the rules of 1/3.[22]

A principal result of these distinctions is the light they shed on different stages of the work. The presentation of the project, then a work-in-progress, at the Wayne P. Hughes Tactical Symposium contained results that differed somewhat from those presented here, and an earlier draft contained yet a third set of slightly-different numbers. What was happening? Was I changing my theory of how the Battle of the Atlantic worked? No, nor was I even changing my model very much; mostly, I was debugging the computer program so that it more faithfully enacted the procedures specified in the model. In this I was greatly aided by a seeming "frill," namely, a graphical depiction of the action of the model. By watching it, I was able to observe, for example, that once in while two convoys would be under attack at once in July 1942, when there was only one pack at sea. This I traced to a bug that manifested itself if two convoys and a pack were in the same square at once on an odd-numbered day: Both convoys would get sighted, the following day would be even numbered (so the convoys did not move), and in one ninth of the cases both sightings would, under the rule of 1/3, convert to attacks, creating the anomaly.

While the reduction of the model to computer code should not alter the model, it can have the effect of making it more definite. Only through the process of turning the gamelike rules of the model into a computer program did I realize several important points about the rules, e.g., that it matters greatly in what order the rules of 1/3 are applied. If, for example, the die is rolled for rescues (turning "under attack" convoys back into "unsighted" ones) before it is rolled for attacks (turning "sighted" convoys into "under attack" ones, then each attack is guaranteed to last at least one day. Contrariwise, if the rules are applied in the opposite order then there is a 1/3 chance that an attack will end as soon as it begins. As noted in Section 2, some attacks (possibly as many as a third) really were abortive, so I chose the latter option.

I found another bug, under which wolf packs were being given the opportunity to find convoys both before the convoys moved and after. This amounted to saying that the packs could search two squares in one day, when even one is probably generous. This bug, though, was not really a bug at all, because it was a faithful replication of what I had written down in describing the rules of the chessboard model. But it was at variance with the wartime operations researchers' *theory* of search, or at least with their findings regarding U-boat capabilities. Accordingly, I stuck with the theory and modified the model and the program. As one might imagine, the effect was a substantial reduction in the number of U-boat attack days.

The partial resolution of another discrepancy between the model and the computer program, not really characterizable as a "bug," restored some of these attack-days, When enacting the model by hand, I—without really realizing it—tended to make sensible choices when assigning wolf packs to newly compromised convoys. In the original version of the computer program, a newly compromised convoy was duly assigned to the nearest wolf pack. After 1 created the graphical display, however. 1 realized that this is not always the right choice, because the nearest pack might be behind the convoy, and a more distant pack that lay between the convoy and its objective might be able to make the intercept sooner. So I added a somewhat more complicated choice-making routine for the wolf packs, which takes into account the direction of travel of the convoy.

[21] I would also include, at somewhere near the level of theory, some of the basic findings of the wartime operations researchers, such as the approximate area of ocean that a wolf pack could be expected to examine in a single day.

[22] Mathematically, these rules are "geometric" distributions, the discrete analogue of exponential distributions or processes. Wartime work readily showed that "random search" (e.g., casting about blindfolded) could be described as memoryless, and that real-world searches could often be characterized as "random" without much loss of accuracy. Even modest target motion so readily frustrates attempts by the searchers to be systematic that the searchers can be considered to be moving randomly with respect to the targets, making the memoryless exponential distribution fit the resulting distribution of search times. Game theorists addressed this problem, but it long went unsolved, as described by Isaacs [32], In 1979, Shmuel Gal [19] proved that memoryless search is a solution of the "mobile hider game" in the sense that a searcher can always do at least as well (in the sense of long-run averages) as he would if he were memoryless, and a savvy hider can always keep the searcher from doing any belter, though the result had already been in use for some time as a "folk theorem." In the real world and in Washburn's video-game-style experiments conducted with military officers, the random search model has usually provided a good fit.

### 6.7. You *Can* Get Out More Than You Put In

Taking a model to be (among other things) an explanation, a model such as that presented here differs from the historian's "mental model;' the statistician's curve fit, and some (but not all) versions of "seasoned military judgment," in that it starts elsewhere than with the events it seeks to explain: To arrive at attack-days, the chessboard model staits with distances, speeds, the distance at which a convoy could be seen, and so on.

Because it originated other than with values of the quantities it is designed to estimate, we were able to test it by comparison against those quantities. (Hence one wag's assertion that "a systems analyst is somebody who can fit a family of curves to a given point."[23]) The military man's unstated mental model might have this feature, but the statistician's mathematical model does not and the historian's mental model probably does not. The way in which the model conducts us from statements about U-boat density and speed, etc., through attack-days and to a rejection of the supposed "saturation effect" provides a good counterexample to the claim that "you can't get anything out of a model that you didn't put into it."

The point at which a Monte Carlo model is sufficiently complex to produce meaningfully "emergent" results is about the same as the point at which it becomes nearly impossible to debug: One has difficulty discriminating the emergent results from the manifestation of bugs. One solution, which I have attempted to follow, is to write so simple a model that it can be debugged by inspection. Another, which 1 have also followed, is to endow the model with a graphical output feature (however rudimentary), so as to allow it to be watched while in operation. (A well-known model of land warfare had such a feature added only after years of use, whereupon it was discovered that, unbeknownst to all, the program had been stacking up all the forces at a single point in the center of the battlefield!) More complicated programs can be written in modules, which each module tested separately, but this approach can only go so far, because some bugs arise from the interactions of modules. At that point, what one needs is some *theory.*[24]

## 7. SUGGESTIONS FOR FUTURE WORK

*I don't believe any game that can't be played as a parlor game.*

—Martin Shubik (quoted in [58, p. 260])

The work presented here answers the questions posed at the beginning, but it raises more questions and opens up avenues for future work. Some of these are suggested here.

### 7.1. More Validation

A further validation attempt could compare the model's computed attack-days resulting from hunts of compromised convoys, and its computed attack-days against other convoys, to the historical numbers of sightings resulting from each source. It could track the flow of events in the model and compare them to the history at a greater level of detail, e.g.. keeping track of sightings, the relative proportions of the various causes of broken-off contacts: arrival at the East or West extreme of the operational area, "rescue," or ULTRA-based escape from a sighting that had not yet matured into an attack.

### 7.2. Application to Another Period

The model could easily be applied to an earlier period in the war, 1941, during which prompt decryption of Enigma messages supposedly saved many merchant vessels. In the words of a prominent historian of the U-boat war:

> The outstanding success of 1941 was in the preventive area, made possible by a quantum jump in the quality of intelligence. It is possible to relate the ups and downs of the struggle in this period to the flow of ULTRA material, but there are so many other factors in play that the case seems Not Proven. At the same time there can be no doubt that informed evasive routing saved a large if unquantifiable number of ships, perhaps hundreds.
>
> [70, p. 231]

Quantification could be attempted with the chessboard model.

### 7.3. Application to Another Campaign

The American submarine effort in the Pacific was conducted quite differently from the German U-boat campaign in the Atlantic. Japanese convoys were small and lightly escorted. American submarines operated singly much of the time, and when the did operate in groups later in the war, the groups were small by Atlantic standards. The Americans apparently benefited from signals intelligence.

It would be interesting to make a chessboard model of the American submarine effort in the Pacific, or perhaps a

[23] The wag might even have had a U-boat-related example in mind, Figure 8 on page 109 of [64], in which convoys' losses are related to the amount of air escort provided to them and the speed at which the convoy moved.

[24] I am indebted to Timothy J. Horrigan for highlighting the role of theory in catching these bugs.

smaller region such as the Sea of Japan, validate it, quantify the contribution of SIGINT, and so on. A somewhat more ambitious model would be able to investigate the question of whether or not the Americans, for all the success of large German wolf packs in the Atlantic, were right to operate submarines individually or only in small groups.

### 7.4. Expansion of the Model

**It** would not be at all difficult to expand the model to include other critical components of the Battle of the Atlantic, such as the transits of the Bay of Biscay, the deployment to the Atlantic from Germany of new boats on their initial cruises, and the actions of the tanker U-boats. An outline of such an expansion appears in my book [44, p. 110]. The Bay could be represented by another chessboard, at reduced scale, where transits would probably have to be represented on an individual U-boat basis.

The advantage of this treatment is that it would introduce a realistic random element into the U-boat circulation model expounded in *U-Boats in the Bay of Biscay* [44]: The deterministic calculations in the book cry out for replacement by a stochastic model.

Incidentally, one expansion that 1 do not particularly recommend is the replacement of the model presented here by a model that treats the action in the mid-Atlantic on an individual U-boat-by-U-boat basis. 1 have created such a model, and while it works well, it has no particular advantage over the present model in which the wolf pack is the unit of account.

### 7.5. Use of Human Players

The computer-commanded U-boats and convoys usually behave fairly sensibly. The U-boats commit occasional "blunders," and there is certainly room to wonder if the convoys are really doing the best they could.

One way to investigate these questions would be to convert the simulation into a game that could be played by human players. Some people play such games for fun, and a site on the World Wide Web that afforded them the opportunity to play a U-boat simulation would doubtless attract many players, whose performance could then be considered as data in a later study. The Web would be the ideal venue for such a game, because some means of keeping the two sides from knowing the positions of each others' forces (except as revealed by sightings or SIGINT) would be needed. More laboriously, the game could be played in person, with the services of a referee, like the doubleblind variant of chess known as *Kriegspiel.*

### 7.6. Separation of Decryption from Direction-Finding

The model treats all Allied signals intelligence as having been ULTRA, which is not the case: radio-direction finding played a strong role, though the record is muddied by the fact that some reported uses of radio direction-finding were in fact covers for uses of ULTRA decrypts.

Functionally, the main distinction is that direction-finding reported current positions (while they were still current, so it was better than ULTRA in this regard), whereas ULTRA could be used to build up a picture of the future. At the cost of added complexity, the model could be made to distinguish between U-boats compromised by radio direction-finding and U-boats compromised by ULTRA. An important step, perhaps the most important step, would be to decide exactly how this distinction is to be reflected in the convoys' actions.

## ACKNOWLEDGMENTS

Wayne Hughes offered advice, and encouragement in a variety of forms. Others helped out as well. Robert Butterworth, who had helped materially by giving me a quiet place to work during an early phase of the project, also helped through useful comments on a draft. So did Michael Callaham, Dean Cheng, W.J.R. Gardner, Wade Hinkle, Timothy J. Horrigan, Arius Kaufmann, Andrew Marshall, Rebecca Ratcliff, Ronald Siegel, Alan Washburn, Christopher Weuve, and others. I didn't necessarily do everything they said to do, so responsibility for defects remains with me.

1 am grateful to Alan Washburn for inviting me to present an earlier version of this work at the Wayne P. Hughes Tactical Symposium, held 30 May 2000 at the U.S. Naval Postgraduate School.

The editor of Military Operations Research Society *Phalanx* and that of this publication kindly agreed with my request that [47] and this article contain some overlap regarding background and data.

My wonderful wife, Molly McCue, withstood the whole process.

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*The archive material on the German submarine campaign against British and Allied shipping in the Second World War is simply colossal. It may well be the most extensively documented campaign in all history, as befits its duration, spread, and complexity. [. . .] The vast documentation of the campaign has itself spawned a huge related literature.*

—Dan van der Vat [70, p. 385]

### A Note on Sources

Though the following include a number of what I would consider to be primary sources, secondary sources figure here as well. Historians generally look askance at the use of secondary sources. But if they hold secondary sources in such disdain, why do they continue to create them? I believe that the answer is twofold: First, secondary sources can be better than the primary sources on which they are based, through the resolution of contradictions and the like; second, secondary sources are written by historians for the use of others. I am not a historian, so I am one of these "others," and I am using secondary sources.

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