JAMES T. MILLER and EUGENE W. G. DAVID

BATTLE GROUP GRIDLOCK DEMONSTRATION

Gridlocking is a process for aligning the coordinate systems, called grids, that Naval ships and aircraft use for representing the positions of targets during data exchanges within a Battle Group. Alignment, or gridlock, is achieved by comparing the positions, generated by different Battle Group elements, of commonly observed physical targets and then using the differences in these positions to compute corrections to be applied to subsequent target positions reported over data links. Such a capability is fundamental to the unambiguous exchange of targeting data among Battle Group ships and aircraft and, consequently, to the effective use of Battle Group antiair warfare combatants.

INTRODUCTION

To coordinate the antiair warfare forces within a Battle Group, each combatant of the Battle Group requires an accurate, comprehensive, and reliable radar air picture of the battle area. This picture describes the tactical situation and provides a precise identification of each of the radar targets to each of the participants in the Battle Group. Availability of a complete air picture to each ship or aircraft in the Battle Group not only promotes the effective, coordinated antiair warfare activities of the individual combatants but also supports the dissemination of coordinating directives, situation reports, results of actions, and intentions to others in the Battle Group.

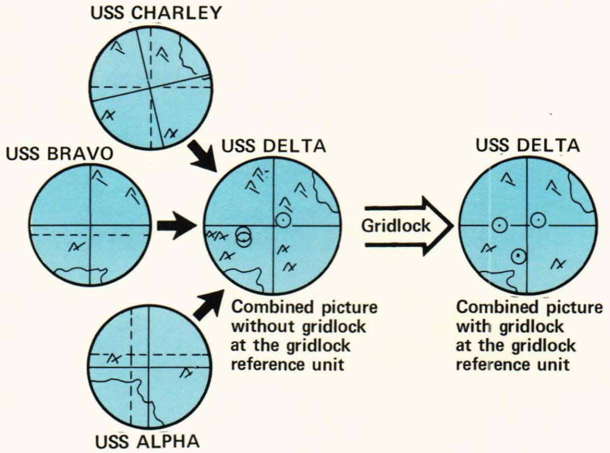

Figure 1 — The three images on the left show the Plan Position Indicator (PPI) pictures developed by three ships or aircraft using their own radar sensors. (The dashes represent true coordinate frames.) The center PPI picture would be the result of integrating these data as seen by the Gridlock Reference Unit without proper coordinate frame alignment, i.e., without gridlocking. The PPI picture on the right represents the resulting picture when gridlocking is properly applied.

In today's Fleet, such a picture is formed by integrating track[1] data on targets observed by the radar suite on each ship or aircraft with track data obtained via the tactical digital data link from radar suites on other combatants. Under ideal conditions, the remote data may be incorporated directly into a ship's or aircraft's data base to complement its surveillance ability, providing data in regions inaccessible to it because of geometry, countermeasures, or limitations of its own sensors. Under realistic conditions, however, such integration is difficult because of numerous navigational and radar biases (i.e., systematic errors) that degrade the data exchange process. If these biases are not corrected, the track information received from remote radars for a particular physical target and the corresponding track information from ownship radars will not align spatially. If remote tracks are sufficiently misaligned when compared with ownship tracks, one target may be erroneously identified as several targets, as illustrated on the left side of Fig. 1. Such situations consume computer processing, personnel, and data link resources, and can lead to an overengagement of the target (i.e., too many Battle Group weapons used against the target). Under other conditions, with sufficient misalignment, two or more tracks may be mistakenly identified as one target, which can result in an underengagement of the target. Clearly, both situations cause an erroneous air picture to be propagated through the Battle Group processing and decision chain, with the attendant potential for an inappropriate response to the actual tactical situation.

To remove these biases, a function is provided in the data exchange process between Battle Group ships and/or aircraft that assesses the misalignment between the remote and ownship track data and provides corrective transformations to bring these local and remote tracks into alignment, as shown on the right side of Fig. 1. When the corrections are properly performed, the corrected remote data set can be used (as in the ideal case) to enhance the effectiveness and coordination capability of the Battle Group. The process that performs this alignment is termed *gridlock*.[2]

GRIDLOCKING CONCEPT

To understand how gridlocking works, consider the analogy of a mechanic adjusting the timing on a car. At the instant the sparkplug on cylinder number one is fired, the mechanic, using a timing light, measures the difference in position between a small timing mark on the engine crankshaft pulley and a corresponding mark on the engine block. If the two marks do not appear to be aligned, the mechanic rotates the distributor until the two marks line up, indicating proper timing of the engine.

Gridlocking works in much the same way. The differences in the remote and local track positions of a given target are measured at a selected time and compared. Based on several such comparisons, the gridlock algorithm adjusts the coordinate transforms (the formulas used to transfer a set of points from one unit's coordinate system to another) until the two track data bases (local and remote) are precisely aligned, thus minimizing the positional differences between targets that have been tracked by both local and remote radar sites. Whereas the mechanic measures one parameter (the distance between the timing marks) and adjusts one parameter (the distributor position), the gridlock process measures several parameters (e.g., X and Y positional differences) and adjusts several other parameters (e.g., ownship position or the north alignment of ownship coordinate frame) to effect the desired alignment.

These adjustments are made by using the track positional differences to estimate corrections to the parameters adjusted. In the jargon of the Naval Tactical Data System (NTDS),[3] these corrections, estimated by the gridlock function, are called *pads*. During link data exchanges, the pad values are used to align track positions received or transmitted over the link. The number of pads needed depends on the type of misalignment (translational, rotational, etc.) between the remote and local data sets.

In a multiunit Battle Group, rather than combatants aligning to each other, the gridlock process is simplified so that only one alignment is required. In particular, one combatant in the Battle Group is chosen as the standard, called the *Gridlock Reference Unit* (GRU), and all other combat systems are required to align to it. Data transmitted over the link are first aligned to the GRU by applying the transmitting unit's pads. Because all track data on the link are aligned to the GRU, the receiving ship or aircraft, knowing its own relationship to the GRU from its own computed pads, performs the reverse process; i.e., it brings the received link data (from all others in the Battle Group) into alignment with its own data base. Thus, only one set of pads is required for any combatant to communicate with any other.

Note that this process leads to a situation where all the track data on the link are aligned to the selected standard, i.e., the GRU coordinate frame. Because the GRU coordinates may be in error when compared to an absolute geodetic frame, such a process is termed *relative alignment* or *relative gridlocking*. To bring this GRU coordinate frame (and, consequently, the link data exchanges) into geodetic alignment, additional navigational data inputs are required to determine the relation of GRU coordinates to the geodetic coordinates. Such a process is termed *geodetic gridlocking*.

Because of its minimal need for navigational information, relative gridlocking provides a Battle Group with the ability to perform precise data exchanges even in the event of navigation system failure. Indeed, when performed properly, relative gridlocking can provide high-precision alignments with navigational suites currently available. In particular, the current implementation of gridlock by NTDS is a relative gridlock process.

THE CURRENT IMPLEMENTATION

The current implementation of the gridlock process in the shipboard computers by NTDS was originally driven by the requirements of manual tracking of radar targets and the limited computational resources available in the 1950's. As a result, the quality of the alignment achievable in the current implementation is limited to that which was acceptable when it was designed. For example, because of other demands for limited computational and manual resources involved in NTDS, pad estimation is performed infrequently (every 30 to 45 minutes or whenever a major error is observed on the Plan Position Indicator). Also, because the actual alignment can shift significantly with time, sizeable misalignments are observed even when the gridlocking function is performed properly.

Furthermore, when pad estimates are made, only limited amounts of track data are used, principally because the current process (including tracking) is manual. As a result, random fluctuations in the position of the tracks are not averaged out by the current pad estimation process, and erroneous pad values may be generated. Also, theory indicates that if a spatially diverse set of mutual tracks is not used, the individual biases may not be resolved adequately, which can lead to inappropriate corrections for new tracks that enter the system.

To be accurate, the gridlock algorithm design should accommodate all of the biases in the data base. The current NTDS gridlock process incorporates the ability to estimate constant X and Y translation biases and, in some cases, constant rotation biases. Actual evaluations of radar data between two sites indicate that these three biases are insufficient to assure precise alignment, as will be discussed later. As a consequence, the current NTDS design is limited in the quality of alignment it can achieve.

Finally, and very important from the user's point of view, the NTDS implementation has no way to assess the quality of the alignment actually achieved. For example, an operator is provided with a display of the pad values actually used, but he has no way to judge if they are the correct pad values. Therefore, some measure of effectiveness of the gridlock process is needed to support higher-level coordination and control decisions.

GRIDLOCK IMPROVEMENT EFFORT

As the nature of the naval threat has evolved, requirements for precision alignment to support weapons coordination have increased. Fortunately, the introduction of automated radar tracking systems and high-speed minicomputers, developed in response to the changing threat, now make it practical to improve gridlock.

Because of these developments, APL initiated a development effort through its Battle Group Antiair Warfare Coordination (BGAAWC) Program under the direction of the AEGIS Shipbuilding Project (PMS-400) of the Naval Sea Systems Command, to demonstrate substantial improvement in the current gridlocking process. The goals of the gridlock development are to raise the quality of gridlock alignment achievable by current Fleet combatants to a level comparable to the accuracies of their radars and, when combined with other improvements, to significantly improve the weapons coordination capability of today's Fleet.

These goals will be achieved through a series of steps, culminating with a demonstration of precision gridlocking at sea with operational equipment during normal Battle Group activities. The demonstration will consist of an actual alignment of one ship's combat system, the Gridlock Demonstration Unit, with another ship acting as the GRU. This will be achieved by a small equipment suite installed on the Gridlock Demonstration Unit and by appropriate changes on the GRU. Extension of this demonstration to other combatants will require similar suites on each added ship or aircraft.

Currently, the development of a Gridlock Demonstration System is directed towards refining the intra-Battle Group or relative gridlock capability, first on shipborne platforms and then on airborne platforms. A follow-on effort is aimed at extending this relative concept to geodetic alignment by the use of navigational data and track information on cooperating ships or aircraft in support of track data exchanges with other Battle Groups, shore stations, satellites, etc. The primary effort to date, while dedicated to relative gridlock improvement, is guided by the anticipated expansion to the aircraft and geodetic applications.

The gridlock improvement effort consists of four tasks:

1. *Concept Development, Assessment, and Analysis*—development and assessment of various techniques for accomplishing the desired alignment and provision of necessary analytical support for the conceptual design;
2. *Data Collection and Reduction*—collection and reduction of simultaneous track data from multiple sources for quantitative assessment of biases in operational systems and for experimental validation of candidate algorithms;
3. *Data Analysis*—development and design of improved gridlock bias estimation and correction techniques using collected data; and
4. *Implementation*—design, implementation, and evaluation of the concept in an open ocean environment with existing operational systems.

Each of these tasks will now be described in more detail.

Concept Development, Assessment, and Analysis

The general objectives of this task are to develop and assess a gridlock improvement concept and to generate supporting analysis. In particular, consideration of the requirements of the gridlock process, the structure of the current intraforce link (i.e., Link 11), and various limitations on existing ships and aircraft leads to a system concept design for the demonstration outlined in Fig. 2. For this design, a minicomputer (AN/UYK-20) is placed between the current NTDS combat system computer elements and the tactical data link terminal. By disabling the current gridlock process in NTDS (a simple manual procedure), the gridlock minicomputer can perform all the functions necessary to align both the transmitted and received track data.

Estimation of the pads is performed in the gridlock computer by using ownship track data obtained through an interface with the ship's tracking computer (to ensure availability of the maximum number of common tracks, i.e., tracks observed by both ships) and the corresponding remote GRU tracks obtained over the tactical data link. This interface is required because NTDS restricts the number of ownship tracks transmitted over the link and therefore available to the Gridlock Demonstration System. Note that in this configuration, only tracks received from NTDS are actually transmitted to the link. The gridlock computer then

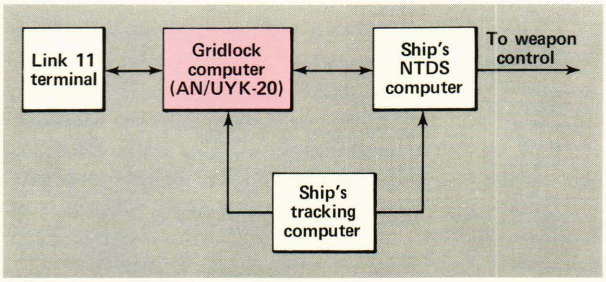

Figure 2 — By inserting a minicomputer between the shipboard NTDS computer and the communication Link 11 terminal, both the gridlock error estimation and Link 11 data correction processes can be performed without modifying either system. However, to assure that all ownship track data are available to the gridlock computation (not all ownship data are transmitted over Link 11), a separate interface is required to the ship's tracking computer.

1. Determines which tracks in the ownship files are common with tracks from the GRU;
2. Computes new pad values based on differences between the GRU and the ownship data by use of these common tracks;
3. Computes and applies the necessary corrections to the track data exchanged over the link.

In this process, the entire data set of common tracks is used. Each common data point is weighted with a software Kalman filter[4] algorithm, so that random fluctuations in individual track data will not overly influence the error estimates. In addition, the computer assesses and displays the quality of alignment actually achieved and provides for the data extraction necessary to assess and document the demonstration.

The result is a completely automatic gridlock alignment that is free from operator interaction and error. Moreover, it is maintained continuously so that drifts in the pad estimates (because of movement of the units or calibration shifts) will be compensated for as they occur. Finally, it requires no modification to the NTDS combat system or to the tactical data links, except for small procedural changes.

Data Collection and Reduction

Because so little information was available on the actual biases present in shipboard data, the data collection and reduction task was initiated to determine actual biases, to test analytical approaches to estimating corrective pads, and to test the computer programs to be used in the Gridlock Demonstration System. For the collection process, three-dimensional radar digital data recorders were installed at two spatially separated sites in the Washington, D.C., area. Processed radar video data (from available aircraft target returns) were digitized and recorded simultaneously from both sites. Digital data tapes from both sites were then reduced by APL. The reduction process is illustrated in Fig. 3.

Each digital radar tape was processed through an automatic tracking system at APL. This involved (a) centroiding, which estimates the mean angle in elevation and bearing as well as the mean range using the digitized radar returns for each target; and (b) tracking, which differentiates targets from radar clutter and estimates movements (speed and heading) based on successive radar returns from the target. Outputs of the tracking process were saved and the results for both sites time-aligned by using synchronizing time marks stored on the tapes. The data from the sites were then correlated to form a comprehensive data base of the track picture observed at both sites.

Figure 4 is a plot of data collected over a half-hour period during a cooperative effort between the Naval Research Laboratory's (NRL) Chesapeake Beach Facility and APL, using AN/SPS-39 radars at both sites. Future plans include a similar data collection at sea with operational AN/SPS-48C radars (a more modern three-dimensional radar), E-2C aircraft, and AEGIS AN/SPY-1 radar systems.

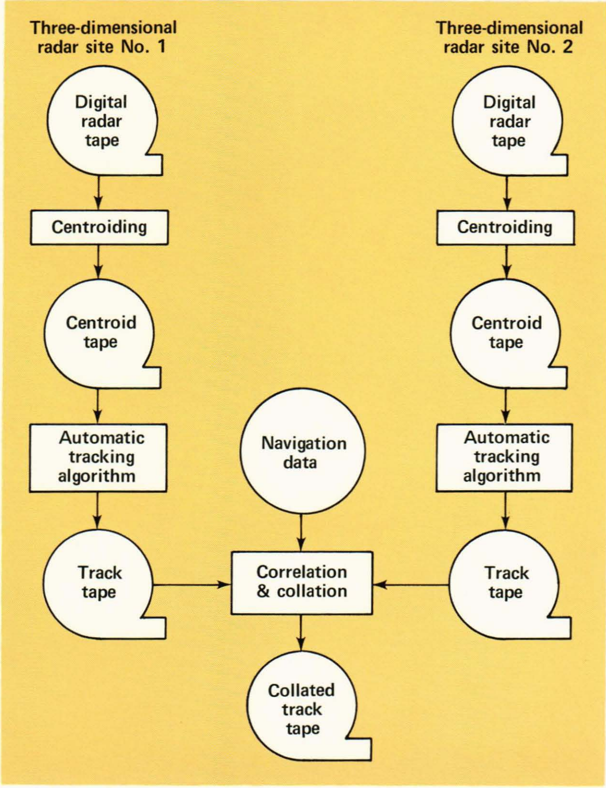

Figure 3 — To evaluate the magnitude and nature of the biases in an actual Naval radar system and to provide a basis for evaluating gridlock algorithm design and implementation, simultaneous radar recordings are made at two sites. The recordings are processed off-line to develop simultaneous track data bases. The track files are then correlated and collated to provide a simultaneous track picture seen by both sites.

Data Analysis

One of the purposes of the data analysis task is to evaluate the nature and magnitude of the biases to be expected in the radar data. Because biases are manifested as differences in the parameters of the tracks observed by the two sites for the same targets, parameter differences for correlated track pairs were studied. Figure 5 shows a sample plot of the azimuth difference between the NRL tracks translated to APL and the correlating APL track as a function of the bearing of the APL track. This plot shows quite clearly the presence in this data base of sizeable biases in bearing that are bearing-dependent. Such biases had not previously been considered in the development of gridlocking systems.

Another part of the analysis task is to assess the effectiveness of various bias estimation techniques, primarily by measuring the quality of alignment achieved when the pads estimated by a particular technique are applied to the correlated track data. One method of assessment is by means of a visual presentation of correlated tracks observed by two

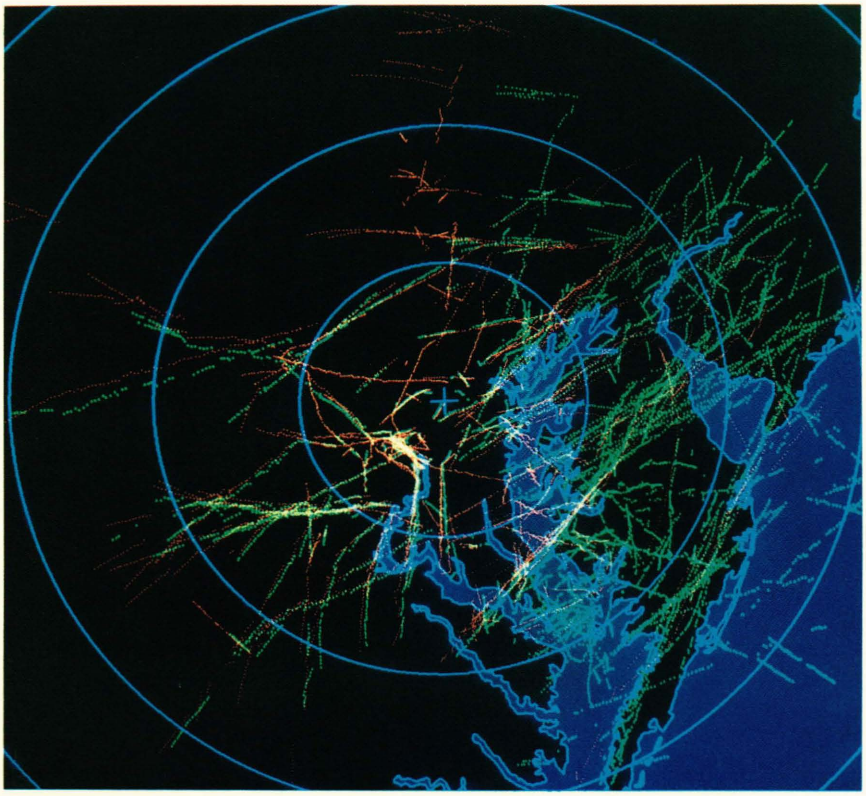

Figure 4 — The results of reducing simultaneous track data collected over a half-hour period from the NRL (green tracks) and APL (red tracks) are shown. Range rings are at 40-nautical-mile intervals from APL (center); the NRL site is at 35 nautical miles and 149.6° relative to APL. No gridlocking has been applied in this picture. The misalignments that can be seen between the red and green tracks are the result of radar misalignments since the precise positions of the two sites were known. Note the large number of tracks to the east detected by NRL but not by APL. They are a consequence of blanking conditions imposed on the APL radar to minimize electronic interference. Similar conditions can be seen to the west of APL for the NRL data.

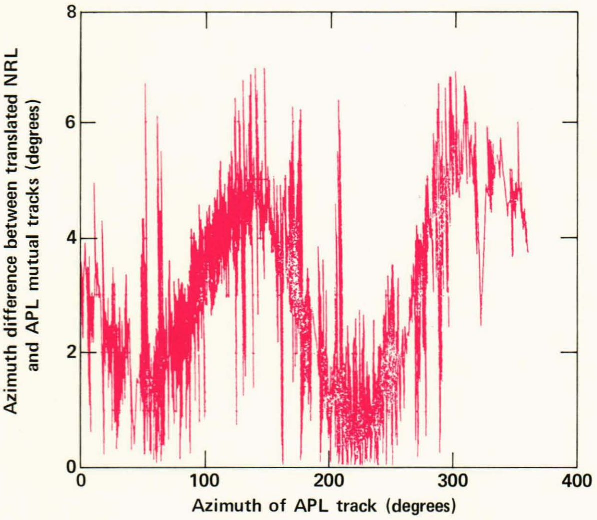

Figure 5 — Azimuth errors observed when NRL and APL data bases are compared in the APL coordinate frame. This plot shows the azimuth difference between NRL tracks translated to APL and the corresponding APL tracks as a function of the azimuth. These types of biases are not accommodated by current NTDS algorithms, indicating the need for improvements in the current design.

sites. Figure 6 is a sample presentation of the correlated NRL and APL tracks observed east of APL; Fig. 6a shows uncorrected tracks and Fig. 6b shows gridlock-corrected tracks. The alignment demonstrated in Fig. 6 is for a Kalman algorithm that estimates seven pads: X,Y translational pads and velocity pads (these rates pertain to the airborne gridlock design), a constant-bearing pad, and two pads associated with the previously described biases in bearing that are bearing-dependent (Fig. 5).

A quantitative evaluation of the alignment achieved by three techniques is given in Fig. 7, in which the average distance between correlating tracks during each scan is presented for the same data period shown in Fig. 6. This average distance between mutual tracks is one measure of the effectiveness of gridlock alignment being used in the Gridlock Demonstration System. The top curve represents this average distance evaluated for NRL data translated to the APL location, using precise curved-earth coordinate transforms based on the known site locations but without gridlock alignment. This plot illustrates the best quality of radar alignment that could be achieved with the most precise navigational information available today, given the types of radars used in this experiment.

The middle curve in Fig. 7 is a plot of the same average distance after correction by means of pads derived from an optimized algorithm similar to the current NTDS algorithm. (This does not accommodate the bearing-dependent biases.) The bottom curve represents the Kalman algorithm used in Fig. 6. The bottom curve is comparable to an estimate of the root-mean-square sum of the measurement noises for the two radars used; thus, because this approaches the theoretical limit for this estimating process, further refinement was not pursued. In addition, experimentation indicates that this algorithm converges rapidly — typically within 50 iterations (e.g., five

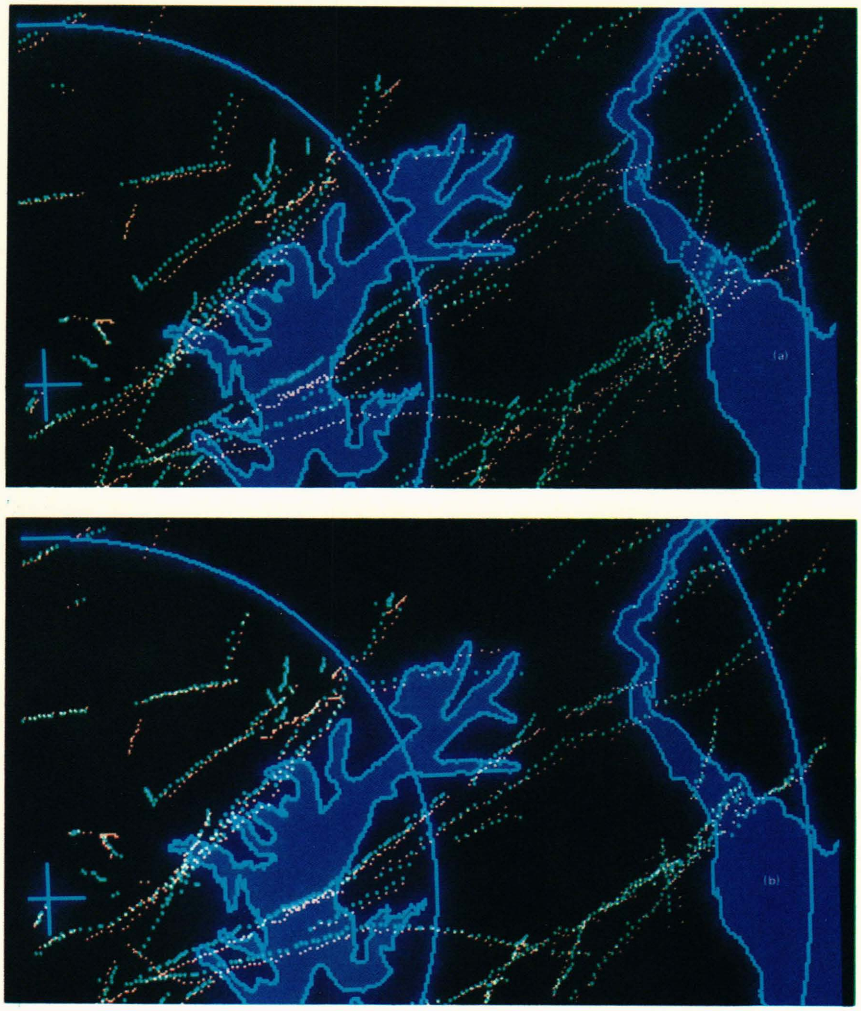

Figure 6 — These *before* (a) and *after* (b) enlargements of the correlated tracks in the region east of APL illustrate the effects of gridlocking. NRL tracks are shown in green and have been translated to APL by using exact curved-earth coordinate transforms. APL tracks are shown in red. The misalignment in the uncorrected (ungridlocked) data is obvious. For the corrected data, the improvement in the alignment is dramatic. False correlations in the corrected data base, however, are evident. Misalignments can also be observed near the ends of corrected tracks as one site loses contact with the target but continues to extrapolate its position sufficiently to maintain a rough correlation with the other site track.

link updates from ten common track pairs or ten link updates from five common track pairs). Hence it was selected for the at-sea demonstration system.

Finally, these algorithmic techniques have the advantage that they require no navigational input, except for rough initial estimates, as long as mutual tracks are available. This permits precise data exchange in the absence of external navigational aids. Navigation data are required, however, to maintain the alignment during periods when no common data exist between the two sites or during the possible extension to geodetic gridlock.

Implementation

Implementation of the at-sea demonstration system encompasses equipment acquisition, computer program development, and testing necessary to prepare and operate the Gridlock Demonstration System aboard ship. Figure 8 presents the equipment configuration for the current Gridlock Demonstration System design. The equipment in the shaded area is required for the actual operation of the system. The other equipment is required for documentation and control of the demonstration. Only one Gridlock Demonstration System suite is required because the GRU needs no gridlock function.

Development activities at APL include development of the demonstration system as well as of a wraparound simulator, i.e., a computer that simulates all the interfaces (both inputs and outputs) necessary to evaluate the detailed computer program design and that permits the introduction of recorded radar data. Subsequent activities include testing between land sites and between land site and ship. These tests will use the facilities of the Fleet Combat Direction Systems Support Activity (FCDSSA) at Dam Neck, Va., and various ships in the area. The final testing process entails the installation of the Gridlock Demonstration System aboard a ship, followed by a series of tests, first with the land-based FCDSSA facility and the AEGIS Combat System Engineering Development Site at Moorestown, N. J., and ultimately with another ship at sea. Data collected during these demonstrations will be returned to APL for evaluation.

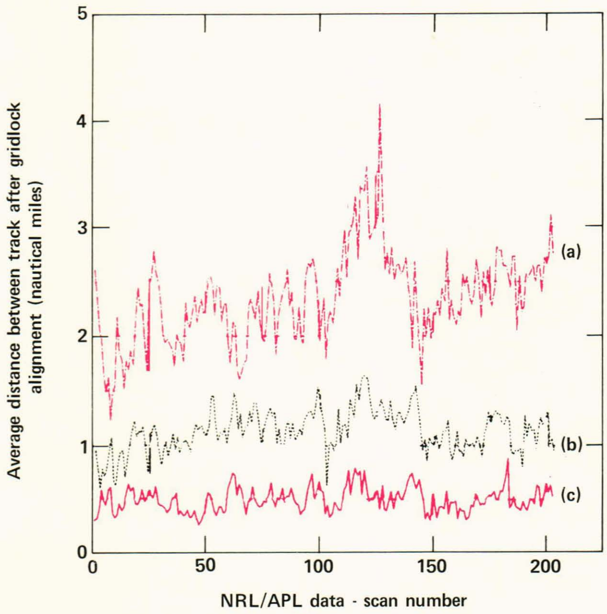

Figure 7 — To quantify the differences in alignment quality achieved via various gridlocking techniques, the average distance in nautical miles between NRL tracks translated to APL and APL radar tracks was evaluated for each scan. Plot (a) illustrates this distance for navigational alignment only, i.e., the known geodetic positions of both sites that were used to align the two data sets. No other alignment correction was applied. Plot (b) illustrates the quality that could be achieved with a properly redesigned NTDS algorithm, which corrects for constant translational and rotational biases only. Plot (c) illustrates the alignment achieved when an algorithm accommodates the bearing-dependent biases as well as translational and rotational biases. This value is comparable to an estimate of the measurement noise for the AN/SPS-39 radar used; thus, it represents essentially the statistical limit that could be achieved with these data. Fluctuations in these curves are a consequence of measurement error of the radars and the variations in the spatial distributions of the tracks observed.

CONCLUSION

It is essential to rapidly distribute precise radar track information on threats confronting a Battle Group to all ships and aircraft of the Battle Group in order to coordinate the individual combatant's responses to the threats. As the relationship between the threat data distributed and the response required of the Battle Group has evolved, the need for tighter Battle Group coordination has emerged. This has, in turn, increased the requirement for precise data exchanges to ensure effective employment of the Battle Group. Fundamental to meeting these requirements is the improvement of the data registration, or gridlocking, of the individual combatant ships and aircraft.

Experiments conducted with APL and NRL equipments have indicated that significant improvements in the quality of gridlock alignment can be achieved by properly utilizing track data generated by the automatic tracking systems currently being introduced into the Fleet. Further, these improvements can be realized, at least for the intra-Battle Group problem, without having to upgrade greatly the navigational capability of ships and aircraft to modify the current data links or tactical data systems. Once implemented, the improved gridlock system should be realized with a minimum of operator intervention. Alignment can be maintained continuously and automatically thereafter, without operator burden, as long as common track data are available.

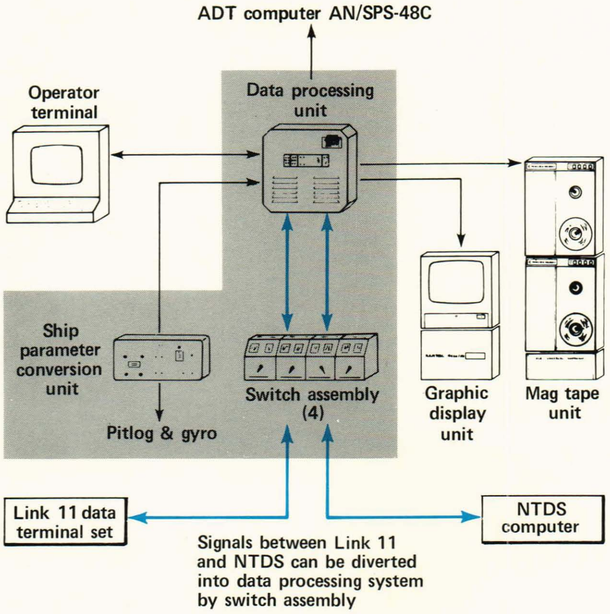

Figure 8 — The suite of equipment shown, currently proposed for installation on the Gridlock Demonstration Unit, is the only equipment installation necessary to support the gridlock demonstration. (Only small procedural changes are required on the Gridlock Reference Unit.) Equipment in the shaded area is required for the actual gridlock operation; the other equipment is needed to document and control the demonstration.

Gridlocking improvements are being pursued actively as part of the BGAAWC Program at APL. Successful demonstration will be followed by the introduction of improved gridlock throughout the Fleet.

REFERENCES and NOTES

[1] The term *track* as used here should not be confused with target tracks produced by fire control tracking radars. The latter typically operate in a dedicated mode from target acquisition to target kill evaluation and produce high-quality track data, with accuracies on the order of one milliradian or less. Search radars such as the AN/SPS-48C operate at a much lower data rate as constrained by their mechanical antenna scan period and hence produce position estimates of much lower quality, on the order of a few milliradians at best. The term *track* for these radars is used for reasons of conventional acceptance. The radars should more properly be termed *plotting radars*.

The AN/SPY-1A AEGIS radar combines both search and fire control functions in a single radar and provides quality track data comparable to that produced by dedicated fire control radars. This capability results primarily from the use of coherently integrated high-resolution waveforms and phased-array noninertial beam scanning.

[2] Historically, the coordinate frames used by ships or aircraft to report target or track positions are called *grids*. The process of aligning the grids to a common standard became known as gridlocking.

[3] The Naval Tactical Data System employs computers, displays, and digital data links, which function to share track and identification tasks among Battle Group elements.

[4] R. E. Kalman, "A New Approach to Linear Filtering and Prediction Problem," *J. Basic Eng.* **82**, 35-45 (Mar 1960).