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Methodology for Coupling the Air and Ground Modules in the State-of-the-Art Contingency Analysis Code

O. L. Smith

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DEPARTMENT OF ENERGY

Printed in the United States of America. Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road, Springfield, Virginia 22161
NTIS price codes—Printed Copy: A03; Microfiche A01

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ORNL/TM-10785

Instrumentation and Controls Division

METHODOLOGY FOR COUPLING THE AIR AND GROUND MODULES IN THE STATE-OF-THE-ART CONTINGENCY ANALYSIS CODE

O. L. Smith

Date issued: December 1988

Prepared by the
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831
operated by
MARTIN MARIETTA ENERGY SYSTEMS, INC.
for the
U.S. DEPARTMENT OF ENERGY
Under Contract No. DE-AC05-84OR21400

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ABSTRACT

This report describes the development of a methodology to couple the air and ground modules of the State-of-the-Art Contingency Analysis (SOTACA) code. Important conceptual differences between the air and ground modules that must be bridged include (1) the overall measure of battle progress used in the ground module versus its absence in the air module and (2) the use of pairwise comparisons to measure attrition in the ground module versus the use of probability-of-detection/ probability-of-kill parameters in the air module. To provide an overall measure of battle progress, all ground and air confronters are included in the power and vulnerability valuation procedure of the ground module. The air and ground module attrition methodologies are cast in a common format that allows them to be directly summed. Coding changes for the coupling procedure basically reflect changes in parameterization of the existing methodologies rather than reconceptualization. The procedure is examined in a test case.

1. INTRODUCTION

Phase I and Phase II development of the air module for the State-of-the-Art Contingency Analysis (SOTACA) code provides the methodology and algorithms for attrition among air and air-defense units. Coupling of air and opposing ground forces is to be implemented in Phase III, as documented in Engineering Change Proposal (ECP) S-E-0019: Research and develop techniques to implement the interaction of ground and air-to-ground weapons in the SOTACA model. The analysis described here is based on the air and ground modules of version 2.8, and the task is summarized in Fig. 1. Solid arrows indicate interactions among forces that are in place in version 2.8 air and ground modules. Dashed lines indicate links that are to be implemented in Phase III.

Section 2 of this report develops a relatively straightforward method of combining the air and ground modules that retains the methodologies of both and entails little conceptual restructuring of either. To illustrate the methodology and to aid understanding of some aspects of the recoding that it may entail, a stand-alone FORTRAN test case was synthesized from sample problems given in SOTACA documentation; this is described in Sect. 3.1. The same test problem was then implemented in SOTACA, version 2.8, to help confirm that the existing air and ground module methodologies will accommodate much of the proposed procedure and that the necessary changes are conceptually straightforward extensions; this test is summarized in Sect. 3.2.

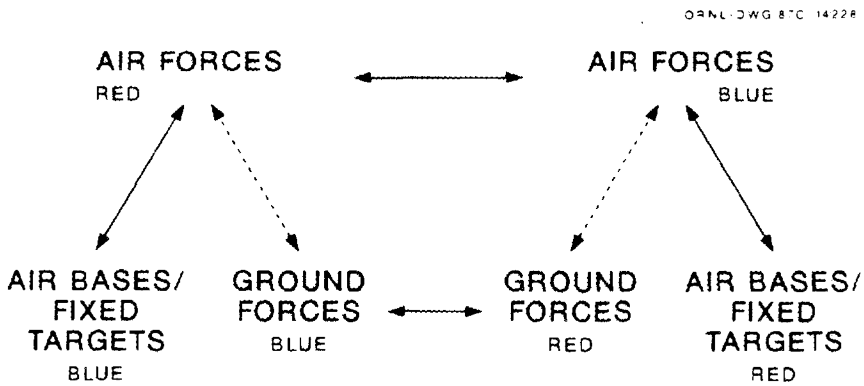

Fig. 1. Summary of linking of air and ground modules. Solid lines indicate intra-modular links in place (Phases I and II; version 2.8). Dashed lines indicate links to be implemented in this task (Phase III).

2. COUPLING THE AIR AND GROUND METHODOLOGIES

2.1 PERTINENT DIFFERENCES BETWEEN AIR AND GROUND MODULES

Merging the air and ground modules requires negotiating certain conceptual differences between their algorithms, principally the following.

A. Overall measure of battle progress (weighted force ratio and FLOT).

The weighted force ratio used to quantify conflict outcome in the ground module has no counterpart in the air module, which indicates that the ground module should retain its role as overall valuator of confronter worth (power and vulnerability) and battle progress (force ratio or FLOT). This should result in conceptually minor revision of the ground module; valuation of power and vulnerability of both air- and ground-type confronters has already been exercised in the pairwise comparison methodology.

B. Attrition.

When the modules are linked, ground forces may be attrited by air as well as by ground units, and air forces may be attrited by opposing air or by ground forces with anti-air capability. A disparity exists in the measures used to quantify the effectiveness of forces in the two modules. The pairwise comparison algorithm of the ground module is a judgmental procedure not based on specific battle processes and therefore lacks an absolute scale of reference. The air module expresses force effectiveness in terms of measurable battle processes such as frequency of detecting and killing targets. The nature of this difference is such that there is no common element in the two methodologies that permits rigorous translation between their scales of force effectiveness. In the combined model a given unit may attrite opponents in both modules, and the coupling procedure must treat the differing scales of shooter effectiveness in such a manner that they do not conflict or introduce ambiguity.

2.2 ATTRITION IN THE AIR AND GROUND MODULES

The first step in the coupling procedure is to cast existing air and ground attrition equations in a common format wherein attrition contributions may be directly summed.

From the SOTACA <u>Analyst's Guide to Theory</u>,[1] Sect. 4.5.1, the algorithm for attrition of ground confronters is, with a change of notation,

$$B_{j2} = B_{j1} \exp(-kW/B_{j1}) \quad , \qquad (1)$$

where B_{j1} is the quantity of confronter j on side B at time 1, B_{j2} is the same parameter a time interval Δt (e.g., a cycle) later, W is the weighted power of all opposing confronters on side A, and k is the attrition coefficient. Equation (1) may be reduced to difference form in the following manner. Using the definition $\Delta B_j \equiv B_{j2} - B_{j1}$, Eq. (1) may be rewritten as

$$\Delta B_j^g = -B_j[1 - \exp(-kW/B_j)] \quad , \tag{2}$$

in which the subscript 1 has been dropped and superscript g indicates ground component.

The attrition algorithm for the air module is taken from Appendix A of the report <u>Detailed Design for the SOTACA Air Module (Phase II)</u>.[2] For simplicity of discussion but without apparent loss of generality for present purposes, factors treating distribution of fire are omitted. Retaining the symbols defined previously, attrition of confronters on side B by side A is given by

$$\Delta B_j^a = -B_j\{1 - \prod_{i=1}^{I}[1 - d_{ij}\ k_{ij}]^{(A_i\ f_i)}\} \quad , \tag{3}$$

in which d_{ij} is the number of targets detected in a time interval, k_{ij} is the probability of a kill given detection, f_i is the firing rate of shooters A_i, and superscript a indicates air component.

The total attrition of confronters B_j attacked by both air and ground forces is then the sum of contributions from Eqs. (2) and (3),

$$\Delta B_j^t = \Delta B_j^g + \Delta B_j^a \quad . \tag{4}$$

2.3 COUPLING THE MODULES

The following strategy couples the modules in a manner that addresses principal modular differences noted above with little conceptual restructuring and without introducing new formulations.

A. Overall measure of battle progress (weighted force ratio and FLOT).

All air and ground confronters are included in the power and vulnerability valuation procedure of the ground module. In particular, aircraft, airbase air-defense, and other fixed targets are included, together with air attack and anti-air categories of power.

Since aircraft may carry greatly varying munition loads, the question arises, how can the pairwise comparison methodology include weapon load effects? Several comments are offered in response. It may be noted that the variability of aircraft value is not necessarily the same as variability of munition types and loads. SOTACA input is designed to assign enough of each munition to impair a target to a specified degree. Greater amounts (sorties) of a weaker munition are assigned than for a stronger munition. This tends to smooth out the worth of the aircraft as a function of munition type. The air module's calculation of attrition of targets by an aircraft does not differentiate among munition types. For each aircraft type, a single set of air-to-ground p_k and p_d values is input for all munitions to achieve a rate of kill ($p_d \times p_k$). Given this treatment of munition types in the attrition calculation, it appears to be neither appropriate nor profitable to introduce a higher level of resolution (value as a function of munition type) in the valuation of confronters for the overall battle progress (FLOT) calculation.

Although variability of munition type may be greater for aircraft, the same problem exists in valuing certain ground weapons. Tanks, for example, are commonly equipped with a gun in the 100-mm range and one or two machine guns. Also, the problem of variable worth is implicit for <u>every</u> weapon in its usage. A tank's large gun is worth something against a lightly fortified machine gun emplacement and something else against another tank. The problem of variable weapon value is inherent in the pairwise comparison methodology, which, as implemented in SOTACA, makes an initial assessment of weapon value and uses it throughout a given run without reference to actual usage in progress. For any weapon, the initial valuation is necessarily global and meant to represent an average over all uses to which the weapon will be put during conflict.

It is conceptually possible to implement a variable weapon value in SOTACA that would reflect actual munition usage. For an aircraft with two or more munition types, a vector of relative worth could be input [e.g., (1.0, 0.7,...)]. The initial pairwise comparisons could be performed on the basis of the munition of greatest relative value. During a simulation, the comparison matrix could be re-solved automatically, using the relative value as a multiplier on the initial input to reflect the present aircraft (or other weapon) munition loading. However, this level of detail may exceed that of SOTACA as a whole.

The key issue here is the establishment of an overall measure of battle progress. Such a measure clearly must include the air components. SOTACA is designed to use FLOT as a measure; presuming that this measure is to be retained, events in air engagements must be incorporated into this measure. At some point the relative values of air confronters must be compared with those of ground confronters. Even if air engagements are given their own measures of progress, analogous to each ground conflict, overall battle progress cannot be stated without adding air progress to ground progress. There is no evident way to do this that does not involve comparing air and ground confronters. Including air confronters in the pairwise comparison methodology of the ground module seems a suitable way to include them in the FLOT calculation.

B. Attrition.

(1) Ground-to-ground plus air-to-ground attrition. Ground units that receive fire from both air and ground forces have two components of attrition. A natural way to combine them is to continue calculating attrition from ground fire in the ground module, while calculating the air-to-ground component in the air module. Attrition from only ground fire would be determined by Eq. (2), which would be used (in the calibration step) to set the attrition coefficient k of ground attrition in the ground module. Air-to-ground attrition would be determined using p_d and p_k parameters in Eq. (3). Total ground attrition is then the sum [Eq. (4)].

Aircraft are included in the pairwise comparisons in the ground module only for the purpose of determining an overall measure of battle progress (i.e., the overall power ratio and FLOT). When calculating the attrition of ground units in the ground module, the power used in the attrition formula includes only the ground confronters that are present in the conflict. Aircraft would not be included. The same approach is currently used in the SOTACA ground module: In the initial pairwise comparisons, all confronter types are valued against each other; however, in the calculation of attrition in any particular ground engagement, projected power used in the attrition calculation is summed for only those confronters actually present.

(2) Air-to-air plus ground-to-air attrition. Attrition of air units by both air and ground forces would be expressed in terms of the p_d-p_k methodology.

Coding changes for the above coupling procedure basically reflect changes in parameterization of existing methodology. The main revision in the ground module is the inclusion of air and air-defense forces in confronter valuation. In the calibration step, attrition coefficients for these forces are set to zero. Air-to-ground attrition is passed from the air module. The salient revision in the air module is expansion of the detection and kill probabilities to include air-to-ground and ground-to-air interactions of all ground forces. SOTACA currently treats only air-defense elements.

3. TEST CASE

To illustrate and test the above methodology, a sample problem was synthesized in part from the ground module case described in the Analyst's Guide to Theory,[1] Sect. 4, and the air module cases shown in the Detailed Design of the SOTACA Air Module,[2] Sect. 4. The test problem was developed in two steps. First, a simplified stand-alone code was written to explore coupling methodologies. Then, when SOTACA version 2.8 with the implemented air module became available, the test case was installed in SOTACA for further study and confirmation of the planned coupling procedure. Confronters, force structure, and intermodule links of the test case are shown in Table 1. The case is intended to include enough detail and variety to examine the principal features of the linking methodology described in Sect. 2.

3.1 STAND-ALONE MODEL

A testbed program was written in FORTRAN on a VAX 8600 computer. To aid in understanding problems that may arise in the actual process of coupling the air and ground modules in SOTACA, the testbed code was generated by first developing simplified stand-alone air and ground modules and then linking them. The ground module was used as the driver, with the air module called as a subroutine; little change was needed in the air module. A short addition was made to the ground module to include the contribution of attrition from the air module. This mainly involved mapping the confronter numbering system of the air module onto that of the ground module.

3.1.1 Simplified, Testbed Ground Module

Table 1 lists Blue and Red confronter types and quantities. Aircraft distinguished in the air module are grouped for valuation in the ground module, as are airbase air defenses (SAMs+Guns). For simplicity, each confronter type is implicitly assumed to be a unit. Confronters included in both modules, and thus linking them, are indicated by listing intermodule targets.

The pairwise comparison matrices for Blue confronter power are shown in Table 2. Below-diagonal elements, which are reciprocals, are not listed.

Pairwise comparisons of Blue general vulnerability are given in Table 3 and Blue relative vulnerability in Table 4.

Table 1. Test case force structure, confronter types, and quantities (Links between air and ground confronters are indicated)

Blue confronter type	Quantity	Intermodule link
1st Blue TF		
Lt tank	54	Red aircraft
Arm car	10	
Mort	9	
Anti-air gun	6	Red aircraft
2nd Blue TF		
Aircraft (F-4,F-15)	4	Red tank, artillery
3rd Blue TF		
Aircraft (F-16,A-10)	4	Red airbase
4th Blue TF		
Airbase air defense (SAM+Gun)	15	
Red confronter type		
1st Red TF		
Tank	60	Blue aircraft
BMP	20	
Artillery	18	Blue aircraft
Guerilla team	5	Blue aircraft
2nd Red TF		
Aircraft (Rair1,Rair2, Rair3,Rair4)	10	Blue tank, anti-air
3rd Red TF		
Airbase air defense (SAM+Gun)	12	Blue aircraft

Ground force Blue confronter attrition data are shown in Table 5. In anticipation of coupling to the air module, the attrition rates of aircraft and airbase air defenses are set to zero by inputting constant confronter levels. Anti-air (field unit) has a component for ground attrition. This will be added to air-to-ground attrition of this confronter in the air module. Airbase anti-air units are assumed not to experience ground attrition in this test case but would be treated similarly if such attrition occurred.

Red confronter data follow a similar pattern; only the attrition data are shown to note that the aircraft and airbase confronter values are input as constant to yield zero attrition coefficients for these confronters that are attrited in detail in the air module (Table 6).

Table 2. Pairwise comparisons of Blue confronter power, by category

	Lt tank	Arm car	Anti-air	Mort	Aircraft	AB AD[a]
			Anti-armor			
Lt tank	1	5	5	1	2	5
Arm car		1	1	0.3	0.4	1
Anti-air			1	0.1	0.1	1
Mort				1	1	5
Aircraft					1	5
AB AD						1
			Anti-air			
Lt tank	1	1	0.1	1	1	0.1
Arm car		1	0.1	1	1	0.1
Anti-air			1	10	10	1
Mort				1	1	0.1
Aircraft					1	0.1
AB AD						1
			Air attack			
Lt tank	1	1	1	1	0.1	1
Arm car		1	1	1	0.1	1
Anti-air			1	1	0.1	1
Mort				1	0.1	1
Aircraft					1	10
AB AD						1

[a]AB AD = airbase air defense.

Table 3. Pairwise comparisons for Blue general vulnerability

	Lt tank	Arm car	Anti-air	Mort	Aircraft	AB AD[a]
Lt tank	1	0.33	1	0.33	1	1
Arm car		1	2	1	2	2
Anti-air			1	0.5	1	1
Mort				1	2	3
Aircraft					1	0.5
AB AD						1

[a]AB AD = airbase air defense.

Table 4. Pairwise comparison for Blue relative vulnerability

	Anti-armor	Anti-air	Air attack
		Lt tank	
Anti-armor	1	5	1
Anti-air		1	0.1
Air attack			1
		Arm car	
Anti-armor	1	5	1
Anti-air		1	0.1
Air attack			1
		Anti-air	
Anti-armor	1	5	0.1
Anti-air		1	0.1
Air attack			1
		Mort	
Anti-armor	1	5	1
Anti-air		1	0.1
Air attack			1
		Aircraft	
Anti-armor	1	0.1	0.1
Anti-air		1	1
Air attack			1
		AB AD[a]	
Anti-armor	1	5	0.1
Anti-air		1	0.1
Air attack			1

[a]AB AD = airbase air defense.

3.1.2 Simplified, Testbed Air Module

Types and quantities of confronters in the air module are shown in Table 7 with the intermodule links and the missions of confronters. Ground confronters are in attack mode. Blue air has two missions; Red

Table 5. Blue confronter quantities for calculating attrition coefficients

Confronter	Starting	After 3 hr
Lt tank	54	51
Arm car	10	8
Anti-air	6	5
Mort	9	7
Aircraft (all)	8	8
AB AD[a] (all)	15	15

[a]AB AD = airbase air defense.

Table 6. Red confronter quantities for calculating attrition coefficients

Confronter	Starting	After 3 hr
Tank	60	55
BMP	20	15
Artillery	18	17
Aircraft	10	10
Guerilla team	5	4
AB AD[a]	12	12

[a]AB AD = airbase air defense.

air has one. Duration of each relative to mission time zero is noted. Blue mission 1, close air support, is in conflict with opposing air and ground defenses in forward battle area (theater states 2+3 in air module nomenclature) for 8 hr and in unopposed air (TS 1) thereafter. Blue air mission 2, attack airbase, is in conflict with Red airbase ground defenses (TS 7) for 4 hr and in unopposed air (TS 1) before and thereafter. (SOTACA includes intermediary states omitted here.) The one Red mission, close air support, is in conflict with opposing air and ground defenses in the forward battle area (TS 2+3) for 6 hr and in unopposed air (TS 1) thereafter.

Table 7. Air module confronters with missions noted

Blue confronter type	Quant	Intermodule link	Mission
G1. Lt tank	54	Rair1,2,3,4	
G2. Airbase SAM	10		
G3. Anti-air (gun)	6	Rair1,2,3,4	
G4. Airbase anti-air (gun)	5		
A1. F-4	2	Red tank, artillery	1. Close air/
A2. F-15	2	Red tank, artillery	0-8 hr
A3. F-16	2	Red airbase SAM, anti-air	2. Attack airbase/
A4. A-10	2	Red airbase SAM, anti-air	0-4
Red confronter type			
G1. Tank	60	Blue F-4, F-15	
G2. Airbase SAM	12	Blue F-16, A-10	
G3. Artillery	18	Blue F-4, F-15	
G4. Guerilla team	5	Blue F-4, F-15	
A1. Rair1	2	Blue Lt tank, anti-air	1. Close air/
A2. Rair2	2	Blue Lt tank, anti-air	0-6 hr
A3. Rair3	3	Blue Lt tank, anti-air	
A4. Rair4	3	Blue Lt tank, anti-air	

Kill and detection probabilities of Blue confronters are given in Tables 8 and 9.

Similar kill and detection probabilities were written for the Red confronters of the air module.

3.1.3 Test Run

The test code, as parameterized above, was run in three steps: (1) the stand-alone ground module, (2) the stand-alone air module, and (3) the linked modules. The results are shown in Figs. 2 through 10. It may be noted that in the stand-alone ground module (Figs. 2 and 3), there is no attrition of the aircraft and airbase defenses. In the linked module (Figs. 8 and 9), these quantities are summed from the air module for valuation in the ground module. The various air missions can be seen in the trends of the related curves. Figure 10 is the weighted power ratio, based on valuation of all confronters in the air and ground modules.

Table 8. Kill probabilities of Blue confronters

	Air-to-air			
	Rair1	Rair2	Rair3	Rair4
F-4	0.3	0.25	0.5	0.6
F-15	0.2	0.2	0.4	0.5
F-16	0.3	0.25	0.4	0.55
A-10	0.1	0.5	0.5	0.45
	Air-to-ground			
	Tank	Airbase	Artillery	Guer Tm
F-4	0.3	0.25	0.5	0.6
F-15	0.2	0.2	0.4	0.5
F-16	0.3	0.25	0.4	0.55
A-10	0.1	0.5	0.5	0.45
	Ground-to-air			
	Rair1	Rair2	Rair3	Rair4
Lt tank	0	0	0	0
Airbase SAM	0.2	0.1	0.3	0.2
Anti-air	0.2	0.15	0.1	0.3
Airbase gun	0.1	0.15	0.1	0.1

Table 9. Detection probabilities of Blue confronters

	Air-to-air			
	Rair1	Rair2	Rair3	Rair4
F-4	0.3	0.25	0.5	0.6
F-15	0.2	0.2	0.4	0.5
F-16	0.3	0.25	0.4	0.55
A-10	0.1	0.5	0.5	0.45
	Air-to-ground			
	Tank	Airbase	Artillery	Guer Tm
F-4	0.3	0.25	0.5	0.6
F-15	0.2	0.2	0.4	0.5
F-16	0.3	0.25	0.4	0.55
A-10	0.1	0.5	0.5	0.45
	Ground-to-air			
	Rair1	Rair2	Rair3	Rair4
Lt tank	0	0	0	0
Airbase SAM	0.2	0.1	0.3	0.2
Anti-air	0.1	0.15	0.1	0.3
Airbase gun	0.1	0.15	0.1	0.1

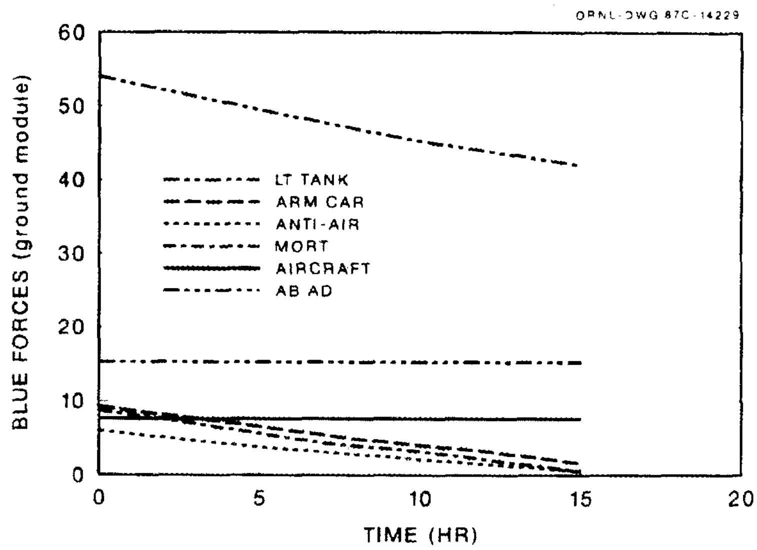

Fig. 2. Stand-alone ground module Blue confronter quantities as a function of time during battle. No attrition of ground forces by opposing air units. Aircraft and airbase air defenses (AB AD) are included for force valuation (power and vulnerability); their attrition coefficients are set to zero.

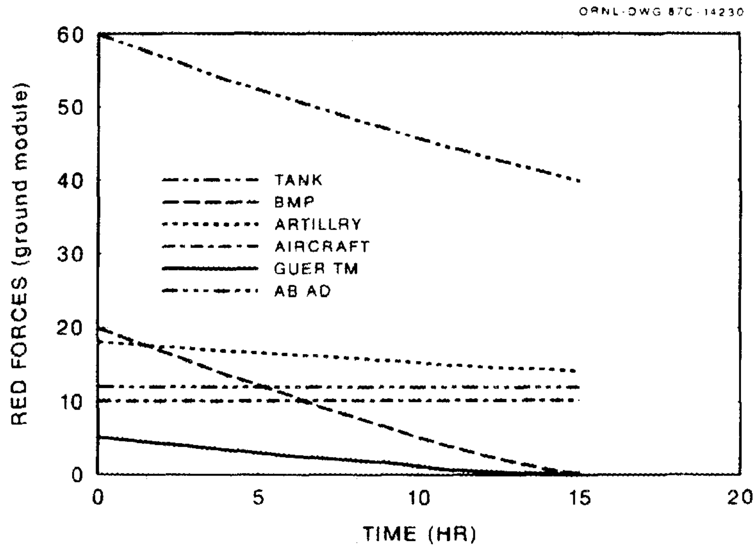

Fig. 3. Stand-alone ground module Red confronter quantities as a function of time during battle. No attrition of ground forces by opposing air units. Aircraft and airbase air defenses (AB AD) are included for force valuation (power and vulnerability); their attrition coefficients are set to zero.

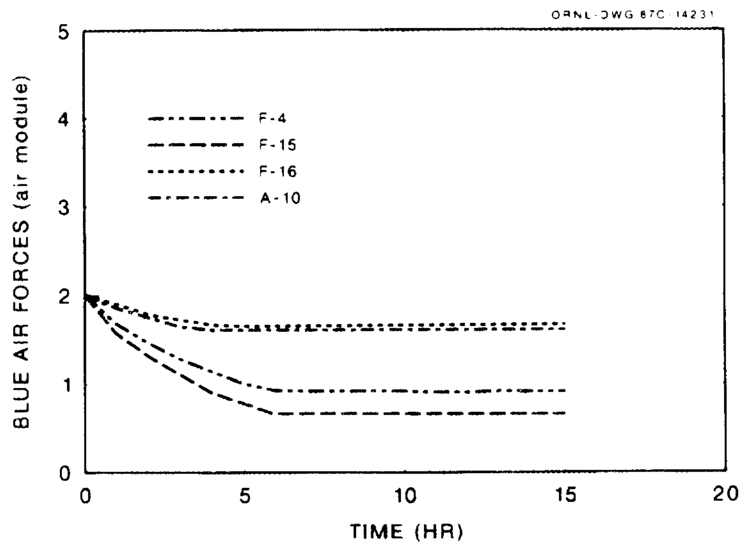

Fig. 4. Stand-alone air module Blue air confronter quantities as a function of time during battle. Blue confronters F-4 and F-15 on mission close air support during 0-8 hrs; F-16 and A-10 on mission airbase attack during 0-4 hrs. Attrition is by air-to-air interaction and by the anti-air power of opposing ground units with anti-air capability.

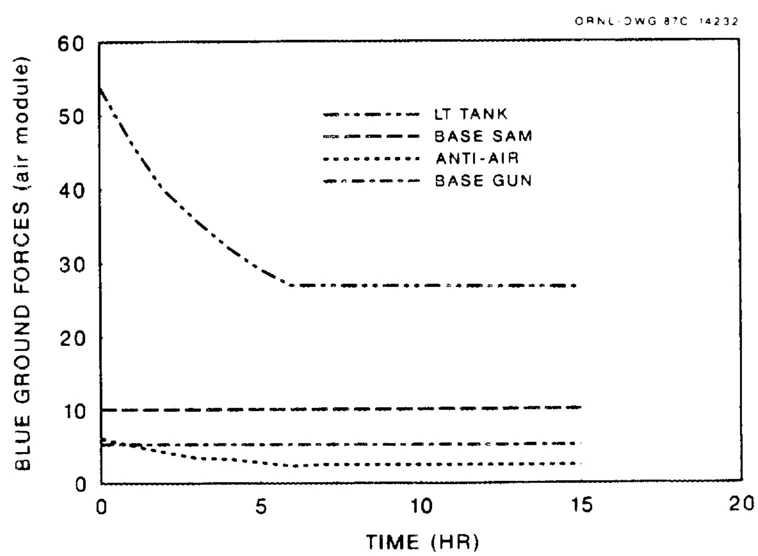

Fig. 5. Stand-alone air module Blue ground confronter quantities as a function of time during battle. Attrition is by air-to-ground interaction; no attrition of ground units by opposing ground forces. Opposing Red air forces are on mission close air support during 0-6 hrs; Blue airbase defenses not attacked.

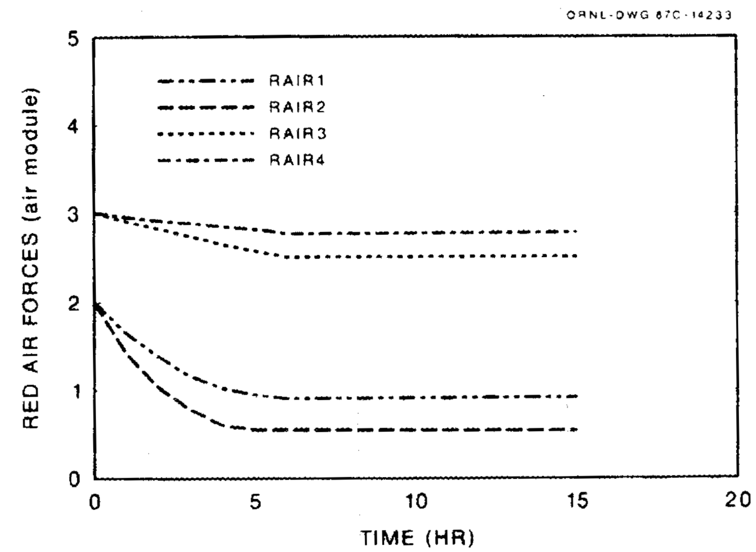

Fig. 6. Stand-alone air module Red air confronter quantities as a function of time during battle. All Red air units on mission close air support during 0-6 hrs. Attrition is by air-to-air interaction and by the anti-air power of ground units with anti-air capability.

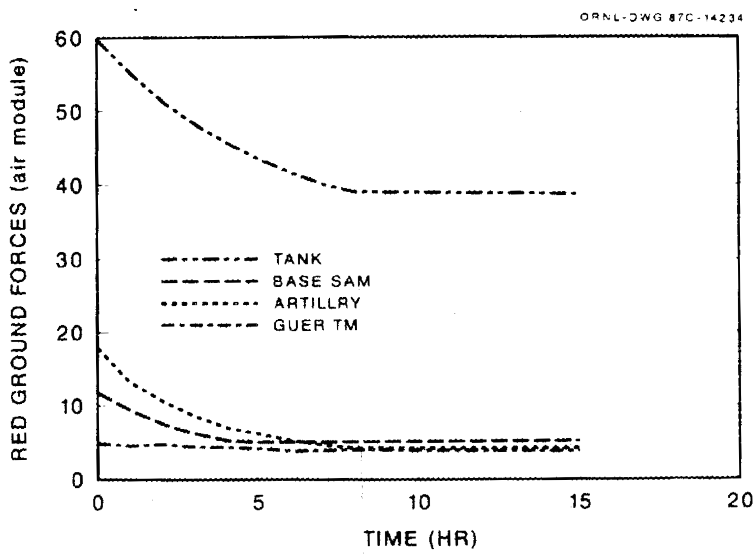

Fig. 7. Stand-alone air module Red ground confronter quantities as a function of time during battle. Attrition is by air-to-ground interaction; no attrition of ground units by opposing ground forces. Opposing Blue air on missions close air support during 0-8 hrs and airbase attack during 0-4 hrs.

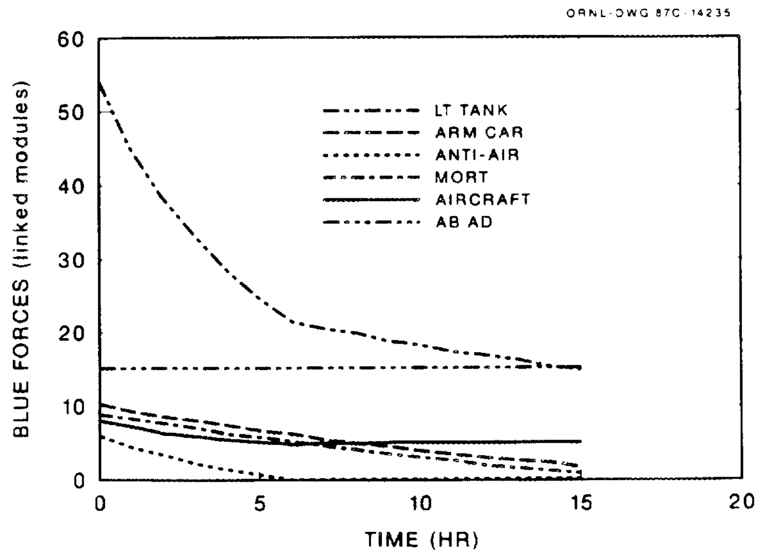

Fig. 8. Linked ground and air module Blue confronter quantities. Aircraft is the sum of Blue air forces calculated in air module (Fig. 4). Ground forces are the net of attrition in air and ground module calculations (combines Figs. 2 and 5).

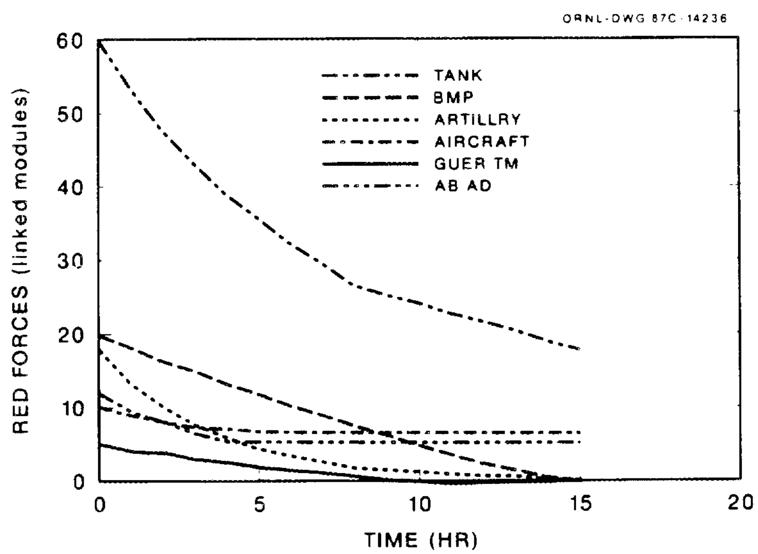

Fig. 9. Linked ground and air module Red confronter quantities. Aircraft is the sum of Red air forces calculated in air module (Fig. 6). Ground forces are the net of attrition in ground and air module calculations (combines Figs. 3 and 7).

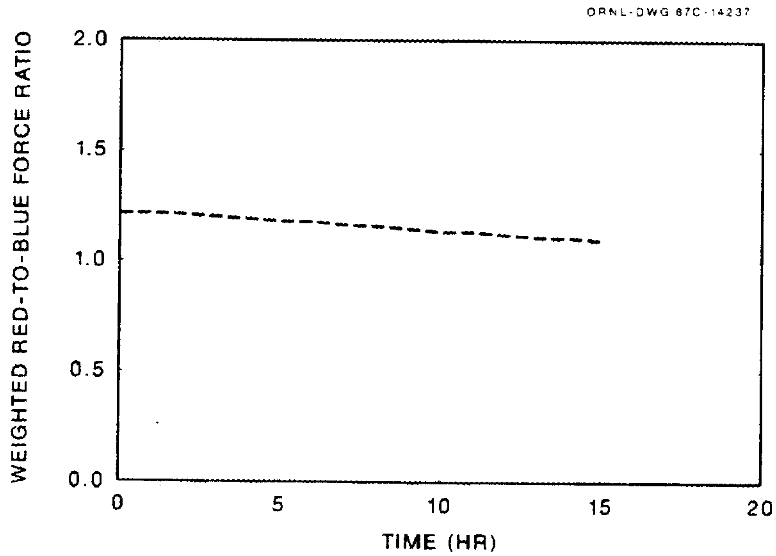

Fig. 10. Linked ground and air module measure of battle outcome: weighted Red-to-Blue force ratio (FLOT not shown). All confronters in the ground and air modules are valued by the pairwise comparison methods of the ground module.

3.2 TEST CASE IN SOTACA VERSION 2.8

The test problem was installed in SOTACA version 2.8 (1) to assess the extent to which existing methodology will accommodate the proposed coupling procedure and (2) to confirm the anticipated degree of revision where it will not. The principal features of the procedure are the inclusion of air units in the pairwise comparisons of the ground module for FLOT determination and the attrition of ground forces by air units. The first of these features was accomplished in the test case through introduction of anti-air and air attack categories of power. Attrition of air confronters was set to zero in the attrition calibration menu. This is an elaboration of the data input procedure; no coding revision is required. However, it may be desirable to change the code so that air confronters are omitted entirely from the attrition calibration menu.

Blue Task Force (TF) 1, a mobile ground force that was routed through the test case network, included an anti-air unit that was marked AD (air defense) in the confronter definition menu. When this TF was attacked in the battlefield by a Red air unit (Red TF 3) flying close air support for Red TF 1, SOTACA attrited the Blue TF 1 anti-air unit. There is thus a partial interaction between air and mobile ground forces in place in the code; extension to all ground forces would appear to be achievable with modest code revision.

A change needs to be made to allow input of ground attrition of ground air-defense units. In the ground forces attrition calibration menu, SOTACA lists all ground confronters, including field and airbase anti-air units; however, attempts to include ground attrition of the anti-air units is overridden and nullified by the code. The code also needs the capability to include air units with mobile ground forces.

3.3 CONCLUSION

The test case appears to confirm that the coupling procedure described in Sect. 2 is at least conceptually a straightforward extension of the existing SOTACA methodology.

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