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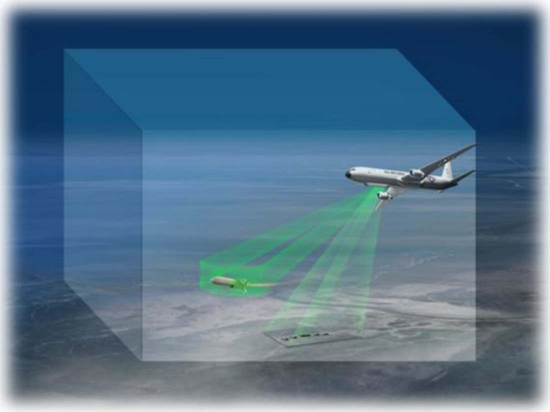
E-10A MC2A Systems Engineering Case Study

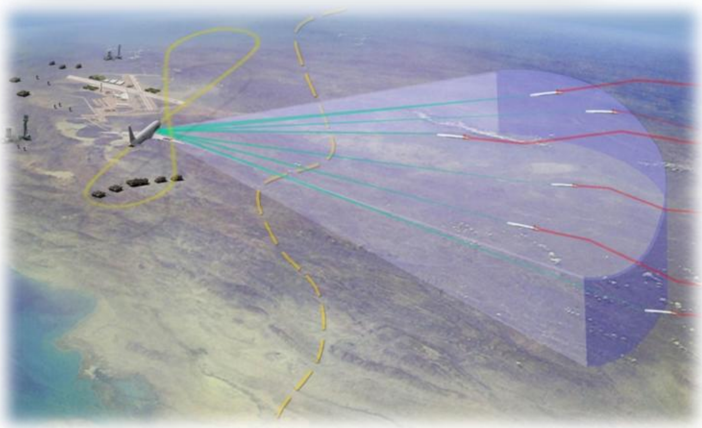
Air Force Center for Systems Engineering

William Albery

E-10A MC2A
SYSTEMS ENGINEERING
CASE STUDY

WILLIAM ALBERY, Ph.D.





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Foreword

At the direction of the former Secretary of the Air Force, Dr. James G. Roche, the Air Force Institute of Technology (AFIT) established the Air Force Center for Systems Engineering (AF CSE) at its Wright Patterson AFB campus in 2003. With academic oversight by a subcommittee on systems engineering, chaired by then-Air Force Chief Scientist Dr. Alex Levis, the AF CSE was tasked to develop case studies of SE implementation during concept definition, acquisition, and sustainment. The committee drafted an initial case outline and learning objectives, and suggested the use of the Friedman-Sage Framework to guide overall analysis.

The Department of Defense is exponentially increasing the acquisition of joint complex systems that deliver needed capabilities demanded by our warfighter. Systems engineering is the technical and technical management process that focuses explicitly on delivering and sustaining robust, high-quality, affordable solutions. The Air Force leadership has collectively stated the need to mature a sound systems engineering process throughout the Air Force. Gaining an understanding of the past and distilling learning principles that are then shared with others through our formal education and practitioner support are critical to achieving continuous improvement.

The AF CSE has published nine case studies thus far including the A-10, KC-135 Simulator, Global Hawk, C-5A, F-111, Hubble Telescope, Theater Battle Management Core System, International Space Station and Global Positioning System (GPS). All case studies are available on the AF CSE website, http://www.afit.edu/cse. These cases support academic instruction on SE within military service academies, civilian and military graduate schools, industry continuing education programs, and those practicing SE in the field. Each of the case studies is comprised of elements of success as well as examples of SE decisions that, in hindsight, were not optimal. Both types of examples are useful for learning.

Along with discovering historical facts, we have conducted key interviews with program managers and chief engineers, both within the government and those working for the various prime and subcontractors. From this information, we have concluded that the discipline needed to implement SE and the political and acquisition environment surrounding programs continue to challenge our ability to provide balanced technical solutions. We look forward to your comments on this E-10 case study and our other AF CSE published studies.

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1 Systems Engineering Principles

1.1 General Systems Engineering Process

The Department of Defense continues to develop and acquire joint systems and to deliver needed capabilities to the warfighter. With a constant objective to improve and mature the acquisition process, it continues to pursue new and creative methodologies to purchase these technically complex systems. A sound systems engineering process focused explicitly on delivering and sustaining robust, high-quality, affordable products that meet the needs of customers and stake holders must continue to evolve and mature. Systems engineering is the technical and technical management process that results in delivered products and systems that exhibit the best balance of cost and performance. The process must operate effectively with desired mission-level capabilities, establish system-level requirements, allocate these down to the lowest level of the design, and ensure validation and verification of performance, meeting cost and schedule constraints. The systems engineering process changes as the program progresses from one phase to the next, as do the tools and procedures. The process also changes over the decades, maturing, expanding, growing, and evolving from the base established during the conduct of past programs. Systems engineering has a long history. Examples can be found demonstrating a systemic application of effective engineering and engineering management, as well as poorly applied, but well-defined processes. Throughout the many decades during which systems engineering has emerged as a discipline, many practices, processes, heuristics, and tools have been developed, documented, and applied.

Several core lifecycle stages have surfaced as consistently and continually challenging during any system program development. First, system development must proceed from a well-developed set of requirements. Second, regardless of the evolutionary acquisition approach, the system requirements must flow down to all subsystems and lower level components. And third, the system requirements need to be stable, balanced and must properly reflect all activities in all intended environments. However, system requirements are not unchangeable. As the system design proceeds, if a requirement or set of requirements is proving excessively expensive to satisfy, the process must rebalance schedule, cost, and performance by changing or modifying the requirements or set of requirements.

Systems engineering includes making key system and design trades early in the process to establish the system architecture. These architectural artifacts can depict any new system, legacy system, modifications thereto, introduction of new technologies, and overall system-level behavior and performance. Modeling and simulation are generally employed to organize and assess architectural alternatives at this introductory stage. System and subsystem design follows the functional architecture. System architectures are modified if the elements are too risky, expensive or time-consuming. Both newer object-oriented analysis and design and classic structured analysis using functional decomposition and information flows/data modeling occurs. Design proceeds logically using key design reviews, tradeoff analysis, and prototyping to reduce any high-risk technology areas.

Important to the efficient decomposition and creation of the functional and physical architectural designs are the management of interfaces and integration of subsystems. This is applied to subsystems within a system, or across large, complex system of systems. Once a solution is planned, analyzed, designed, and constructed, validation and verification take place to ensure satisfaction of requirements. Definition of test criteria, measures of effectiveness (MOEs), and measures of performance (MOPs), established as part of the requirements process, takes place well before any component/subsystem assembly design and construction occurs.

There are several excellent representations of the systems engineering process presented in the literature. These depictions present the current state of the art in the maturity and evolution of the systems engineering process. One can find systems engineering process definitions, guides, and handbooks from the International Council on Systems Engineering Electronic Industries Association, Institute of Electrical and Electronics Engineers, and various Department of Defense (DoD) agencies and organizations. They show the process as it should be applied by today's experienced practitioner. One of these processes, long used by the Defense Acquisition University (DAU), is depicted by Figure 1-1. It should be noted that this model is not accomplished in a single pass. This iterative and nested process gets repeated to the lowest level of definition of the design and its interfaces.

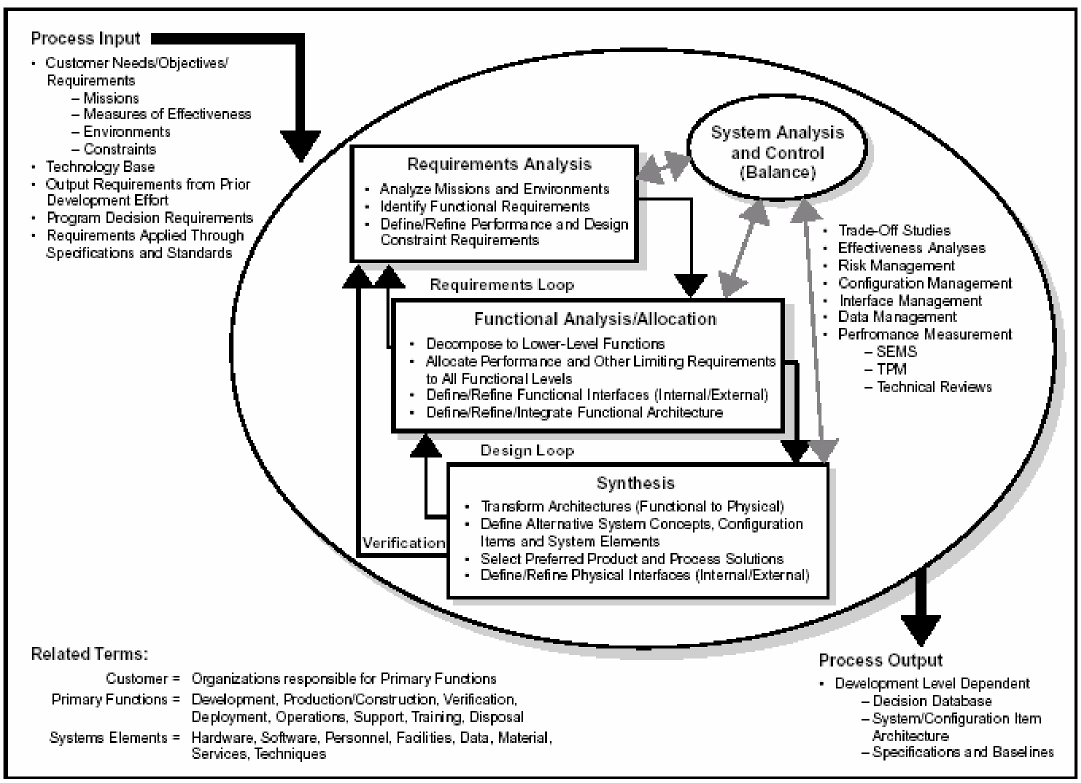

Figure 1-1. The Systems Engineering Process as Presented by DAU

1.2 DoD Directive 5000 Series

During President Richard Nixon's first term, Secretary of Defense Melvin Laird faced congressional attempts to lower defense spending. The cause was the Vietnam War and the rising cost of defense acquisition, as well as emerging energy and environmental programs. Laird and David Packard, his deputy, recognized the need for a mechanism to control and manage spending especially with the coming fiscal constraint. In May 1969, Packard formed the Defense Systems Acquisition Review Council to give advice on the acquisition of major weapon systems. It was chartered to review major milestones as well as conduct occasional management reviews. One year later in 1970, Packard issued a policy memorandum that was to become the foundation for the DoD 5000 series of documents which were first issued in 1971, and as of January 2008 have been reissued 10 times. The original purpose of the DoD 5000 series was to improve the management of acquisition programs and include policy to streamline management, decentralize execution, and use appropriate management structures.[1] The 1971 issue of the DoD 5000 series established the following program considerations (abbreviated here) pertaining to progression of a program through the acquisition process.[2]

4. System need shall be clearly established in operational terms, with appropriate limits, and shall be challenged throughout the acquisition process … Wherever feasible, operational needs shall be satisfied through the use of existing military or commercial hardware …
5. Cost parameters shall be established which consider the cost of acquisition and ownership … Practical tradeoffs shall be made between system capability, cost and schedule …
6. Logistic support shall also be considered as a principle design parameter …
7. Programs shall be structured and resources allocated to assure that the demonstration of actual achievement is the pacing function … Schedules and funding profiles shall be structured to accommodate unforeseen problems and permit task accomplishment without unnecessary overlapping or concurrency.
8. Technical uncertainty shall be continually assessed … Models, mock-ups, and system hardware will be used to the greatest possible extent to increase confidence level.
9. Test and evaluation shall commence as early as possible. A determination of operational suitability, including logistics support requirements, will be made prior to large scale production commitments …
10. Contract type shall be consistent with all program characteristics, including risk …
11. The source selection decision shall take into account the contractor's capability to develop a necessary defense system on a timely and cost-effective basis …
12. Management information/program control requirements shall provide information which is essential to effective management control … Documentation shall be generated in the minimum amount to satisfy necessary and specific management needs.

1.3 Evolving Systems Engineering Process

The DAU model, like all others, has been documented in the last two decades, and has expanded and developed to reflect a changing environment. Systems are becoming increasingly complex internally and more interconnected externally. The process used to develop the aircraft and systems of the past was a process effective at the time. It served the needs of the practitioners and resulted in many successful systems in our inventory. Notwithstanding, the cost and schedule performance of the past programs are fraught with examples of some well-managed programs and ones with less-than-stellar execution. As the nation entered the 1980s and 1990s, large DoD and commercial acquisitions were overrunning costs and behind schedule. Aerospace industry primes were becoming larger and more geographically and culturally distributed and worked diligently to establish common systems engineering practices across their enterprises. However, these common practices must be understood and be useful both within the enterprise and across multiple corporations and vendor companies because of the mega-trend of teaming in large (and some small) programs. It is essential that the systems engineering process effect integration, balance, allocation, and verification and be useful to the entire program team down to the design and interface level.

Today, many factors overshadow new acquisition, including system-of-systems (SoS) context, network-centric warfare and operations, an increased attention to human systems integration, and the rapid growth in information technology. These factors are driving a more sophisticated systems engineering process with more complex and capable features, along with new tools and procedures. One area of increased focus of the systems engineering process is the informational systems architectural definitions used during system analysis. This process, described in the DoD Architectural Framework (DoDAF)[3], emphasizes greater reliance on reusable architectural views describing the system context and concept of operations, interoperability, information and data flows, and network service-oriented characteristics.

1.4 Case Studies

The systems engineering process to be used in today's complex system and system-of-systems projects is a process matured and founded on principles developed in the past. Examination of systems engineering principles used on programs, both past and present, can provide a wealth of lessons to be used in applying and understanding today's process. It was this thinking that led to the initiation of the Air Force Center for Systems Engineering case study effort, as well as the present continuation of that effort.

The purpose of developing detailed case studies is to support the teaching of systems engineering principles. They will facilitate learning by emphasizing to the student the long-term consequences of the systems engineering and programmatic decisions on program success. The systems engineering case studies will assist in discussion of both successful and unsuccessful methodologies, processes, principles, tools, and decision material to assess the outcome of alternatives at the program/system level. In addition, the importance of using skills from multiple professions and engineering disciplines and collecting, assessing, and integrating varied functional data will be emphasized. When they are taken together, the student is provided real-world, detailed examples of how the process attempts to balance cost, schedule, and performance.

The utilization and misutilization of systems engineering principles will be highlighted, with special emphasis on the conditions that foster and impede good systems engineering practices. Case studies should be used to illustrate both good and bad examples of acquisition management and learning principles, to include whether:

- every system provides a satisfactory balanced and effective product to a customer;
- effective requirements analysis was applied;
- consistent and rigorous application of systems engineering management standards was applied;
- effective test planning was accomplished;

- there were effective major technical program reviews;
- continuous risk assessments and management was implemented;
- there were reliable cost estimates and policies;
- they used disciplined application of configuration management;
- a well-defined system boundary was defined;
- they used disciplined methodologies for complex systems ;
- human systems integration was accomplished;
- problem solving incorporated understanding of the system within the larger operational environment.

The systems engineering process transforms an operational need into a system or system-of-systems. Architectural elements of the system are allocated and translated into detailed design requirements. The systems engineering process, from the identification of the need to the development and utilization of the product, must continuously integrate and balance the requirements, cost, and schedule to provide an operationally effective system throughout its life cycle. Systems engineering case studies highlight the various interfaces and communications to achieve this balance, which include:

- The program manager/systems engineering interface between the operational user and developer (acquirer) essential to translate the needs into the performance requirements for the system and subsystems.
- The government/contractor interface essential for the practice of systems engineering to translate and allocate the performance requirements into detailed requirements.
- The developer (acquirer)/user interface within the project, essential for the systems engineering practice of integration and balance.

The systems engineering process must manage risk, both known and unknown, as well as both internal and external. This objective will specifically capture those external factors and the impact of these uncontrollable influences, such as actions of Congress, changes in funding, new instructions/policies, changing stakeholders or user requirements, or contractor and government staffing levels.

1.5 Framework for Analysis

The Air Force Center for Systems Engineering case studies will present learning principles specific to each program, but will utilize the Friedman-Sage framework[4] to organize the assessment of the application of the systems engineering process. The Systems Engineering case studies published by the Air Force Institute of Technology employed the Friedman-Sage construct and matrix as the baseline assessment tool to evaluate the conduct of the systems engineering process for the topic program.

The framework and the derived matrix can play an important role in developing case studies in systems engineering and systems management, especially case studies that involve systems acquisition. The Friedman-Sage framework is a nine row by three column matrix shown in Table 1.

Table 2. A Framework of Key Systems Engineering Concepts and Responsibilities

Concept Domain	Responsibility Domain		
	1. Contractor Responsibility	**2. Shared Responsibility**	**3. Government Responsibility**
A. Requirements Definition and Management			
B. Systems Architecting and Conceptual Design			
C. System and Subsystem Detailed Design and Implementation			
D. Systems and Interface Integration			
E. Validation and Verification			
F. Deployment and Post Deployment			
G. Life Cycle Support			
H. Risk Assessment and Management			
I. System and Program Management			

Six of the nine concept domain areas in Table 1 represent phases in the Systems Engineering lifecycle:

A. Requirements definition and management;

B. Systems architecting and conceptual design;

C. System and subsystem detailed design and implementation;

D. Systems and interface integration;

E. Verification and validation;

F. Deployment and post deployment.

Three of the nine concept areas represent necessary process and systems management support:

G. Life cycle support;

H. Risk assessment and management;

I. System and program management.

While other concepts could have been identified, the Friedman–Sage framework suggests these nine are the most relevant to systems engineering in that they cover the essential life cycle processes in systems acquisition and the systems management support in the conduct of the process. Most other concept areas that were identified during the development of the matrix appear to be subsets of one of these. The three columns of this two-dimensional framework represent the responsibilities and perspectives of government and contractor, and the shared responsibilities between the government and the contractor. In teaching systems engineering in DoD, there has previously been little distinction between duties and responsibilities of the government and industry activities. While the government has responsibility in all 9 concept domains, its primary objective is establishing mission requirements.

Figure 1-2. Artist's concept of the E-10A showing the BMC2 Suite

2 E-10A System Description

2.1 Characteristics

The Northrop Grumman E-10 MC2A (Figure 2-1) was planned as a multi-role military aircraft to replace the Boeing 707 based E-3 Airborne Warning and Control System (AWACS) Sentry, E-8 Joint Surveillance Target Attack Radar System (J-STARS), and RC-135 Rivet Joint aircraft in US service. It was based on the 767-400ER commercial airplane.

Figure 2-1. The E-10A (conceptual photo)

2.2 Development

In 2003, the Northrop Grumman Corporation, Boeing, Raytheon Multi-Sensor Command and Control Aircraft (MC2A) Team was awarded a $215 million pre-*system development and demonstration* (SDD) contract for the development of the aircraft. The MC2A was intended to be the ultimate theater-wide combat control center.

While the Northrop Grumman E-8 J-STARS aircraft are a fairly recent development (1996), they were the last such type to be based on the 707. Installing the high technology systems envisaged for the MC2A on an increasingly obsolete airframe would not have provided the capability required. The availability of powerful and reliable turbofans allowed a twinjet to be considered such as the 767.

The goal of integrating air- and ground-search radars on a single airframe was still too challenging and the decision was made 2003 to not pursue a full air and ground surveillance single platform; electronic interference between the air- and ground-surveillance radars as well as the power requirements for both systems were cited as the reason.[5] Instead the USAF decided to plan on two separate E-10 fleets to be integrated with the proposed Space-Based Radar system, air and space-based ELINT/signals intelligence (SIGINT) assets, and space-based IMINT satellites. SIGINT is intelligence-gathering by interception of signals. ELINT refers to electronic intelligence; IMINT refers to imagery intelligence. The E-10A would have been the central command authority for all air, land, sea, and space forces in a combat theater. The E-10A was also considered for use as a command center for unmanned combat air vehicles.

2.3 E-10A Capabilities

The E-10A was designed to be globally responsive and 24/7 persistent. The E-10A was to be the hub of a spoke wheel that interacted with air, land, sea, and space assets (Figure 2-2). Land and sea assets included joint services and combined connectivity. Space assets involved space connectivity via satellites. BMC2 included the ability to develop an air tasking order of execution, dynamic re-tasking, time critical targeting operations and improved combat identification (friend or foe). Target evidence accrual in the BMC2 suite would allow for the association, correlation and fusion of information from various sources as evidence towards positive classification and/or identification. The E-10A was to provide battlespace awareness by fusing persistent sensors. The Active Electronically Scanned Array (AESA) MP-RTIP radar would provide enhanced detection capability of both ground moving targets as well as air moving targets. UAVs could be controlled from the E-10A platform. The E-10A's persistent surveillance capability, horizontal integration, and moving target (air and ground) defense would enable faster, better informed decisions which would shorten the kill-chain.

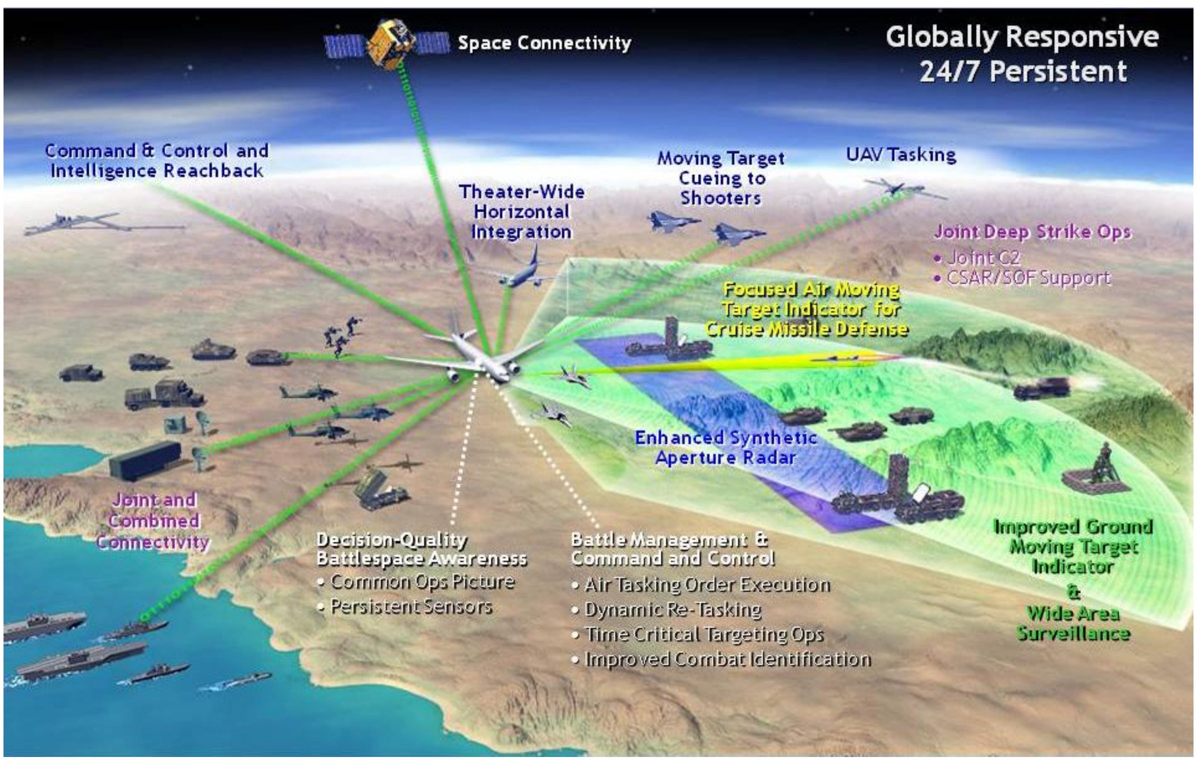

Figure 2-2. E-10A Capabilities[6]

The capability of the E-10 MC2A was to be raised incrementally, with each phase known as a "spiral."

- Spiral 1 - MP-RTIP

  This version would have provided substantial Joint Cruise Missile Defense (CMD) capability with focused Air Moving Target Indicator (AMTI) modes and augment the E-8 Joint STARS in the ground surveillance role.

Figure 2-3. USAF E-8C Joint STARS

- Spiral 2 - AWACS Capability

  This version would have replaced the E-3. It was expected that the Spiral 2 version would use a variant of the Boeing Wedgetail's Multi-role Electronically Scanned Array.[ii]

Figure 2-4. USAF E-3 Sentry

- Spiral 3 - SIGINT Platform

  This version was intended to replace a wide range of SIGINT/ELINT aircraft including the RC-135 Rivet Joint. No plans existed to develop this version.

[ii] It was designed for Royal Australian Air Force (RAAF) under "Project Wedgetail." The 737 AEW&C has also been selected by the Turkish Air force (under "Project Peace Eagle") and the Republic of Korea Air Force ("Project Peace Eye") and has been proposed to Italy and the UAE.

Figure 2-5. USAF RC-135 Rivet Joint

2.3.1 Scale-back

In January 2006, the Air Force FY07 budget request revealed a reshaping of the E-10 program, with the cancellation of the E-10A SDD program, but maintained funding for the development and testing of a single demonstration aircraft, now known as the E-10A Technology Development Program (TDP) (Appendix C). The TDP would flight test the MP-RTIP Wide-Area Surveillance (WAS) radar, and conduct flight demonstrations of the E-10A's CMD capability. The SDD elimination was designed to be a cost cutting measure and part of a larger reorganization and redefinition of the Air Force's mission including the retirement of the E-4B and F-117 fleets, as well as the elimination of all but 58 B-52s.

2.3.2 Cancellation

The E-10 finally disappeared at the end of FY2007 as budget pressures and competing priorities pushed it completely out of the budget (Appendix D). The USAF maintained funding for the MP-RTIP radar and that may eventually put the radar on the E-8, or on a new aircraft, possibly the same airframe as the next aerial tanker. The smaller version of the MP-RTIP AESA designed to be flown on the RQ-4B Global Hawk has been flight tested on the Scaled Composites Proteus aircraft.

2.4 Specifications (767-400ER)[7]

General characteristics:

- Crew: 2
- **Length:** 201 ft 4 in (61.3 m)
- **Wingspan:** 170 ft 4 in (51.9 m)
- **Height:** 55 ft 4 in (16.8 m)
- **Empty weight:** 229,000 lb (103,872 kg)
- **Max takeoff weight:** 450,000 lb (204,116 kg)
- **Powerplant:** 2× P&W PW4000-94 or GE CF6-80C turbofan, PW: 63,300 lbf or GE: 63,500 lbf (PW: 281.6 kN or GE: 282.5 kN) each

Performance:

- **Maximum speed:** Mach 0.86 (568 mph, 913 km/h)
- **Cruise speed:** Mach 0.80 (530 mph, 851 km/h)
- **Range:** 5,600 nmi (10,370 km)
- **Service ceiling:** 40,100 ft (12,200 m)

Principal Characteristics

767-400ER

			Basic	Maximum
Maximum taxi weight		lb (kg)	401,000 (181,890)	451,000 (204,570)
Maximum takeoff weight		lb (kg)	400,000 (181,440)	450,000[1] (204,120)[1]
Maximum landing weight		lb (kg)	350,000 (158,760)	350,000 (158,760)
Maximum zero fuel weight		lb (kg)	330,000 (149,680)	330,000 (149,680)
Fuel capacity		U.S. gal (L)	23,980 (90,770)	23,980 (90,770)
Cargo volume				
Forward options	5 pallets[2]	ft³ (m³)	2,075 (58.8)	
	20 LD-2s	ft³ (m³)	2,400 (68.0)	
Aft option	18 LD-2s	ft³ (m³)	2,160 (61.2)	
Bulk		ft³ (m³)	345 (9.8)	
Maximum volume capability[3]		ft³ (m³)	4,905 (138.9)	

[1] Loading restrictions apply
[2] 96- x 125-in pallets
[3] 20 LD-2s forward + 18 LD-2s aft + bulk

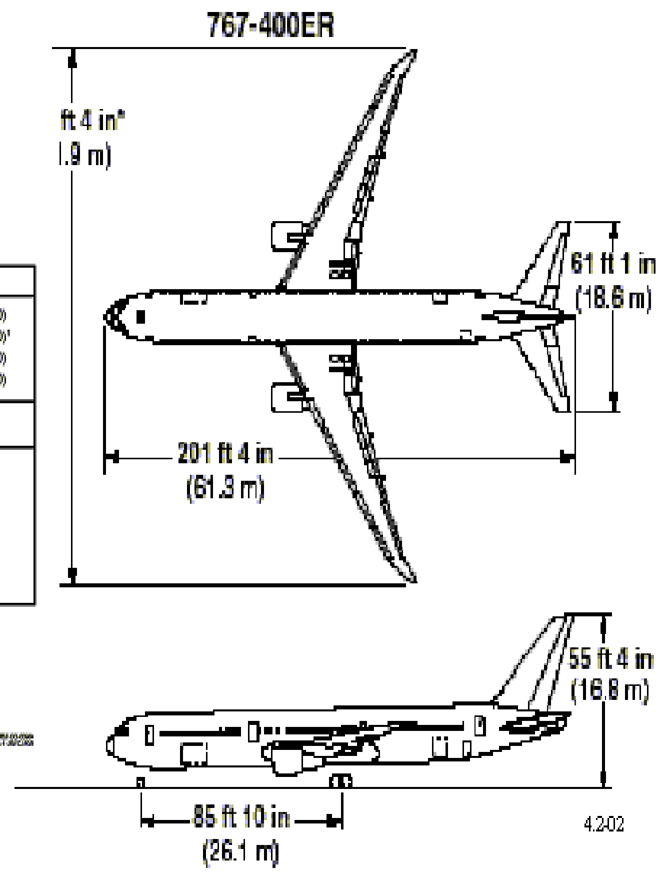

Figure 2-6. Boeing B767-400 ER Physical Characteristics[7]

Table 3. E-10 History of Significant Events[6]	
Radar Technology Insertion Program (RTIP) Operational Requirements Document (ORD)	Jun 99
MP-RTIP Milestone II Defense Acquisition Board (DAB) Approval by USD/AT&L	Jan 00
J-STARS RTIP Acquisition Decision Memorandum (ADM)	Feb 00
MP-RTIP Acquisition Program Baseline (APB) Agreement	Nov 00
MP-RTIP Single Acquisition Management Plan (SAMP) approved by USD/AT&L	Nov 00
MP-RTIP Requirements Revalidated to USD/AT&L Joint Requirements Oversight Council (JROC) Memorandum	Nov 00
MP-RTIP ADM (Restructure from RTIP)	Dec 00
Special Study 8 validated need for MP-RTIP (JROC approval)	Apr 01
Multi-sensor Command & Control Aircraft (MC2A) CONOPS (COMACC approval)	May 01
MP-RTIP analyses of alternatives (767 platform recommendation/cost effectiveness)	Feb 02
CSAF/SECAF approval of 767-400ER	Feb 02
USD/AT&L (Strategic and Tactical Systems) Approval of 767-400	Mar 02
MP-RTIP 767 Sensor Study (aka Madigan Study, evaluated radar size)	Mar 02
MP-RTIP sensor size/placement on 767 study	Jun 02
FY 04-09 Defense Planning Guidance (DPG) directs Air Force to acquire four aircraft with MP-RTIP	Jul 02
MC2A Sensor Trade Study (program office)	Aug 02
Multi-sensor C^2 Functionality (MC2F) Mission Needs Statement (JROC approval)	Dec 02
MC2A Initial Requirements Document (AFROCC approval)	Jan 03
Mission Design Series (MDS) Designation for MC2A as E-10A	Jan 03
OIPT Program Acquisition Summary Report	Apr 03
E-10A Abbreviated Acquisition Summary Approved	Apr 03
MC2A Air Force Way Ahead (CSAF/SAF direction)	Apr 03
JROC Revalidation of MP-RTIP Key Performance Parameters (KPPs) & MCA CONOPS Review	Jul 03
E-10A MC2A Capabilities Development Document (CDD) (AFROCC approval)	Nov 03
MP-RTIP ADM	Dec 03
Joint Staff/J6 Interoperability Certification of E-10A CDD	Jun 04
E-10A Working IPT (WIPT) for Onboard BMC2	Sep 04
E-10A CDD JROC Approval	Oct 04
Program Budget Decision (PBD) 753 Restructuring E-10A Program	Dec 04
CSAF Decision on Way Forward Post PBD 753	Jan 05
E-10 Technical Feasibility Study Competed	Dec 05
QDR Directs E-10 Demo program; cancellation of the E-10A SDD program	Jan 06
OSD/ATL & SECAF sign E-10 ADM	May 06
FY08 POM Deliberations	Jun 06

3 The E-10 Story

The E-10A Multi-Sensor Command & Control Aircraft (MC2A) program was initiated in 2001 by Commander Air Combat Command (COMACC) General John Jumper. It ran from 2001 to 2006 at a cost of $1.2B when it was cancelled. The intent was to recapitalize aging AWACS/ J-STARS 707 fleets and insert the latest radar/communications technology on a new wide body. The Air Force envisioned the E-10A as a replacement for three specialized aircraft: the E-8 J- STARS air-to-ground surveillance aircraft, the E-3 AWACS air-to-air surveillance aircraft and the RC-135 Rivet Joint SIGINT aircraft. The Air Force terminated the program in 2006 due to pressing Service budget constraints.

The E-10A was being developed to provide precision targeting for killing air and ground targets as well as time critical mobile targets including surface-to-air missiles, missile launchers, etc. The E-10A was going to shorten the timeline from the sensor to the shooter, support the Joint Strike Fighter (JSF) and F/A-22 concept of operations (CONOPS) and ensure that if the enemy shot at us we could rapidly target and eliminate the enemy. The E-10A's warfighting advantages included shortened sensor-to-shooter timelines, rapid decisive operations with respect to battle management and communications decisions close to the fight, persistent surveillance, detection and tracking of cruise missiles and horizontal integration.

The E-10A was designed with basically three subsystems. The MP-RTIP sensor, which was largely designed prior to work beginning on the other subsystems, was an active electronically scanned array radar that concurrently supports both air and ground based missions. The aircraft platform was the second subsystem. This subsystem was based on modifying a Boeing 767-400 extended range aircraft to carry the radar subsystem as well as the third subsystem, the BMC2 subsystem. The BMC2 subsystem included the radios, networking, computers, and software used by operators (both on and off-board the aircraft) to perform missions such as CMD and time sensitive targeting. Example application level functionality included track fusion, image exploitation, sensor planning and control, weapon planning, and engagement workflow control.

From a business perspective, the work was accomplished across a number of Government and contractor organizations, contracts, and locations. The principal Government acquisition organization was the Electronic Systems Center, supported by MITRE, located at Hanscom Air Force Base in Bedford, Massachusetts. The prime contractor was Northrop Grumman located in Melbourne, FL. Other Northrop Grumman sectors were involved as well as other companies such as General Dynamics, BAE, Boeing, and Raytheon. Hundreds of engineers were involved in the total program.

The FY04 Defense Planning Guidance[8] stated the "Air Force should program to deploy, by FY10, four aircraft equipped with the MP-RTIP radar for CMD and ground moving target indicator (GMTI) capability. The Air Force should assess transitioning to a new, wide-body aircraft as a part of the FY04 POM submission". The Abbreviated Acquisition Summary signed by Under Secretary of Defense (Acquisition, Technology, and Logistics) in April 03 delayed the 4-aircraft orbit requirement to FYl3. These aircraft were projected to have a spiral 1.0 capability with an open architecture that would allow growth into a full increment 1 (spiral 1.3) capability as documented in the JROC approved (JROCM 2907-04, 10 Nov 04) E-10A MC2A Capabilities Development Document. The FY05 Defense Authorization Act reduced the FY05 program by $115M. During the FY06 Program Objective Memorandum (POM) build the AF reprogrammed $165M into FY06 and $244M into FY07. The Air Force FY06 POM input to Office of Secretary of Defense (OSD) put the E-10 program on track to deliver four operational aircraft capable of meeting the FY04 DPG requirement of a four-aircraft CMD orbit.[8] However, the fourth aircraft was projected for delivery by 2015, a slip of two years.

The Office of the Secretary of Defense released a PBD 753 on 23 December 2004. The PBD put in place a $600M reduction ($300 M in FY06 and $300M in FY07) to the E-10 program (Appendix E). In addition to the non-programmatic reductions the PBD also directed the Air Force to restructure the E-10 program.

The E-l0A System Program Office (SPO) (ESC/MA) and the E-10 System Management Office (AFC2ISRC/SM) provided three options to the Secretary of the Air Force (SECAF) and the Air Force Chief of Staff on 21 Jan 05. Option 1 maintained the same program content found in the FY06 POM input, but delayed Initial Operational Capability (IOC) to 2018. Option 2 moved the test aircraft effort from a "prototype" effort (i.e., 767-400 test aircraft with a planned follow on to operational E-10A aircraft hosted on767-400 platforms) to a 767-400 MP-RTIP radar development aircraft. The actual E-10A operational wide body platform would be determined at a later date. This option would also give the AF the opportunity to move directly to an E-10A/B with ground (J-STARS-like) and airborne (AWACS-like) sensor capability on the same aircraft, if technology allowed. The ground and airborne radar capabilities would have had more capability than the current J-STARS and AWACS radars. Option 3 hosted a less capable version of the new MP-RTIP radar planned for a wide body platform on the current, but updated engines on the J-STARS aircraft. The SECAF and the Air Force Chief of Staff directed implementation of Option 2 and no further study on Option 3. Option 2 could still meet a 2018 IOC date for an E-10.

During the fall of 2005, the E-10 System Management Office, SPO and SAF/AQI conducted a Technical Feasibility Study on an E-10A/B, as requested by ACC/DO. The consulting firm of Booz Allen Hamilton accomplished a six-month, $l M study into combining the functions of an E-10A and a Block 40/45E-3 AWACS onto a single platform, in support of COMACC's 2025 Vision Force Flight Plan. Results were a definitive YES-FEASIBLE, and were briefed to COMACC on 13 Feb 06. At the same time OSD Quadrennial Defense Review (QDR) directed the AF to cancel production of the E-10A prior to a Milestone B decision and to continue with a Technology Demonstrator - essentially the "prototype" mentioned above.

At the brief, the Center asked ACC to sponsor an analysis of alternatives in order to transition the program from an E-10A to an E-10A/B in accordance with the Combat Air Force’s vision. COMACC decided that ACC needed another year to examine its 707 draw down recapitalization plan, which would be the precursor to any OSD-directed formal analyses of alternatives.

The decision by COMACC was to support the Technology Development Program (TDP) per QDR. On 30 May 06, SECAF & OSD/ATL signed an ADM approving the E-10 TDP. The plan was to flight test the MP-RTIP radar and conduct live demonstrations of CMD in FY 10/11.

3.1 Acquisition Strategy

The E-10A was being fielded under an evolutionary acquisition approach and incremental development strategy. The acquisition approach was complex with two sole source efforts and one competitive selection. The MP-RTIP radar was being developed on a 50/50 share contract with Northrop Grumman and Raytheon. The aircraft was procured through the Aeronautical Systems Center Wright-Patterson AFB OH via a Federal Acquisitions Regulation Part 12 sole source Contract with Boeing. Northrop Grumman was selected as the contractor for the BMC2. The E-10A Weapon System Integration (WSI) contract was a tri-company contract of Northrop Grumman-Raytheon-Boeing.

The E-10A acquisition strategy panel decided in Dec 2002 that the MC2A portion of the program, the weapon system integration, would best serve the Air Force if Northrop Grumman, Raytheon, and Boeing teamed on the effort. It was decided not to compete the sensor portion of the effort. Several companies possessed the BMC2 core competency so it was beneficial to compete that part of the program. This acquisition strategy was approved by the OSD 22 April 2003. The final Request for Proposal was received 23 Apr 2003 and the proposal was delivered the next day 24 April. The AF awarded a pre-System Development and Demonstration non-competitive contract to Northrop Grumman to develop the MC2A and also awarded the company a competitive contract to develop the BMC2. The Radar acquisition MP-RTIP was to be performed under a 50/50 teaming arrangement of Northrop Grumman and Raytheon, two fierce competitors. This forced marriage of two competitors presented program management and technical challenges to protect intellectual property while efficiently developing the system.. When the funding was cut for the MP-RTIP development, the 50/50 work share between Raytheon and Northrop Grumman was no longer viable. Northrop Grumman and Raytheon continued development of MP-RTIP under a modified work share agreement.

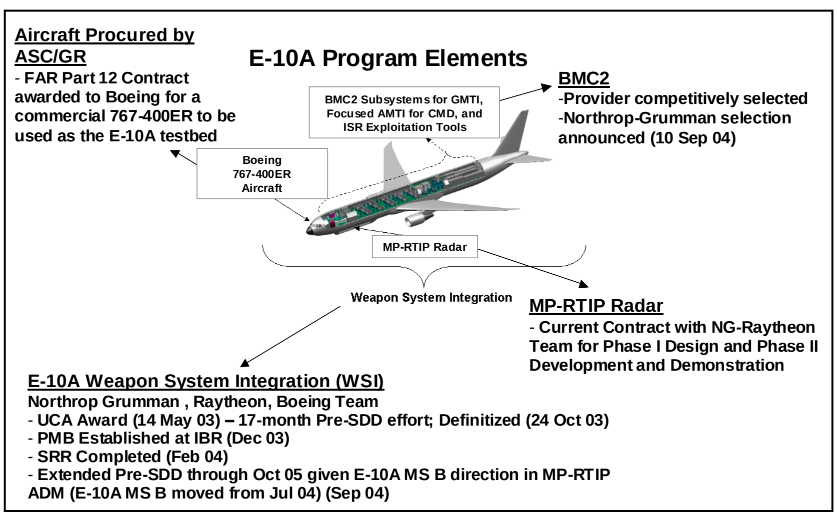

Figure 3-1. The E-10A Program Elements[9]

The E-10A acquisition history began within the RTIP, which was a pre-planned Product Improvement to the J-STARS E-8C weapon system.[6] The RTIP upgrade was designed to replace the J-STARS APY-3 radar with two-dimensional Active Electronically Scanned Array (2D‑AESA) radar, providing significant increases in ground surveillance capability to the warfighter as well as a new CMD capability. Following a meeting of the Defense Acquisition Board, on 28 January 2000, the Under Secretary of Defense (AT&L) approved J-STARS RTIP's entry into Engineering and Manufacturing Development (EMD). However, an EMD contract was never awarded.

1) The MP-RTIP Radar program was to develop modular, scalable 2D-AESA radars employing fourth generation, airborne phased array antenna technology and commercially available digital signal processing technology. The E-10A with MP-RTIP was to deliver a surface surveillance capability (GMTI and SAR imagery) as well as a focused AMTI capability to support the CMD mission. The MP-RTIP program also developed smaller radar for the Global Hawk UAV. For the Global Hawk MP-RTIP variant, only the development effort was funded by the E-10A program.[6]

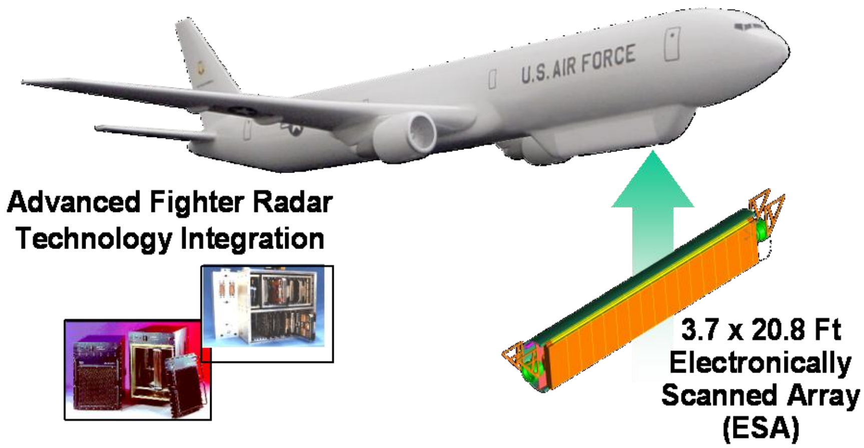

Figure 3-2. The MP-RTIP radar and its planned location[6]

2) A Boeing 767-400ER commercial aircraft was a Federal Acquisition Regulation Part 12 purchase; it was to be militarized for E-10A unique requirements. The first aircraft was purchased during the development phase and was to serve as the E-10A testbed. An additional six aircraft were to be purchased during the production phase and modified to become operational platforms. Had the MP-RTIP been designed to be shorter than 21 ft a smaller variant of the 767-400 (200 or 300) may have been sufficient.[9] The BMC2 suite included all of the non-radar and non-aircraft subsystems including the central computing architecture, networks, data storage, data manipulation and exploitation, communications and data link capabilities.

3) The E-10A WSI contract was for the integration of the MP-RTIP radar, the platform, and the BMC2.

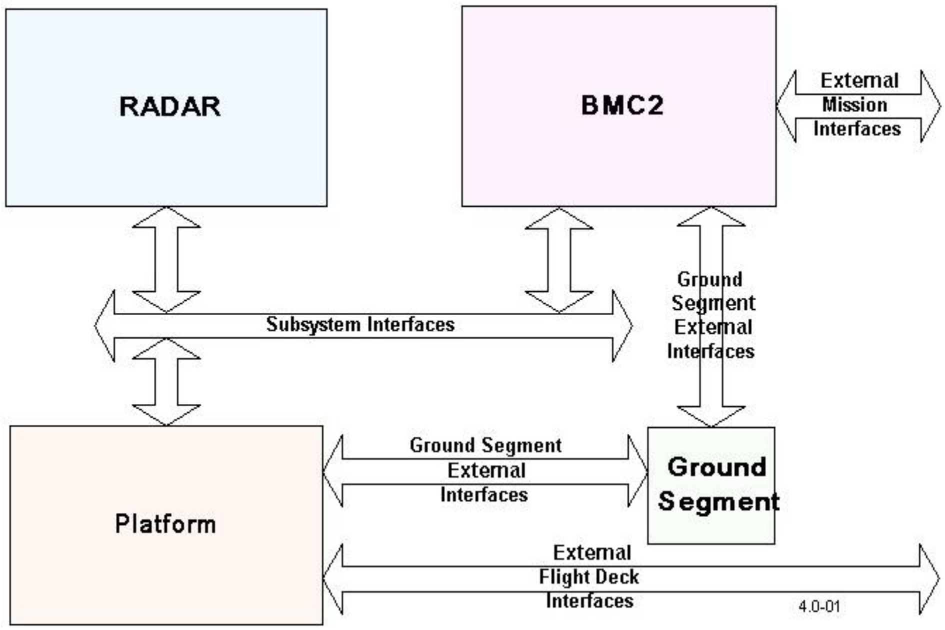

Figure 3-3. E-10A Functional Architecture[6]

3.1.1 Contractors

The E-10A program was managed through three contracts: the MP-RTIP Contract, the contract to purchase the commercial Boeing 767-400ER, and the E-10A WSI contract. The E-10A and MP-RTIP workflow is depicted in the figure below.

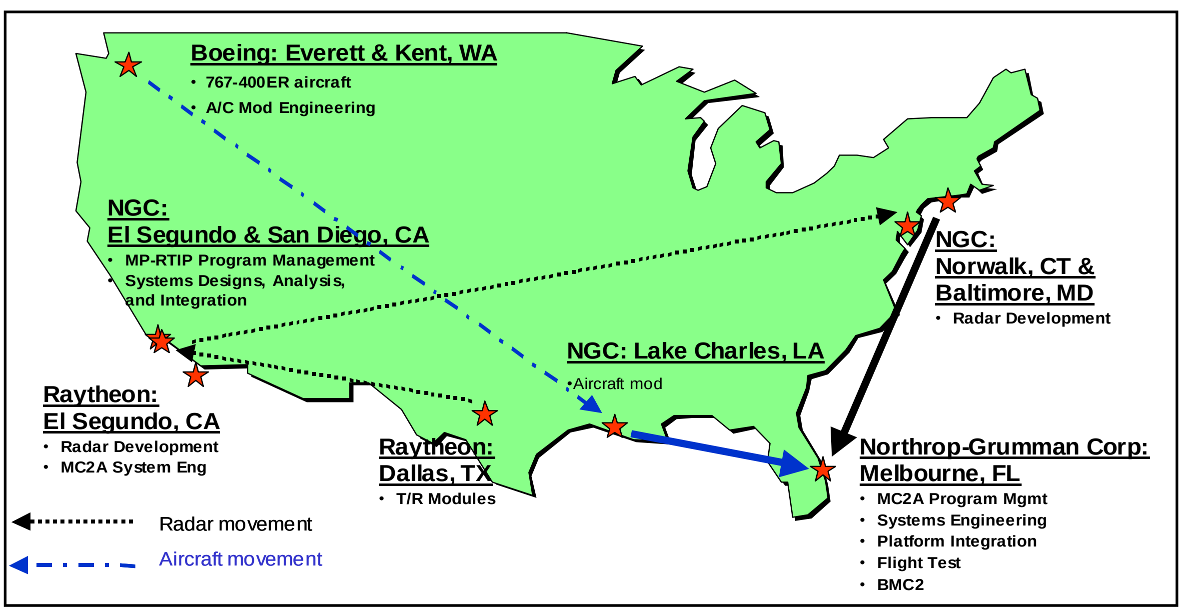

Figure 3-4. The Geographical Separation of the Contractors and the Planned Workflow[6]

3.1.2 MP-RTIP

The MP-RTIP contract strategy leveraged off two major defense contractors in a contractor teaming arrangement. Northrop Grumman Corp. and Raytheon Electronic Systems were brought together and equally shared the MP-RTIP development and production workscope. The workscope was broken out taking advantage of each company's strengths, and further refined with a 50/50 target workshare arrangement. The MP-RTIP contractor team and workshare are depicted below.

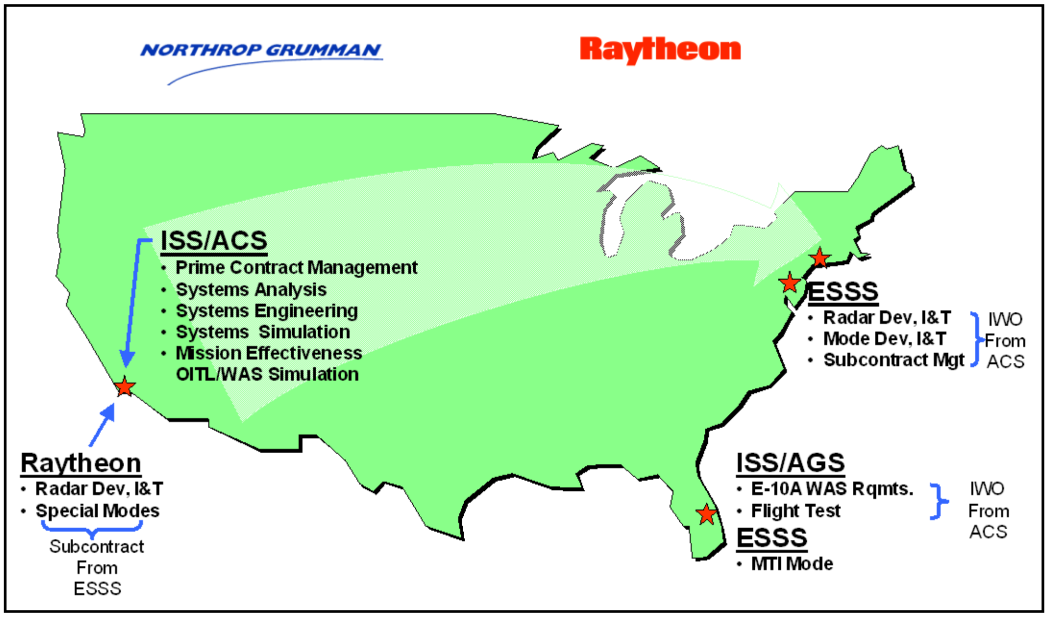

Figure 3-5. The MP-RTIP Contractor Teaming Arrangements[6]

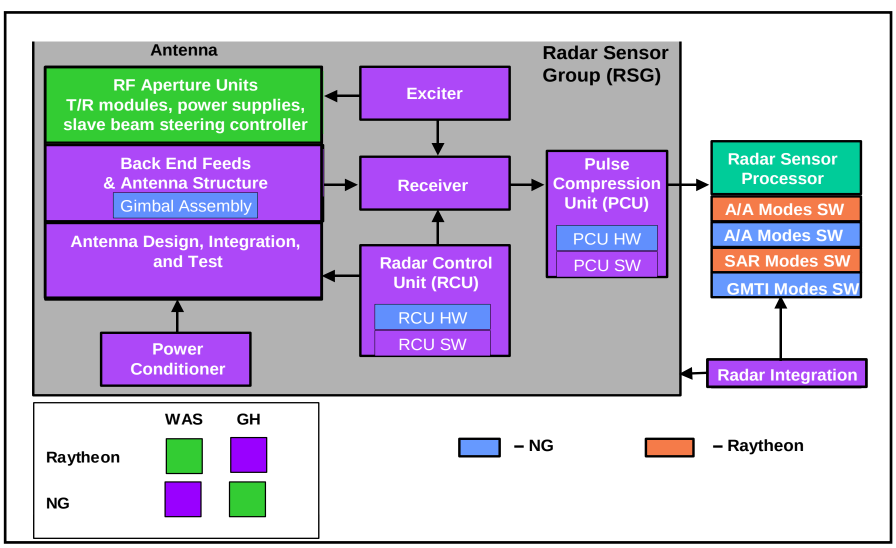

Figure 3-6. The MP-RTIP Contractor Workshare[6]

Problems arose from the forced marriage of the Northrop Grumman and Raytheon Corp. Fierce radar competitors, Northrop Grumman and Raytheon, were forced by the Air Force to collaborate on the development of the radar. This forced marriage of two competitors presented program management and technical challenges to protect intellectual property while efficiently developing the system. Northrop Grumman and Raytheon were responsible for different parts of the radar. In order to protect their parts of the MP-RTIP they considered proprietary they began ‘over labeling’ their subsystems and components as “proprietary.”

The Air Force learned that by forcing a marriage between two competitive contractors, coordination and integration of their final product can be difficult. The Air Force can potentially place itself in a position to be called upon to intervene in decisions of what is and isn’t proprietary, which is a position the Air Force does not want to be in. As a result, meaningful risk assessments are difficult to make because of the proprietary communication barrier. Worse, the risk assessments can be too optimistic and it is easy to hide issues behind the proprietary barrier. Problems continue to be worked in corporate stovepipes, rather than being elevated in a timely manner to the cross-corporate technical leadership. Although the government forced the two companies to team, both companies had to come to agreement on the nature of the teaming e.g. work share. That agreement was based on the program effort and end products as defined at the beginning of the program. As has been described here, the program changed dramatically over time and the assumptions of the original agreement were no longer true. Although NG and Raytheon continued to develop MP-RTIP, the restructuring and eventual cancellation of the E-10 program forced changes in the original teaming agreement.

One can’t force a marriage with a “pre-nuptial agreement” then change the agreement after the marriage and expect it to last. This described the forced arrangement between two competitors, Northrop Grumman and Raytheon on the radar development and the reduction of funds and restructuring during the program.

3.2 BMC2

The BMC2 suite included all of the non-radar and non-aircraft subsystems including the central computing architecture, networks, data storage, data manipulation and exploitation, communications and data link capabilities. The BMC2 suite was to have mission tailorable seats for personnel/operators, next generation battle management decision aids, tailored, fast, and smart information push to the warfighter and sensor-to-shooter capability for air and ground moving targets. The BMC2 was going to provide horizontal integration including intelligence systems and interfaces as well as a distributed common ground system and a regional global information grid. The advanced communications included a Joint Tactical Radio System, SATCOM (satellite communications), HF, UHF, VHF antennae, Single Channel Ground and Airborne Radio System (SINCGARS), Link 11, 16[iii] and a multi-platform common data link.[6]

[iii] **Link 11, 16 are** North Atlantic Treaty Organization (NATO) secure radio systems that provide Line-Of-Sight (LOS) communications. They interconnect air, surface, subsurface, and ground-based tactical data systems, and are used for the exchange of tactical data among the military units of the participating nations. Links 11, 16 will be deployed in peacetime, crisis, and war to support NATO and Allied warfare taskings.

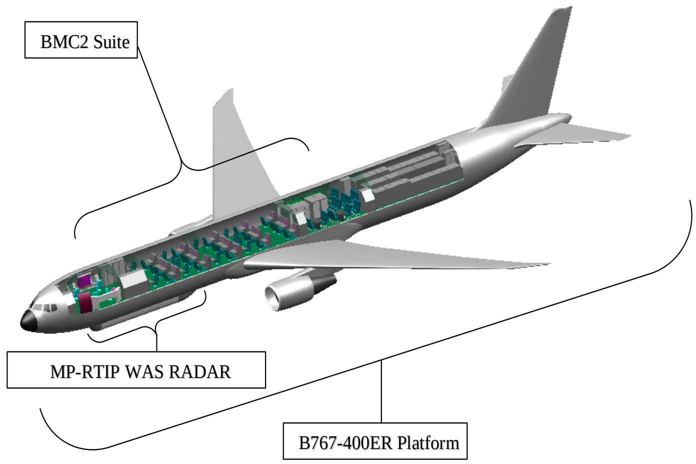

Figure 3-7. E-10A with the two internal subsystems in a Boeing 767-400ER aircraft[6]

3.2.1 The Role of the BMC2 Suite

The concept of the on-board command and control personnel and their duties included a modular, reconfigurable workstation arrangement with common work space stations. The various sections could be reconfigured quickly depending on the mission and curtains could be drawn to partition groups with common duties. (Figure 3-8) The reconfigurable ground staff area could be set up for different mission needs analyses.

Figure 3-8. Conceptual arrangement of the BMC2 suite of the E-10A[6]

One of the major issues that surfaced during the E-10A/B program was: "Do we need an airborne command post? If so, how many people should be onboard the aircraft in order to conduct a BMC2 mission given the proposed capabilities of the E-10?" In their analysis of conducting a BMC^2 mission on the E-10A, Aptima developed a model using *team optimal design methodology* that proposed a crew of 25 to perform the BMC^2 mission.[10] Some planners felt by having large numbers of personnel onboard the E-10B, the Air Force put personnel at risk unnecessarily. Others felt the BMC2 staff needed to be as close to the kill chain as possible and by having them onboard the aircraft they could enable decisions closer to the fight and shorten sensor-to-shooter timelines. If they could successfully perform their duties on the ground in a command center rather than airborne, there was reduced risk in performing the mission. Another consideration that arose was the physics question of simultaneously operating multiple radar systems (one for air and one for ground) on a single platform without creating mission degradation. This was never demonstrated.

The Spiral C consideration, SIGINT/ELINT, onboard the same platform was never planned as well. This group of specialized personnel onboard the E-10C would have to have a quiet environment perhaps secluded from the other BMC2 staff. The physics of having high energy radars coupled with SIGINT/ELINT technology was never demonstrated on a single platform during the E-10A program.

3.2.2 767-400ER Commercial (Green) Aircraft

A contract was awarded to the Boeing Company, Integrated Defense Systems in Seattle, Washington for a Boeing 767-400ER commercial aircraft (Figure 3-9). During SDD, this aircraft was to be provided as Government Furnished Equipment (GFE) to the WSI Contractor to be militarized for E-10A Weapons System Requirements and serve as the E-10A testbed. It never underwent systems integration and the aircraft was later sold as a very important person transport aircraft to the country of Bahrain.

Figure 3-9. The Boeing 767-400ER[6]

3.2.3 Weapon System Integration (WSI)

The E-10A WSI pre-SDD contract was awarded to Northrop Grumman via letter contract dated 14 May 2003 and definitized 24 October 2003 with an effective date of 1 May 2003. The program was managed by Integrated Systems (IS) Airborne Ground Surveillance & Battle Management Systems (AGS & BMS), located in Melbourne, Florida. The tri-co team included elements of Northrop Grumman Integrated Systems in Melbourne, Florida, Raytheon Company Space and Airborne Systems in El Segundo, California and the Boeing Company, Integrated Defense Systems in Seattle, Washington. The selection of Northrop-Grumman as the BMC2 provider was announced on 10 Sep 04. The BMC2 effort was to be accomplished by Northrop-Grumman under this WSI contract.

3.2.4 MC2A Evolution

The plan for MC2A evolution was to implement the function of the Joint STARS E-8C into the E-10A in Spiral 1. Spiral 2 would leverage E-3 AWACS SENTRY Block 40/45 technology into the E-10A. (Figure 3-10).[6]

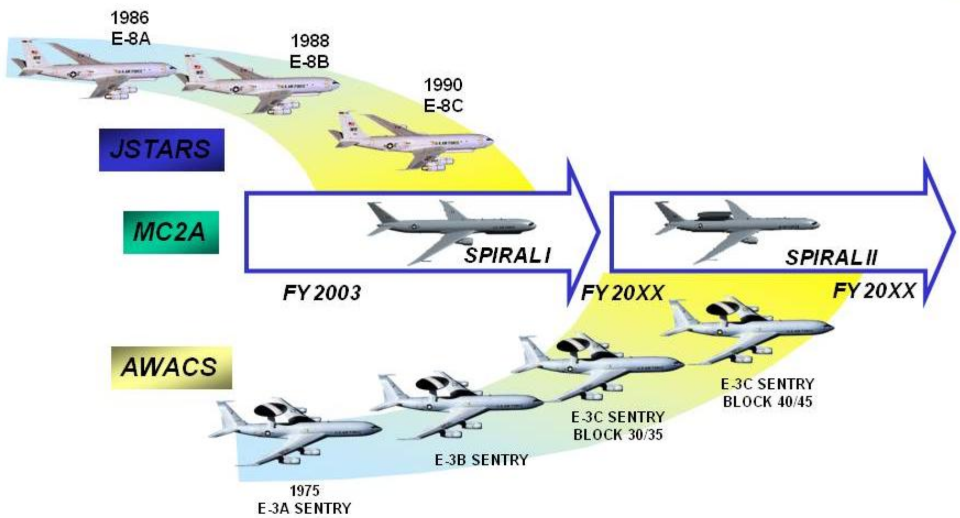

Figure 3-10. MC2A Evolution[6]

3.3 System Development Plan

3.3.1 Development Phases

The E-10A program, as the next generation WAS manned airborne platform, was structured to deliver CMD, advanced integrated ground and air surveillance and targeting capabilities, as well as associated BMC2.

The approved pre-SDD acquisition strategy was comprised of four lanes[6]:

13. ASC/GR's purchase of one Boeing 767-400ER that would become GFE to the WSI prime contractor for modifications that would result in an E-10A testbed for the large variant of the MP-RTIP radar (Contract Awarded, 15 Aug 03).
14. Competition of the BMC2 subsystem–selected provider to become a directed subcontractor to the WSI prime contractor (Contract Awarded, 14 Sep 04).
15. Award of the WSI contract to integrate MP-RTIP, BMC2, and aircraft subsystems to result in an E-10A Weapon System (Contract Awarded, 14 May 03).
16. Continuation of the MP-RTIP radar development effort to build and test the E-10A's radar that would become GFE to the WSI prime contractor (SDD Contract Awarded,
30 Apr 04).

Leveraging from the successes of the pre-SDD acquisition execution, the SDD acquisition strategy was single-laned: subsequent to a successful Milestone B, the existing WSI contract with Northrop Grumman was to be modified to develop, build, and test an E-10A Weapon System, modifying the GFE 767-400ER, integrating the GFE MP-RTIP radar and developing the BMC2 subsystem to meet the user's requirement within cost and schedule.

3.3.2 Program Budget Decision 753

Prior to PBD 753, the E-10A program was proceeding to a Milestone B decision in April 2005. A congressional funding reduction of $300M in FY05 as well as the OSD's FY06-FY07 funding reductions ($300M) that accompanied the restructuring direction resulted in cancellation of the scheduled Milestone B Defense Acquisition Board review. Restructuring options were briefed to senior Air Force leadership and the resultant recommended option was proposed to the Director, Defense Systems (D, DS) in February 2005. This recommended option provided for the developmental flight test and verification of the MP-RTIP WAS sensor during the TDP. This MP-RTIP flight test schedule was consistent with the approved Acquisition Program Baseline (APB) for MP-RTIP, a separate ACAT (Acquisition Category) ID program.[iv] The TDP includes Developmental Test and Evaluation of the MP-RTIP radar and execution of the CMD demonstrations. Agreement in principle was reached with the D, DS to proceed in planning for the restructured program and to seek formal OSD approval of the restructured program in the summer of 2005. In December 2005, Program Decision Memorandum (PDM) II eliminated funding for E-10A SDD and Production. The QDR Report was consistent with the PDM II direction. A subsequent Overarching Integrated Product Team (OIPT), chaired by OSD/AT&L (DS), on 9 March 2006, codified the way forward for implementing the E-10A WAS TDP.

The stakeholders (ACC and Department of Defense) held different visions of what the E-10A was going to provide for the warfighter. OSD supported the MC2A portion of the program but did not support the BMC2. ACC wanted an airborne BMC2 capability but never settled on how many aircraft to request to field for the mission. Early in the E-10 program the Air Force and Navy discussed a common airframe. However, this proposal would have required the Navy to buy a 767-sized aircraft, considerably larger than the 737-sized aircraft they preferred. Neither the Air Force nor the Navy was prepared to compromise their own plans by agreeing to the use of a common airframe and the Navy dropped out of the planning.. The differences should have been settled on in the earlier stages of the program.

ACC was an early supporter and stakeholder of the E-10A program. Chief of Staff of the Air Force and former COMACC General Jumper was fully supportive of the E-10. "The E-10 delivers transformational integration of the sum of the wisdom of our manned, unmanned, and space platforms ending up with a cursor over the target." ACC approved the CONOPS on 8 May 2001 that described the flow down of requirements. There was clear customer sponsorship of the program. ACC played a very active role in the E-10A program throughout the 4-5 years it was active. ACC served as the MP-RTIP lead operating command. They supported the development of the E-10A MP-RTIP and then helped develop CONOPS and operational requirements documents for the Global Hawk MP-RTIP. ACC supported Air Force Operational Test and Evaluation Center for all Global Hawk MP-RTIP OT&E activities. ACC represented the CAF

[iv] ACAT I programs are Major Defense Acquisition Programs (MDAPs). ACAT I programs have two sub-categories. ACAT ID, for which the Milestone Decision Authority (MDA) is USD (A&T) is one of the programs. The D refers to the Defense Acquisition Board (DAB), which advises the USD (A&T) at major decision points.

(Combat Air Forces) as the decision-making authority for POM submissions for the Global Hawk MP-RTIP development life cycle.

The E-10A program was considered dead as of the beginning of FY08 however on 1 Jun 2007 the Air Force awarded Northrop Grumman $12.2M for work related to the E-10A. ESC Hanscom awarded the 12 month contract for a "seamless continuation of pre-SDD program to complete limited risk reduction activities in the areas of BMC2 mission execution and BMC2 kill chain without introducing new requirements."[11] The funds covered the BMC2 and kill-chain risk reduction of the WSI program efforts during the first phase of technology development.

3.4 Model-Based Systems Engineering[12]

The Government and industry employed Model Based Systems Engineering (MBSE) principles as an integral part of the E-10A's systems engineering approach. MBSE lends itself nicely to large-scale, distributed, real-time systems like the E-10A. The use of MBSE helped balance requirements and reduce risks associated with the development of the E-10A.

The application of MBSE with robust, Unified Machine Language-based executable models for the E-10A requirements and initial design work was a success. This approach mitigated risks associated with large heterogeneous organizations attempting to collaborate to build a leading edge large scale distributed real-time system.

There were certain technical and sociological (that is people working with people) challenges that were encountered on the E-10A program. These challenges were significant contributors toward the decision to use an MBSE approach for both systems and software engineering.

3.4.1 MBSE and the Sociological Challenges of the E-10A Program[12]

For programs with the complexity, size, and intended long system life-cycle that was envisioned for the E-10A, the sociological issues should not be underestimated by a program office. These issues are not typically given the attention they need. Too often the immediate focus is on what technologies should be part of the solution, rather than on how a large number of geographically separated engineers can collaborate to get a job done. From Figure 3-4 (on page 18) one can see the geographical separation of the contractors on the E-10A program was formidable.

The first conclusion one could reach is that there was a significant need for common mechanisms to allow a variety of people to collaborate about the system. Associated with this was the need to achieve common understanding of key technical decisions by the project team. While this sounds simple and obvious, developing an approach that supports meaningful reasoning can be a significant challenge. Clearly, there was a critical need for quality data at higher levels of abstraction than software source code. Tools and data were needed to be used that support:

- Multi-disciplinary collaboration
- Multi-organizational collaboration
- Information hiding
- Multiple levels of abstraction
- Data currency
- Data consistency
- Data correctness

Multi-disciplinary and organizational collaboration is a must for effective systems engineering. Individual groups using their own tools and data put at risk the usefulness of their results. Reasons include the difficulty of people understanding each other's results when they use different tools, languages, and data; and the likelihood that these differences result in a significant manual effort to keep the individual results synchronized. The experience from the E-10A program was that given the fast-paced nature of system development, manual synchronization was doomed to fail.

For example, computer/network performance analysts have typically performed a manual translation of the software design into formats that performance analysts/tools can use. Since software engineers are paid to show up to work and build software, the performance engineers quickly end up with a representation of the software that is outdated and decreases the value of their analysis. In addition, if technical management (such as chief engineers and chief architects) are to take action based on the analysis, they end up having to invest significant time understanding both the software and performance engineers' representations of overlapping data. The combination of stale data and different "look and feel" decreases usefulness which can drive up program cost.

Information hiding is an important technique. Information hiding techniques have recently become important in a number of application areas.[13] Digital, audio, video, and pictures are increasingly furnished with distinguishing but imperceptible marks, which may contain a hidden copyright notice or serial number or even help to prevent unauthorized copying directly. Military communications systems make increasing use of traffic security techniques which, rather than merely concealing the content of a message using encryption, seek to conceal its sender, its receiver or its very existence. A reason for information hiding in a project like the E-10A was the need to truly hide data from certain people, yet expose it to other people. For example, since the E-10A was a military project, parts of it were classified at different security levels. While classified data must be protected, one must also ensure that data are available to as many people that need it when they need it and if they have a need to know.

The last three bullets shown on page 25 are not exciting, but are "bread and butter" principles that can be difficult to fully support. Data currency is about knowing whether one is looking at up-to-date information (or at least, being able to map the data to specific builds or milestones). Large programs can take several years to develop, and system sustainment might be done over a number of decades. Left unmanaged, there will be a number of mistaken decisions made simply because the person did not realize they were viewing obsolete data. Consistency aims to achieve harmony among data both horizontally (e.g., between software components) and vertically (e.g., between system and software abstraction levels). Too often, requirements and design artifacts are loosely structured textual statements or graphics (e.g., briefing charts) where there is minimal computer-based enforcement of consistency available.

The cost of manual enforcement (not to mention that this sort of work is not something people tend to like to do – and therefore don't do particularly well) grows as the amount of requirements and design data increase. Finally, data correctness refers to being able to assess the impact of a design choice on the system's ability to meet requirements. Typically, software engineering has a long way to go before it approaches the rigor of more established fields such as radar engineering with respect to analysis.

There were a number of technical challenges identified early in E-10A planning that were anticipated. Challenges identified include:

- Location transparency (internal and external to the aircraft)
- Shared resources (E-10A supported numerous users in a dynamic environment)
- Range of hard and soft timing and performance requirements
- Portability of crew (within E-10A and with other Air Force Platforms)
- Reuse of legacy components
- Security
- Openness and extensibility
- System dynamics (dealing with changing environment and faults)

The ones focused on most in arriving at the need for an MBSE approach were the “moving parts” related challenges. Here, moving parts refer to system dynamics. It is often not until the integration and testing phases that issues with things like system dynamics, performance, and subsystem/component interfaces are discovered. The cost of rework at that point can be prohibitive (not to mention by that time one is often running short on both schedule and funding). A contributor to inadequately detecting system dynamic (moving parts) type problems in the requirements and design phases of a program are the tools and products used during these phases.

Requirements and design products are often static in nature. For example, one typically writes requirements as textual sentences with the key word “shall” in it; e.g., “The system shall track objects that are moving on the ground.” Likewise, design artifacts tend to be static pictures of components and their relationships. Given these fixed products, it should not be a surprise that an engineer has trouble foreseeing dynamic problems.

The approach used for the E-10A system and software initial design included:

- Architecture-centric focus;
- Executable UML-based design models integrated across security levels;
- Publish and subscribe communication in the executable design model;
- Integrated design and analysis, including use of the UML Profile for Schedulability, Performance, and Time;
- Computer enforced linkage of requirements and design;
- Early involvement of testers in definition of system threads.

3.4.2 Architecture-Centric Approach for the E-10A

An architecture-centric approach is one where there is an emphasis on the patterns of connections among system components with defined constraints. The identification of critical system views and the accompanying approach for addressing these views can be a powerful mechanism for making people aware of key technical decisions. E-10A used a variation of the architecture views proposed by Bruce Douglass[14] which are subsystem and component view, distribution view, concurrency and resource view, safety and reliability view, and deployment view. A view for security was added. The set used by E-10A is shown in Figure 3-11. While Northrop Grumman was committed to producing a robust model of the design, they also thought that emphasis on these views was in itself a useful abstraction and had the benefit of not risking the reader getting lost inside a large UML model.

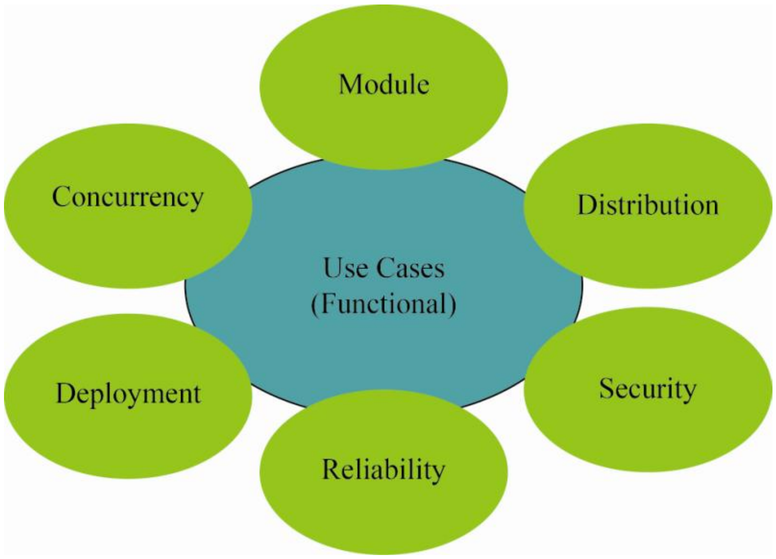

Figure 3-11. E-10A Architecture Views

The E-10A/BMC2 software architecture description document Northrop Grumman produced ended up having sections for these views where the view diagrams were extracts from the UML system model.

It is a key point that the MDSE process did not "replace" the contractor's Capability Maturity Model Integration system engineering process, but rather enhanced the process with robust model driven practices and tools as shown in Figure 3-12. The associated architecture modeling concept was an enabler to perform comprehensive analysis of the system trade space early in the product life cycle for both the E-10A development and its planned integration with other C^2ISR platforms.

Features		*Traditional System Engineering Techniques*		*E-10A Model Driven System Engineering Techniques*
Requirements-driven	☑	Text based tools (DOORS/SLATE) used as Requirements Management repository	☑	Integrated Text/UML tools provide central repository for complete traceability
Integrated visual model repository	☐	Heterogeneous mix of visual modeling artifacts using various languages and tool formats; must be manually linked	☑	Architecture Model serves as common repository for system architecture and related SE artifacts – "visual bandwidth"
Shared knowledge base	☐	Ad hoc domain-specific and architectural rules scattered in various documents	☑	Architecture Model is augmented with domain-specific and architectural integrity rules
Common SE/SWE language	☐	Heterogeneous mix of proprietary and standard languages	☑	UML is common language for specifying SE and SWE work artifacts
V&V	☐	Mostly manual V&V at during formal integration	☑	Early Test/Customer participation starting with preliminary design

Figure 3-12. Model Driven Systems Engineering Features[12]

4 Summary/Conclusion

In summary, the E-10A program was an ambitious program. Perhaps it was too ambitious. The concept of incorporating three missions on one platform may have led to its demise. The physics of generating high energy radar (MP-RTIP) from an airborne platform that was also performing a critical signal listening (SIGINT) mission had never been demonstrated. The program was terminated in 2006 for more pressing Service priorities. Although there was ample support and involvement from the direct customer, ACC, all stakeholders and decision makers (OSD) didn't necessarily agree on the scope of the E-10 program.

Those aircraft the E-10A was to replace continue to age and the mission and roles the E-10A was to fill remain. The E-10A had a major data integration and dissemination role of ingesting data from many sources including Global Hawks and fusing those data making a wide range of data products available to the enterprise. It will be interesting to see as the GMTI Initial Capabilities Document and GMTI analyses of alternatives evolve at ACC whether this concept of an airborne element performing this function is a requirement of the next generation system.

Two products from the E-10 program have been successfully transitioned to other applications. A scaled version (1.5 ft X 5 ft) of the MP-RTIP radar has been developed for the Global Hawk unmanned aerial vehicle to track moving ground targets. The application of MBSE with robust, UML-based executable models for the E-10A requirements and initial design work was a success. MBSE applied to the program mitigated risks associated with large heterogeneous organizations attempting to collaborate to build a leading edge large scale distributed real-time system like the E-10A. MBSE is now being applied to other programs by DoD and companies including MITRE, Northrop Grumman, and Lockheed Martin to name a few.

ACC is currently performing analyses of alternatives for the ISR mission and may come to the conclusion that something like the E-10A is still needed. In a recent Defense News article[14] COMACC Gen William Fraser is quoted as saying "the AF is looking at how its next generation radar aircraft potentially could track threats from maritime targets to ballistic missiles." The article goes on to say "This is reminiscent of the AF's cancelled E-10A program, however, the AF's ancient Boeing 707-based E-8s are suffering numerous problems, including wing spar cracks and engines that can barely power the jets on takeoff in hot climates. The AF is examining whether it will keep those jets in service or replace them. One option being examined is using a version of the Navy's new Boeing 737-based P-8 Poseidon maritime patrol aircraft, which is being outfitted with an advanced 360-degree sea-scanning radar."

Appendix A: A Framework for Systems Engineering Concept and Responsibility Domains

Concept Domain	Responsibility Domain		
	1. Contractor Responsibility	**2. Shared Responsibility**	**3. Government Responsibility**
A. Requirements Definition and Management			
B. Systems Architecting and Conceptual Design			
C. System and Subsystem Detailed Design and Implementation			
D. Systems and Interface Integration			
E. Validation and Verification			
F. Deployment and Post Deployment			
G. Life Cycle Support			
H. Risk Assessment and Management			
I. System and Program Management			

This Friedman-Sage matrix is included as an exercise for the student. Following the explanation in Section 1.5 of this Case Study develop 4-6 systems engineering learning principles from the case study and then insert them into the matrix based on whether they were a contractor responsibility, a government responsibility, or a shared responsibility between the government and the contractor.

Appendix B: Author Biography

William Albery, Ph.D. is the Chief Scientist of Innovative Technologies Corporation (ITC) in Dayton, Ohio. He is a retired 36-year civilian (U.S. Air Force) who technically managed the Wright Patterson AFB human centrifuge facility. From 2005-2008, he was the Crew Interface Systems Engineer on the Air Force Research Laboratory's Rotary-Wing Brownout (RWB) study. In 2007, he organized and now leads a North Atlantic Treaty Organization (NATO) RTO Task Group on RWB that has 9 countries and 20 scientists/engineers and pilots participating. He received his Bachelor of Science degree in Systems Engineering from Wright State University (WSU) in 1971, his Masters Degree in Biomedical Engineering from The Ohio State University (OSU) in 1976, and his Doctorate (PhD) in Biomedical Sciences from WSU in 1987. He is an Associate Professor in the WSU School of Medicine, a Fellow of the Aerospace Medical Association, a Fellow of the Aerospace Human Factors Association, and past President of the SAFE Association. Dr. Albery was a co-author for the AFIT MQ-1/9 Case Study and the author of a Case Study for the C-17. He is a co-PI on the MH-53J/M Case Study and the PI on the E-10 Case Study, also for the AFIT Center for Systems Engineering.

THE UNDER SECRETARY OF DEFENSE

3010 DEFENSE PENTAGON
WASHINGTON, DC 20301-3010

ACQUISITION, TECHNOLOGY AND LOGISTICS

MAY 30 2006

MEMORANDUM FOR THE SECRETARY OF THE AIR FORCE

SUBJECT: E-10A Wide Area Surveillance (WAS) Technology Development Program (TDP) Acquisition Strategy (AS), Test and Evaluation Strategy (T&ES), and Acquisition Decision Memorandum (ADM)

I approve the attached, combined AS and T&ES for the E-10A WAS TDP, consistent with the Quadrennial Defense Review Report (February 6, 2006). The Department recognizes the value in characterizing the WAS Multi-Platform Radar Technology Insertion Program (MP-RTIP) radar on a test-bed air platform to preserve future capability options. This decision and the TDP effort does not prejudge any future decisions for an E-10A Weapon System Program.

Consistent with the schedule contained in the AS, the Air Force is expected to complete the TDP demonstrations by 2011. The TDP will not adversely affect the Global Hawk MP-RTIP development and delivery.

My point of contact for this program is Mona Lush, Deputy Director Acquisition Management, Acquisition Resources and Analysis (OUSD(AT&L)), (703) 697-0476.

Kenneth Krieg

cc: DAB Principals
DAB Advisors

THE UNDER SECRETARY OF DEFENSE

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ACQUISTION, TECHNOLOGY AND LOGISTICS

MAY 3 0 2007

MEMORANDUM FOR THE SECRETARY OF THE AIR FORCE

SUBJECT: Final Termination Acquisition Decision Memorandum (ADM) for E-10A Technology Development Program (TDP)

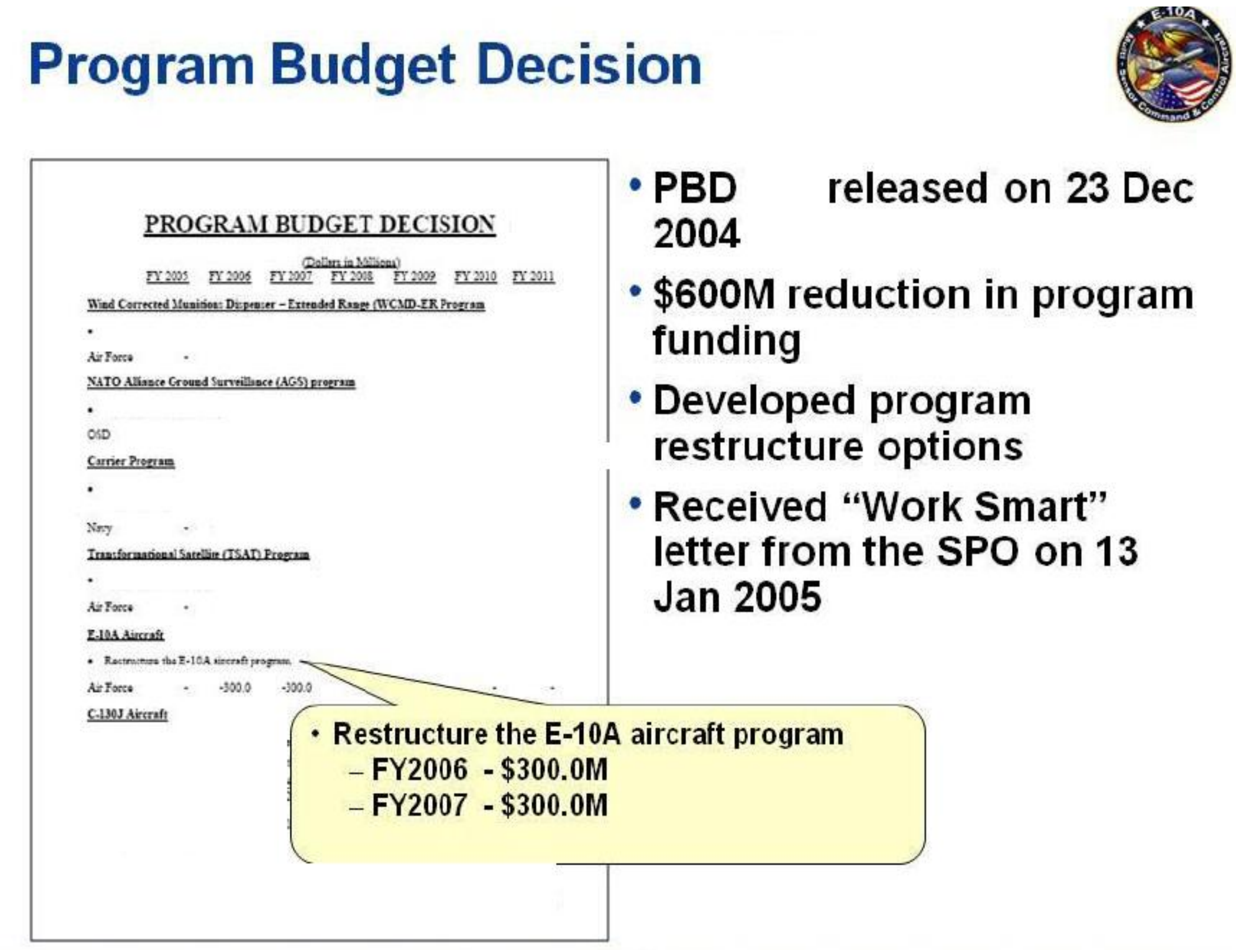
This memorandum is a follow-up to my E-10A TDP ADM dated February 21, 2007, which directed the Air Force to end the E-10A TDP and that portion of the Multi-Platform Radar Technology Insertion Program (MP-RTIP) that was developing the radar for installation on the E-10A. I directed a review of the close-out plan including impacts and costs to program termination.

As a result of this review, I authorize the Air Force to continue limited risk reduction activities in the areas of Battle Management Command and Control (BMC2) Mission Execution, BMC2 Kill Chain, and Radar Hardware Verification. These activities are listed in descending priority order and will be conducted during the 12-month period beginning June 1, 2007, using the best suited contract type, and will not exceed $24 million dollars of previously allocated FY 2007 funds. The goal of this risk reduction effort is to provide options for making an informed decision on the effective use of the E-10A MP-RTIP developed technologies for current and near-term operational systems including Global Hawk and Joint Surveillance Target Attack Radar System. The E-10 radar array activity will be limited to acceptance testing necessary to establish compliance with contract requirements and to obtain minimum engineering performance data to validate the Transmitter/Receiver module performance model.

The Air Force shall ensure these activities will not negatively impact the Global Hawk Block 40 MP-RTIP development and flight testing that continues through FY 2009.

My points of contact are Ms. Mona Lush, Deputy Director, Acquisition Management, Acquisition Resources & Analysis, 703-697-1660, and Mr. Dyke Weatherington, Deputy, Unmanned Aircraft Planning Task Force, 703-695-6188.

Kenneth J. Krieg


Program Budget Decision
PROGRAM BUDGET DECISION
(Dollars in Millions)
FY 2005 FY 2006 FY 2007 FY 2008 FY 2009 FY 2010 FY 2011
Wind Corrected Munitions Dispenser – Extended Range (WCMD-ER) Program
Air Force
NATO Alliance Ground Surveillance (AGS) program
OSD
Carrier Program
Navy
Transformational Satellite (TSAT) Program
Air Force
E-10A Aircraft
Restructure the E-10A aircraft program.
Air Force - -300.0 -300.0
C-130J Aircraft
Restructure the E-10A aircraft program
– FY2006 - $300.0M
– FY2007 - $300.0M
PBD released on 23 Dec 2004
$600M reduction in program funding
Developed program restructure options
Received "Work Smart" letter from the SPO on 13 Jan 2005

Appendix F: DPG

U.S. AIR FORCE

Defense Planning Guidance

MC2A Increment 1

FY04-09 Defense Planning Guidance (DPG)
Special Access Program (SAP) Annex (U)
July 12, 2002

(U) Air Force should program to deploy, by FY 2012, four aircraft equipped with the Multi-Platform Radar Technology Insertion Program radar for cruise missile defense and ground moving target indicator capability. The Air Force should assess transitioning to a new wide-body aircraft as a part of the FY04 POM submission.

29 Sep 03 *Integrity - Service - Excellence*

Appendix G: Acronyms

AESA	Active Electronically Scanned Array
AEW&C	Airborne Early Warning and Control
AMTI	Air Moving Target Indicator
AWACS	Airborne Warning and Control System
BMC2	Battle Management Command and Control
CMD	Cruise Missile Defense
CONOPS	Concept of Operations
COMACC	Commander, Air Combat Command
DAU	Defense Acquisition University
DoD	Department of Defense
DoD AF	Department of Defense Architecture Framework
EMD	Engineering and Manufacturing Development
GFE	Government Furnished Equipment
GMTI	Ground Moving Target Indicator
GPS	Global Positioning System
JROC	Joint Requirements Oversight Council
ISR	Intelligence, Surveillance, and Reconnaissance
J-STARS	Joint Surveillance Target Attack Radar
MBSE	Model Based Systems Engineering
MC2A	Multi-sensor Command and Control Aircraft
MESA	Multirole Electronically Scanned Radar
MP-RTIP	Multi-Platform Radar Technology Insertion Program
OSD	Office of the Secretary of Defense
PBD	Program Budget Decision
POM	Program Objective Memorandum
SAR	Synthetic Aperture Radar
SDD	System Development and Demonstration
SIGINT	Signals Intelligence
TST	Time Sensitive Targeting
2D-AESA	Two-Dimensional Active Electronically Scanned Array
UAV	Unmanned Aerial Vehicle
WAS	Wide Area Surveillance

[1] Ferrara, Joe, "DOD's 5000 Documents: Evolution and Change in Defense Acquisition Policy" *Acquisition Review Quarterly*, Fall 1996, pp109-130.

[2] Department of Defense Directive 5000.1, Subj: Acquisition of Major Defense Systems, DDR&E, 13 July 1971.

[3] DoD Architecture Framework, Version 1.5, 23 April 2007.

[4] Friedman, George and Sage, Andrew, *Case Studies of Systems Engineering and Management*, INCOSE Systems Engineering Journal.

[5] Dawes A, Boeing E-10A The USAF's New Jack-of-all-Trades, Air International Magazine, Aug 2003

[7]Boeing767-400ERTechnicalCharacteristics, http://www.boeing.com/commercial/767family/pf/pf_ 400prod.html.

[8] FY04-09, Defense Planning Guidance, MC^{2}A Increment 1 (Appendix F).

[9] E-10A Program Overview Briefing, ESC/HGB, Hanscom AFB, 21 October 2005

[10] Levchuk M, Paley M, Levchuk Y, Clark D, *Modeling, Simulation, and Experimentation for the E-10 Command and Control Aircraft*, Proceedings of the Organizational Design and Management (ODAM) VIII Special 20th Aloha Anniversary Symposium, Maui, HI, 2007.

[11] Aviation Week, Air Force Extends otherwise Defunct E-10A, 5 June 2007, p.09.

[12] Wheeler T, Brooks M *Experiences in Applying Architecture-Centric Model Based System Engineering to Large-Scale, Distributed, Real-Time Systems, Technical Report*, MITRE Corp, Cleared by Hanscom AFB Public Affairs Case #07-0838, 2007.

[13] Petitcolas F, Anderson R, Kuhn M, Information Hiding: A Survey, *Proceedings of the IEEE*, special issue on protection of multimedia content, 87(7):1062{1078, July 1999.

[14] B. Douglass, "*Real-Time Design Patterns*," ISBN 0-201-69956-7, Addison-Wesley, 2003, p. 68.