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Early Application of Systems Engineering: A Historical Perspective

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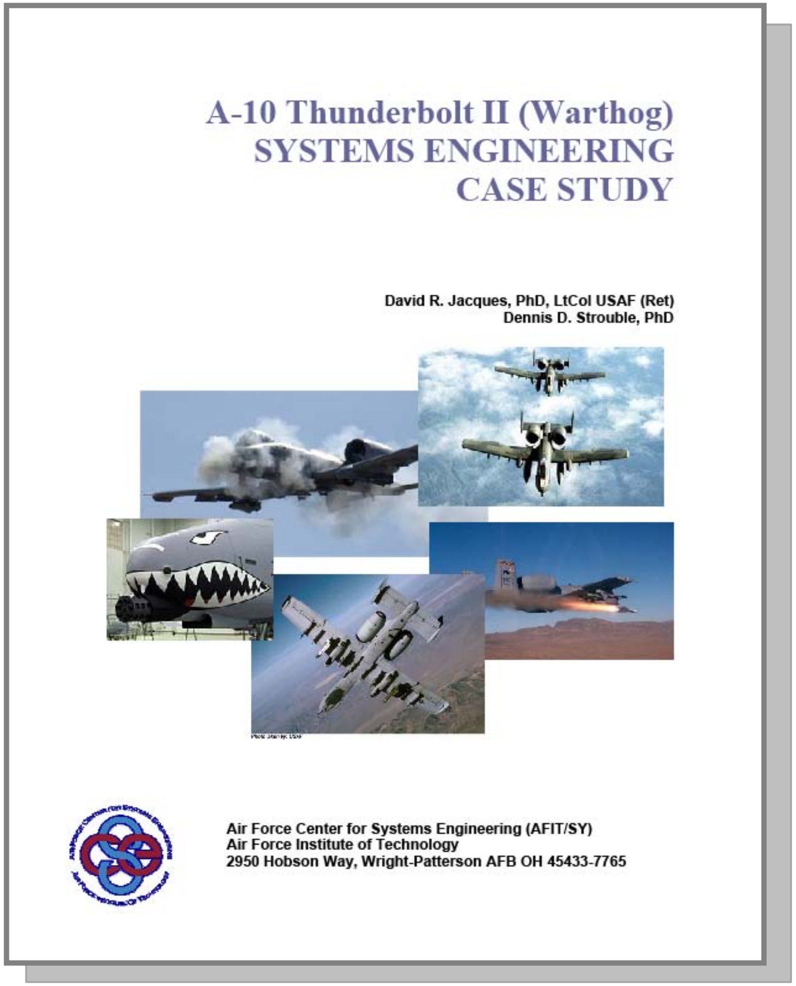
A-10 Thunderbolt II (Warthog)
SYSTEMS ENGINEERING
CASE STUDY

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Early Acquisition Decision Making:

A Historical Perspective

(Based on A-10 and other Systems Engineering Case Studies)

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Disclaimer

Any opinions expressed in this talk are those of the speaker, and do not represent the positions of the Air Force or Department of Defense!

. . . so please don’t tell on me!

Decision

Definition:

1. A choice from among a set of alternatives
2. An irrevocable allocation of resources

But isn't this what we do in engineering design, both at the conceptual level, as well as throughout the development process?

Steps in the Decision Process

1. Formulation of preferences that, for the situation at hand, define good and bad and differentiate levels of goodness
2. Generation of a set of alternatives for consideration of choice
3. Evaluation of alternatives against the decision maker's preference
4. Selection of the preferred alternative in accordance with the decision maker's preference

Sounds easy, right?

Difficulties in Decision Making

- For most problems the range of possible design options is virtually limitless
- Impossible to know exactly how a particular design will perform until it is built and used
  - The operational environment itself is uncertain, let alone how the system will perform in it
- It is not always straight forward to define a valid measure of value
  - Most design problem are multi-attribute
  - Different stakeholders put different “value” on different attributes
- The dimensionality of typical design is so large that simplified models become necessary to support decision making
  - The models themselves introduce uncertainty

Decision Making in Conceptual Design

- What are the operational capabilities that are needed?
- Should a conceptual design effort be undertaken?
- What mix of systems (legacy and new) are likely to achieve the desired operational capabilities?
- For materiel approaches (new systems), which system concept (usually a mixture of technologies) should be the basis of the design?
- Which technology for a given subsystem should be chosen?
- What existing hardware and software can be used?
- Is the envisioned concept technically feasible, based on cost, schedule and performance requirements?
- Should additional research be conducted before a decision is made?

Tenets of Acquisition Policy

1. 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…
2. Cost parameters shall be established which consider the cost of acquisition and ownership… Practical tradeoffs shall be made between system capability, cost and schedule…
3. Logistic support shall also be considered as a principle design parameter…
4. 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.
5. Technical uncertainty shall be continually assessed… Models, mock-ups and system hardware will be used to the greatest possible extent to increase confidence level.
6. 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…
7. Contract type shall be consistent with all program characteristics, including risk…
8. 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…
9. 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.

Lessons from Vietnam

- Air Force largely unprepared for Close Air Support (CAS) mission
  - A-1, A-37 had insufficient payload, loiter
  - Incompatible comm with ground units

- Army doctrine evolving towards air mobile tactics
  - Increased reliance on armed helicopters
  - Initiated development of AH-56 Cheyenne

- Johnson-McConnell Agreement
  - AF retained CAS mission, but recognized role of Army helicopters for fire support
  - Army gave up large fixed-wing transports

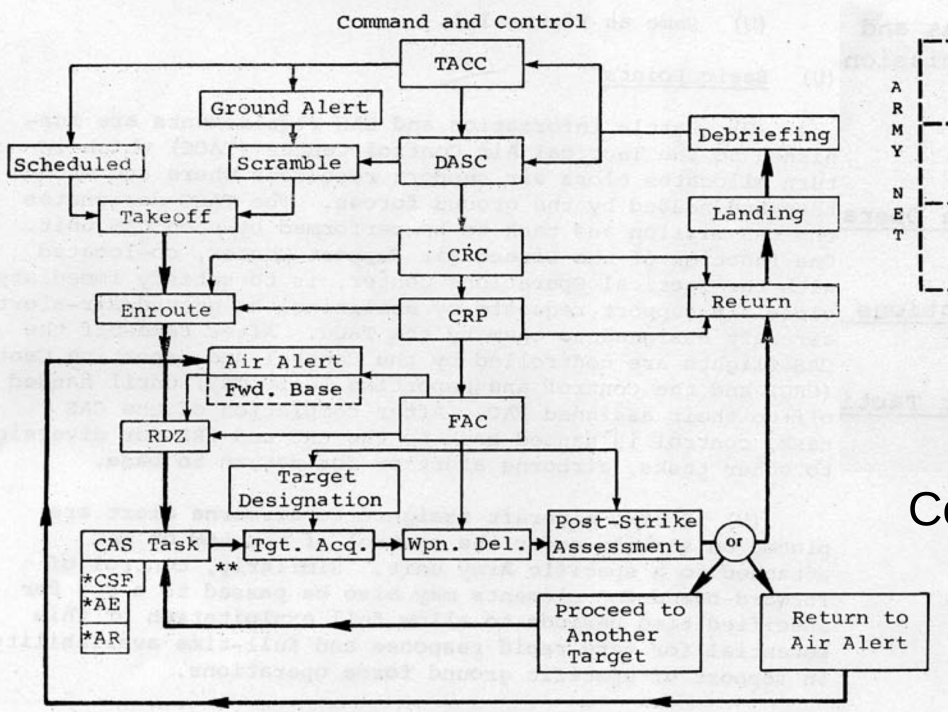
Task Definition

Three Mission Tasks

- Close Support Fire (CSF)
- Armed Escort (AE)
- Armed Reconnaissance (AR)

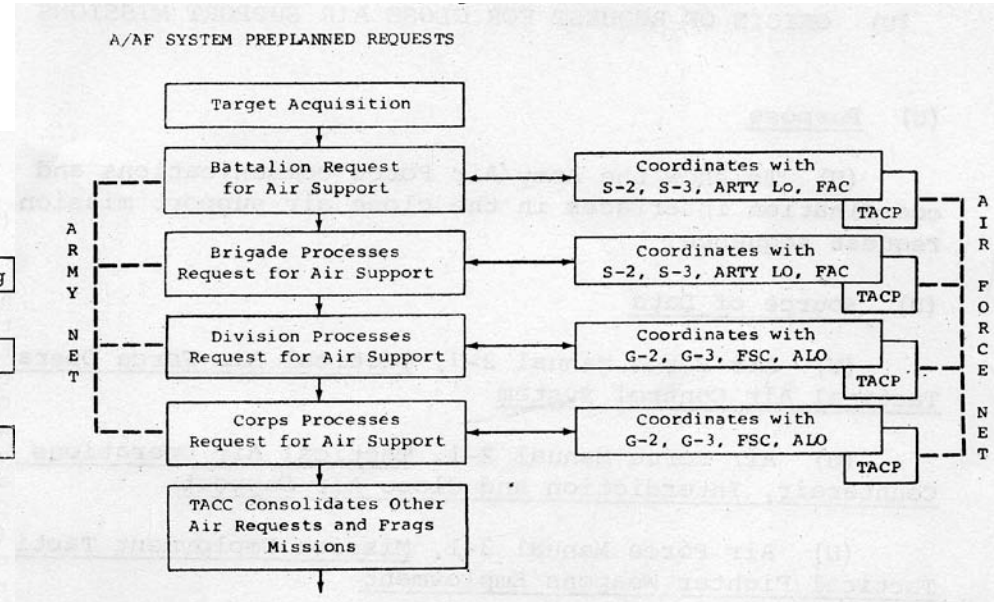
- CSF and AE were considered complementary
- AR involved different weapons and acquisition systems, considered a secondary A-X mission due to parallel development of AC-130 gunship

The System of Systems Perspective



*AR—armed reconnaissance; AE—armed escort; CSF—close support fires
**This sequence occurs every time with CSF and to varying degrees with AR and AE.

The Tactical Air Control System (circa 1968)



Coordination for Pre-Planned CAS Requests

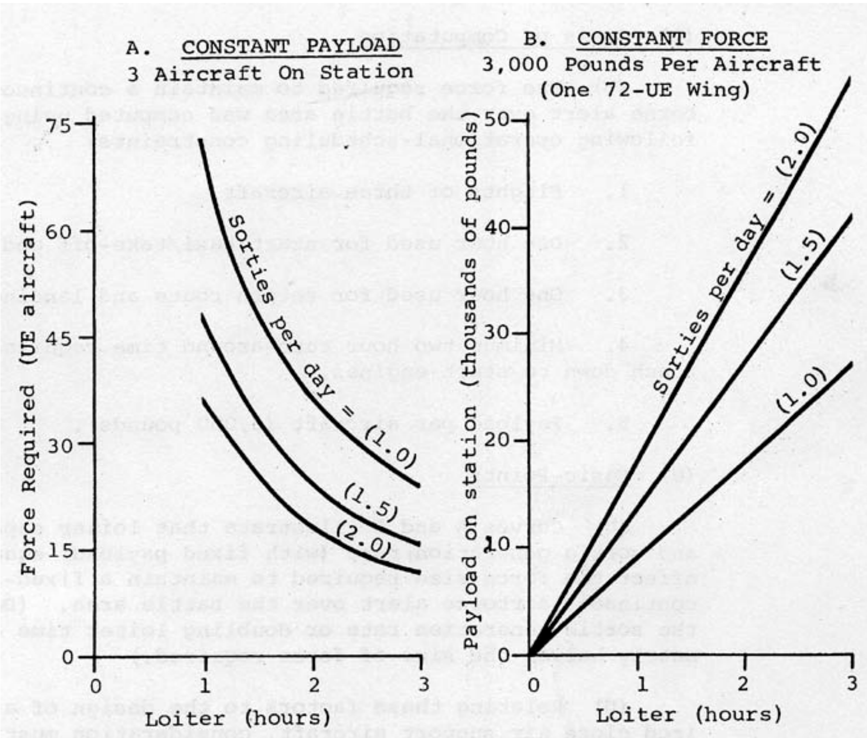
But aren't these simply elements of a mission architecture?

Attributes and Measures

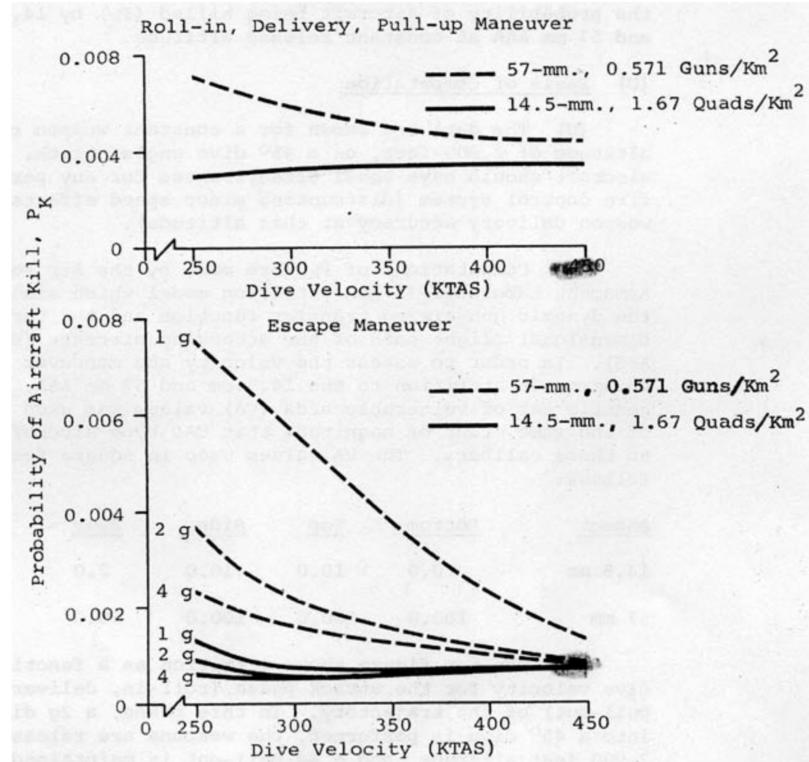
Only four key mission characteristics specified !

- ***Responsiveness*** considered not just speed, but basing locations, availability, loiter time over target, and ability to communicate with ground elements
- ***Simplicity*** emphasized ease of production, maintenance, and low cost
- ***Lethality*** made it clear that it was not an aircraft development effort, it was a weapon system development
- ***Survivability*** concerns would drive redundancy, component placement, protection systems, maneuverability, targeting systems, et.al.
- Mission characteristics drove performance parameters, which resulted in concept aircraft configurations
  - Alternatives evaluated against mission and cost effectiveness measures

Attributes and Measures (ctd.)



Impact of Loiter Time and Sortie Rate on Force Requirements



Relative Aircraft Attrition Versus Velocity and Maneuver

	AFM 26-3 PLANNING MMH/FH	[redacted] ACTUAL SEA MMH/FH AVERAGE
F-4	30	33.2
*F-105	40	27.6
F-100	25	26.6
F-5	17	15.5
A-1	10	14.3
A-37	7	7.8

Maintenance Man Hours/Flight Hour
for Vietnam era Aircraft

Capability of Existing Systems

- F-4, F-111 were the Air Force's primary tactical aircraft of the time
  - Both were expensive, and ill suited to CAS mission
- F-5
  - Initially the Air Force choice for a low-cost tactical fighter
  - Better air-to-air capability than A-7
- A-7D
  - Derivative of existing Navy aircraft
  - Favored by many in OSD, Congress
  - Could not carry a big gun, significantly lower loiter time
  - Would eventually be involved in a flyoff with A-10 prior to production decision
- Army Helicopters?
  - Roles and missions agreements prevented serious consideration

Aircraft Comparison

	A-1J	OV-10 (Impr.)	A-37B	A-X	A-7D	F-4C
Operating weight empty (lb) (includes crew, gun, ammunition)	13,328	9,440	6,200	20,140	19,250	31,097 w/gun pod*
Internal fuel capacity (lb)	2,280	3,680	2,974	7,000	9,750	12,818
External load capacity—with FIF (lb)	9,392	4,394	4,826	16,860	14,000	14,085
Maximum TOGW (lb)	25,000	17,514	14,000	44,000	43,000	58,000
Engines (number/type)	one R-3350	two T-76	two J-85	two T-55	one TF-41	two J-79
Useful load capacity (fuel and ordnance—lbs) for takeoff distance (Ground Run, S.L., Tropic Day) of:						
750 ft	4,000**	1,300**	3,200**	9,000	-0-	-0-
1,000 ft	6,200**	3,600	4,000**	12,500	-0-	-0-
Maximum speed, clean, S.L. (KTAS)	277	262	417	400	607	M 1.2
Best cruise speed, 5,000 ft, maximum ordnance (KTAS)	170	170	265	240	315	420
Ferry range, unrefueled (NM)	2,800	2,600	1,560	2,600	2,600	1,600
Number of ordnance stations	15	7	8	10	8	5
Internal guns (number/caliber)	four 20-mm	four 7.62-mm	one 7.62-mm	one 30-mm	one 20-mm	*(one SUU-16 20-mm pod)

**Cannot land in this distance at any weight.

A-X Concepts

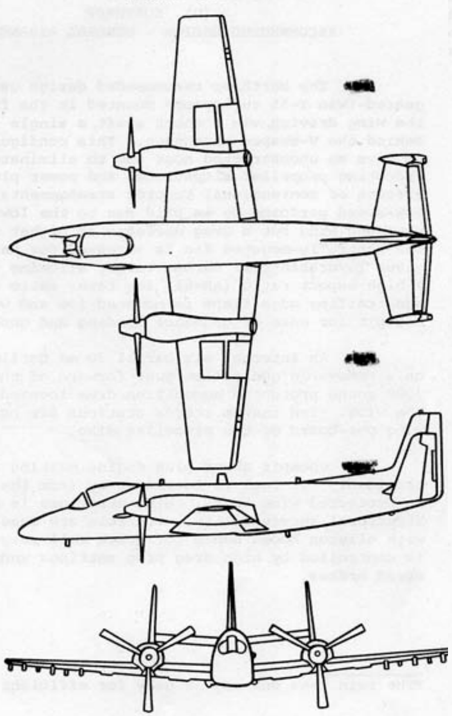
Requirements from Dec 1966 Requirements Action Directive

Performance Parameter	Desired	Required
Gross Weight (lbs)	22,500	30,000
Payload - Mixed Ordnance (lbs)	8,000	6,000
Combat Radius (nautical miles)	---	200
Loiter Time @ Combat Radius (hrs)	---	2
Min Maneuvering Speed @ 5000 ft (knots)	120	150
Turn Radius @ Combat Weight (ft)	1,000	2,000
Max Speed @ Sea Level w/ Ext. Ordnance (knots)	550	450

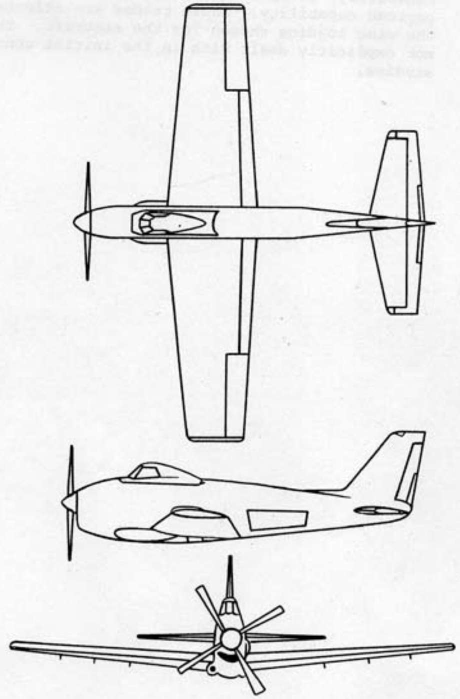
- Concept design studies conducted in 1967
  - Resulted in two government configurations, and four contractor configurations
- Concept determined to be feasible within existing technology
  - Most configurations used turbo-prop designs
  - Identified risk elements included gun/ammunition development and integration, and early IOC
  - Lean avionics packages defined to keep costs down
- Concept Formulation Package (predecessor to Initial Capability Document) completed in 1968

A-X Concepts

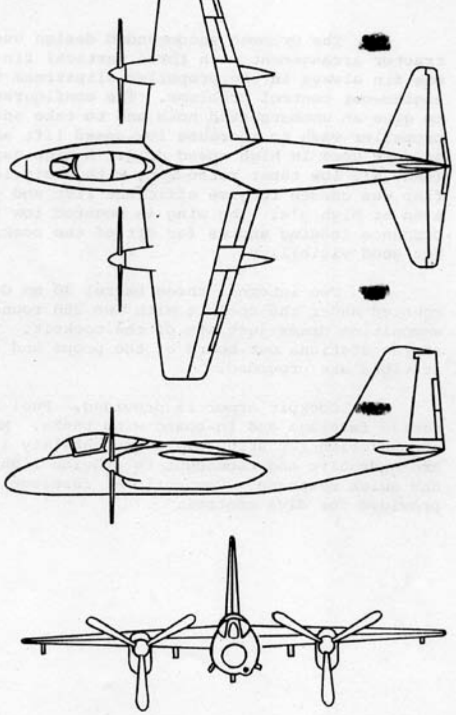
(U) GRUMMAN
RECOMMENDED DESIGN GENERAL ARRANGEMENT
(Figure UNCLASSIFIED)



(U) GENERAL DYNAMICS
RECOMMENDED DESIGN GENERAL ARRANGEMENT
(Figure UNCLASSIFIED)



(U) McDONNELL DOUGLAS
RECOMMENDED DESIGN GENERAL ARRANGEMENT
(Figure UNCLASSIFIED)



Notes: Significant design changes occurred during Concept Definition (now referred to as Concept Refinement)

- Single or twin turboprop propulsion gave way to twin turbofan (leveraged Navy S-37 aircraft development)
- Payload essentially doubled to 16,000 lbs – led to aircraft size/cost growth

Competitive Prototyping

- Recall acquisition tenet # 5
  - Technical uncertainty shall be continually assessed… Models, mock-ups and system hardware will be used to the greatest possible extent to increase confidence level.
- The A-X (termed A-10 after downselect) became a pilot program to demonstrate competitive prototyping on a major system development effort*

* The publication of DoD 5000 did not occur until a few months after the start of the A-X development program, but these policy ideas from the Office of the Secretary of Defense clearly influenced the A-X program formulation. In some respects, the A-X program was a test bed for considerations such as design-to-cost, supportability in design, and competitive prototyping.

A-X Prototyping

- A-X Pilot – Parallel Undocumented Development
  - Favored by DepSECDEF David Packard and AFSC/CC Gen Ferguson
  - Require minimal documentation during the competitive prototype phase to encourage innovation and initiative on the part of the contractor.
  - Expected to reduce technical risk and lead to a better source selection decision at the expense of higher RDT&E cost
- A-X was unique in this approach
  - F-X (later termed F-15), initiated in the same year, followed traditional “paper” Concept Definition approach to source selection

Competitive Prototyping on A-X

- Aircraft
  - Two competitors selected from six bidders for competitive prototyping phase
    - Northrop (YA-9) and Fairchild (YA-10)
    - Competitive fly-off by AF pilots after ~2.5 years in development
    - Downselect based on design, cost, risk, and flying performance
- Gun
  - Two competitors selected to design/build prototype guns
    - GE (GAU-8) and Philco-Ford (GAU-9)
    - Each competitor responsible for separate ammunition development
    - Competitive shoot-off after ~2.5 years in development; only GE was able to demonstrate a satisfactory gun system
- Ammunition
  - After gun downselect, GE directed to retain two ammunition subcontracts
  - Targeted downselect for ammunition was to be two years after IOC for first independent ammunition order; prior orders part of gun contract

A-X Competitive Prototyping Rationale and Outcomes

- Aircraft development was considered low risk, but gun development and integration was considered higher risk
  - Ammunition for gun was also considered higher risk
  - Ammunition cost was projected to make up 90% of the life cycle cost for the gun system
- Aircraft fly-off successful for both Northrop and Fairchild
  - Fairchild A-10 chosen based on cost, risk, and a “simpler” design for manufacture and maintenance
- Gun prototype demonstration eliminated Philco-Ford from consideration, and positively demonstrated feasibility and effectiveness of GE design
- Reports have suggested that extensive efforts in technology development and competition contributed to an 80% reduction in ammunition from the original cost estimate

Other Programs from the Past

- Capability Based Assessment for navigation support
  - Definition of tasks, attributes and measures
- Initiated a joint development program
  - (primarily AF and Navy)

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NAK-Y27442-R1

OTHER USERS OF SYSTEM SATISFYING TACTICAL BOMBING GOALS

OPERATION	ACCURACY / FIX FREQUENCY
• AIRCRAFT SHORT-RANGE MISSILE LAUNCH	0.01 N MI RELATIVE / CONTINUOUS +2 FPS VELOCITY
• MISSILE TERMINAL GUIDANCE	0.01 N MI RELATIVE / CONTINUOUS +0.2 FPS VELOCITY
• AIR DELIVERY OF STORES	0.01 N MI RELATIVE / CONTINUOUS
• AIR TRAFFIC CONTROL	1 N MI ABSOLUTE / INTERMITTENT
• RESCUE	0.1 TO 1 N MI RELATIVE / INTERMITTENT
• POSITIONING GUNS, RADARS, ETC.	
– ON LAND	0.01 N MI RELATIVE / INTERMITTENT
– ON SEA	0.01 N MI RELATIVE / CONTINUOUS
• AIRCRAFT MAPPING	0.1 N MI ABSOLUTE / CONTINUOUS
• SHIP MISSILE LAUNCH	0.1 N MI ABSOLUTE / INTERMITTENT
• SATELLITE TRACKING	0.1 N MI ABSOLUTE / CONTINUOUS

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27

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NAK-Y27441-R1

OTHER DESIRED CHARACTERISTICS

- COVERAGE
  - NOT DEPENDENT ON ACCESS TO THEATER FOR SET UP OF SYSTEM
  - GLOBAL DESIRED
- AVAILABILITY OF FIXES
  - CONTINUOUS
- VULNERABILITY
  - EQUIPMENT LOCATED WHERE PROTECTION AVAILABLE - PREFERABLE OUTSIDE THEATER
  - MINIMUM JAMMING SUSCEPTIBILITY
- PASSIVE USER
  - DESIRED
- COST
  - MINIMUM DESIRED
  - CHARGEABLE TO A VARIETY OF USERS

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31

Legacy Navigation Systems

- Capability Based Assessment considered the adequacy of current and programmed systems

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NAK-Y26582-R1

REPRESENTATIVE GROUND BASED NAVIGATION AIDS

SYSTEM	FREQUENCY	GROUND STATION POWER/ANTENNA	COVERAGE	ACCURACY
LORAN C	90-110 KHz	250 KW PEAK 625 FT HIGH ANTENNA	1500 N.MI. OVER WATER AT NIGHT 800-1000 N.MI. OVER WATER-DAY ~800 N.MI. BASELINE	0.5-1.0 N.MI.
LORAN D	90-110 KHz	3 KW PEAK 300 FT HIGH ANTENNA	300-500 N.MI. ~125 N.MI. BASELINE	0.1 N.MI. ABSOLUTE AT 250 N.MI. 0.01 N.MI. RELATIVE AT 250 N.MI.
OMEGA	10-14 KHz	10 KW AV COMPLEX ANTENNA	GLOBAL WITH 8 STATIONS	0.5 N.MI. - DAY 1 N.MI. - NIGHT 2 N.MI. - DAY/NIGHT PATH

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SUMMARY OF REVIEW

- LORAN D MEETS .01 N.MI. (R) TACTICAL NEED
  - REQUIRES 300 FT ANTENNA IN COMBAT AREA
  - REQUIRES TIME FOR SET UP
  - 300-500 N.MI. RANGE
  - TWO COMPONENT POSITION FIX
- OMEGA MEETS GLOBAL 1 TO 2 N.MI. (A)
  - TWO COMPONENT POSITION FIX
- EXISTING SATELLITES MEETS NON OR SLOW MOVING PRECISION USER NEED
  - SEQUENTIAL MEASUREMENTS
  - 5 TO 10 MINUTES FOR A FIX

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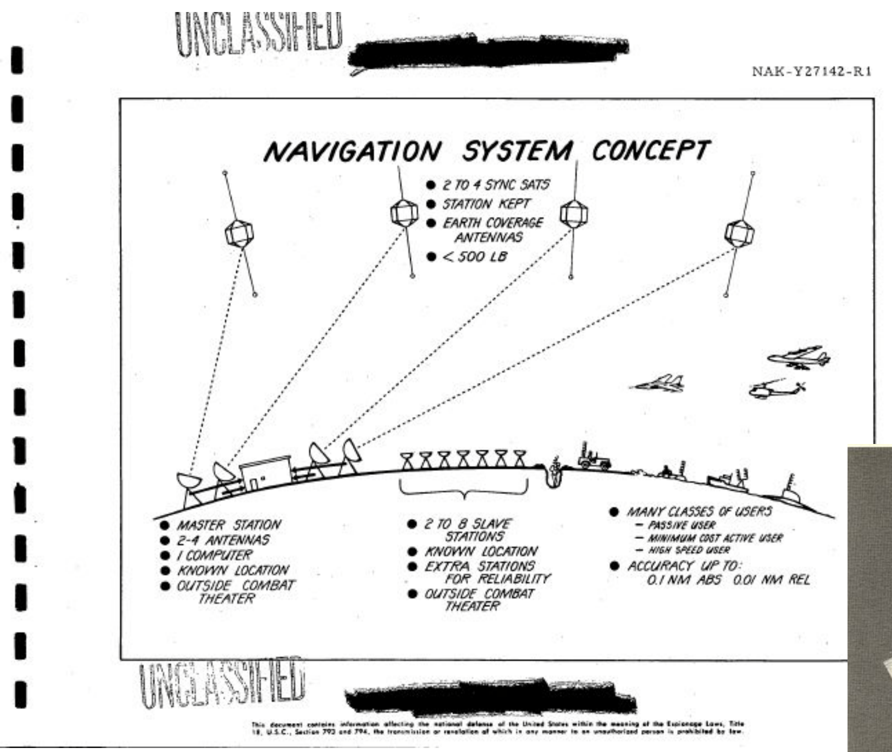
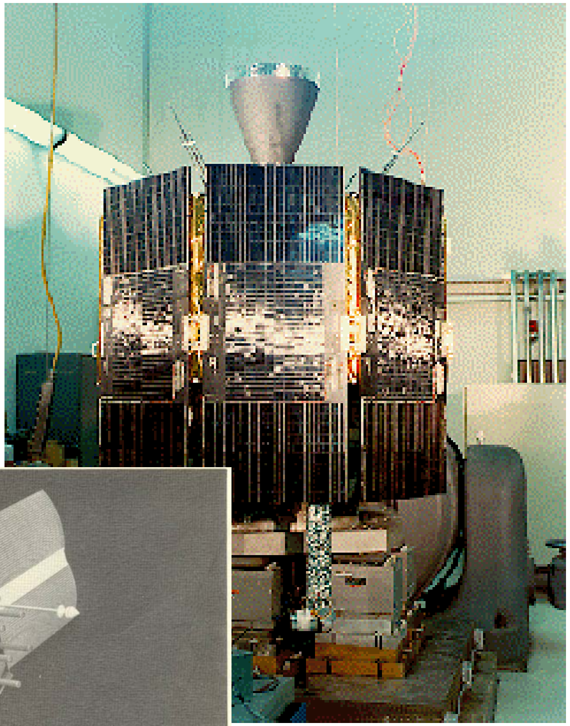
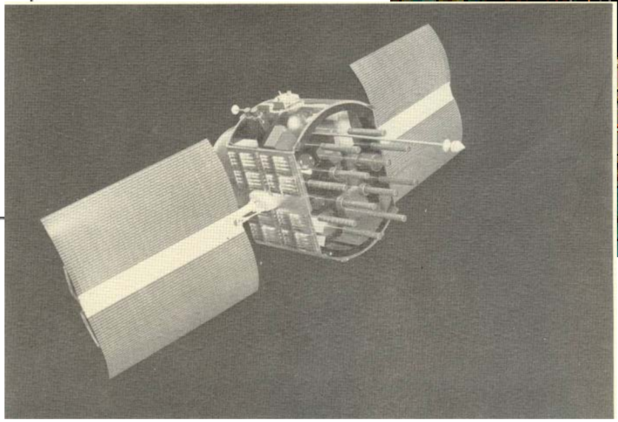
The GPS Concept

- Concept Definition package done in 1967!
- System of Systems Implications







JCIDS 40 Years Early?

Did A-X and GPS concept formulation adhere to (in retrospect) Joint Capability Integration and Development System (JCIDS) principles?

Yes … , kind of …

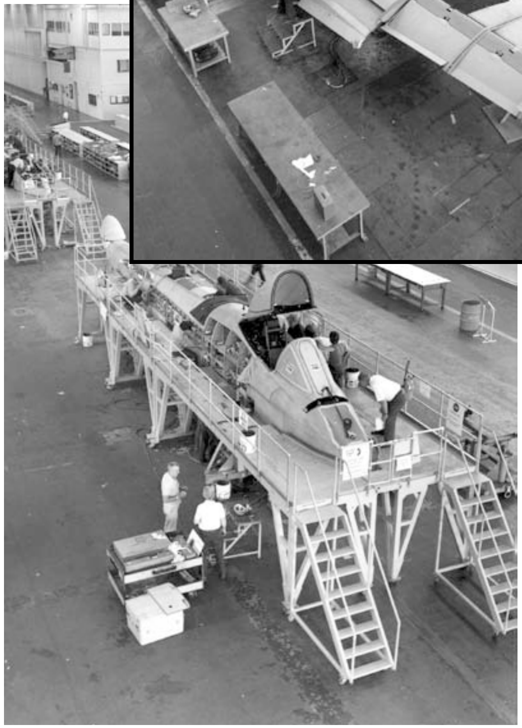
- Clear definition of tasks, conditions and measures
- Consideration of a range of existing systems to provide the needed capability
- Concept formulation traceable to previously defined tasks, conditions and measures

Shortcomings

- With A-X, no serious consideration of the full range of joint warfighting concepts to meet the capability needs
- Others?

Contractor Assessment

- Remember AcquisitionTenet 8?
  - 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…
- Fairchild's production capability and financial healthassessed prior to contract award
  - Had not produced an aircraft in over 15 years
  - Had not modernized production equipment
- Air Force re-assesses contractor prior to production decision
  - Forced changes in capital investment, workforce and management, and production location
- Epilogue – Fairchild ceased to exist shortly after the end of the production run for A-10



Lessons from Other Programs

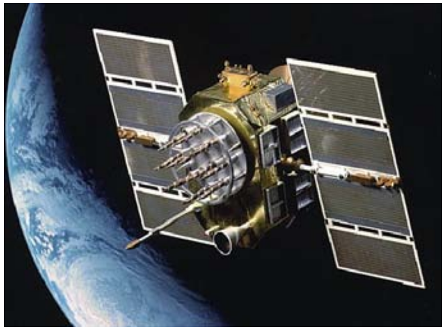
Q: Can you name this aircraft, and who was it developed for?

A: This is the F-111B, developed for the Navy !

- OSD mandated that F-111 be joint (AF/Navy)
  - 80% commonality required
- Air Force and Navy had different mission needs
- F-111B became to big to fit on Carriers – Navy pulls out
- AF continues program, but can't reverse many design decisions

Air Force Center for Systems Engineering Case Studies

Hubble Space Telescope



GPS (Global Positioning System)

F-111 Aardvark

C-5 Galaxy

B-2

TBMCS (Theater Battle Management Core Systems)

Peacekeeper Intercontinental Ballistic Missile

A-10

Website:

http://www.afit.edu/cse/

Additional Case Studies

Global Hawk

KC-135 Simulators

T-6A Texan II

All case studies available as pdf downloads from AFIT web site

www.afit.edu

Follow links to Center for Systems Engineering; case study link found on CSE front page

Conclusion

- An often quoted statement:
  - Those who don’t learn the lessons of the past are condemned to repeat them
- So are we learning them, or repeating them?

Questions?