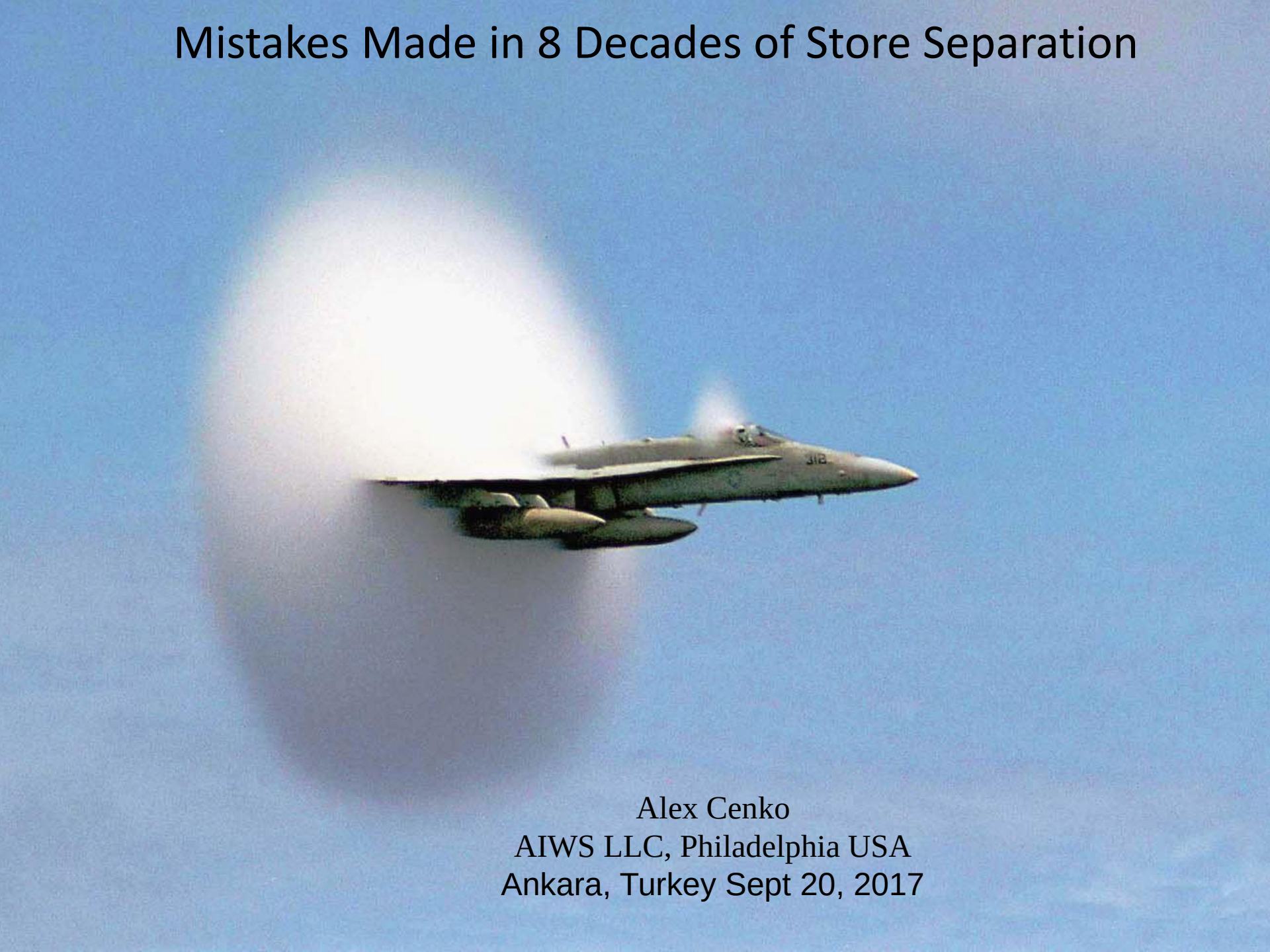
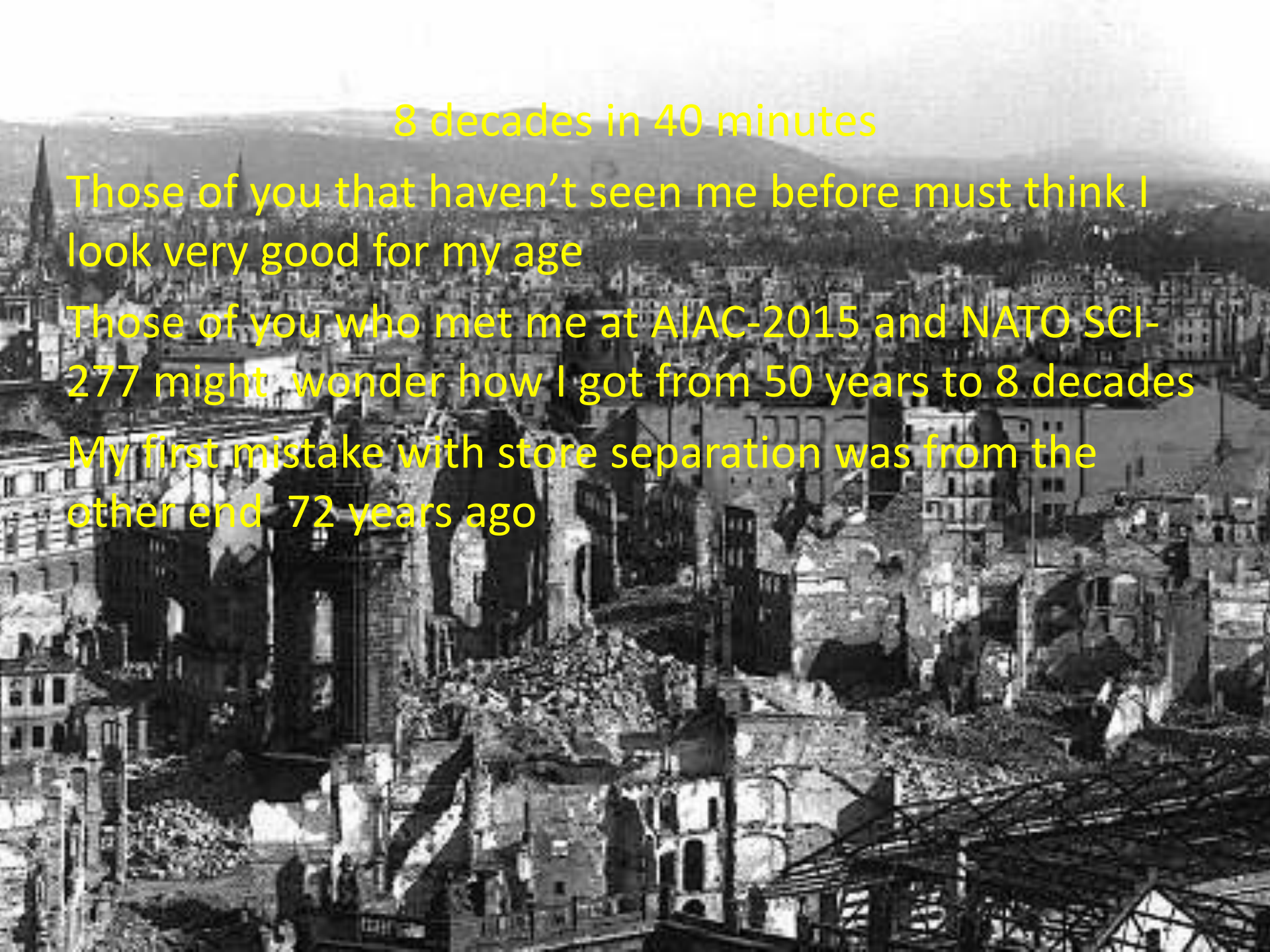
Mistakes Made in 8 Decades of Store Separation



Alex Cenko
AIWS LLC, Philadelphia USA
Ankara, Turkey Sept 20, 2017



8 decades in 40 minutes

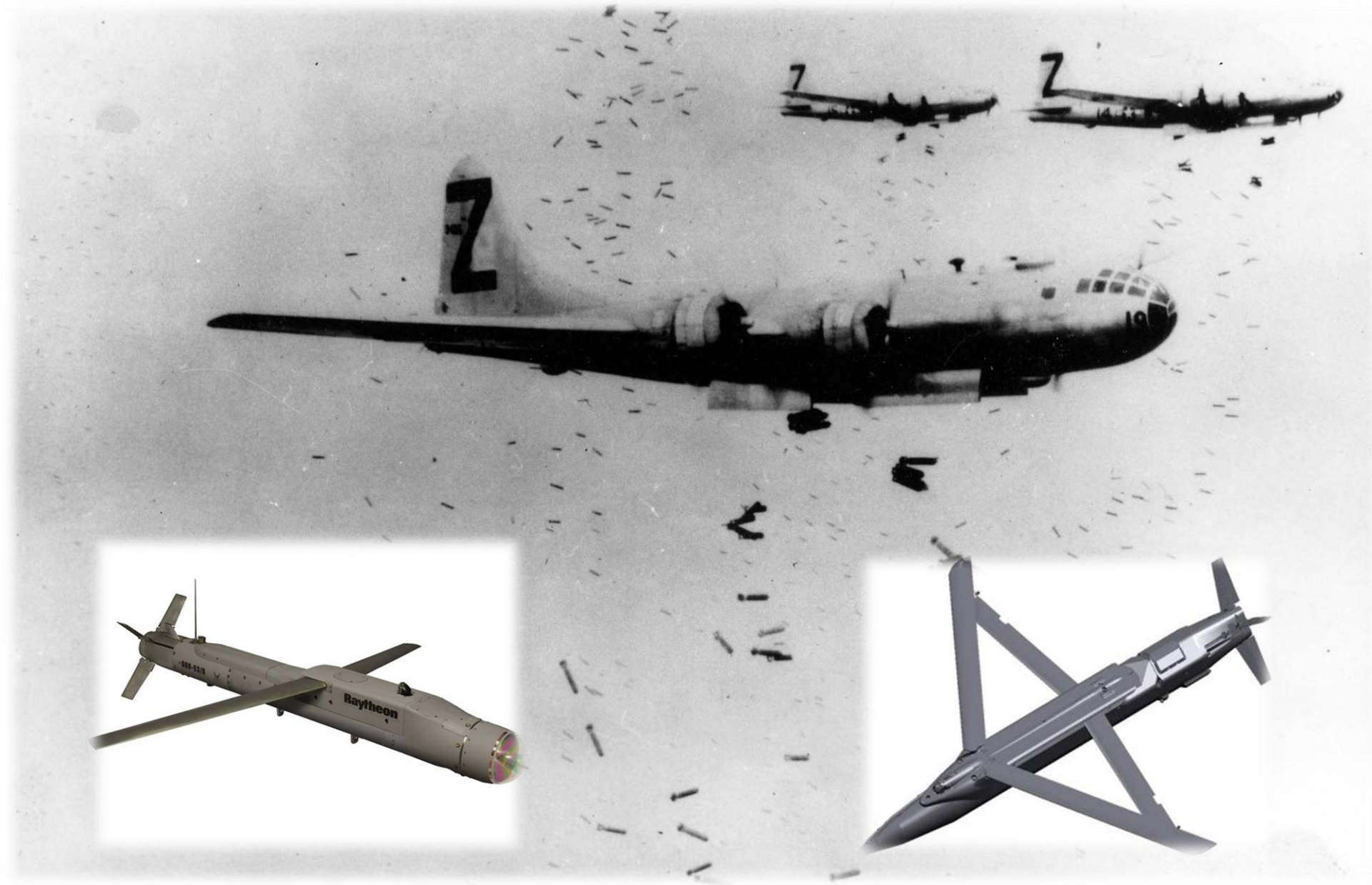
Those of you that haven't seen me before must think I look very good for my age

Those of you who met me at AIAC-2015 and NATO SCI-277 might wonder how I got from 50 years to 8 decades

My first mistake with store separation was from the other end 72 years ago

Aircraft changes in 8 decades

Store Separation Changes in 8 Decades



Very Happy to be at my Favorite Conference

AIAC 2015-022

CFD CHALLENGE II REVISITED AFTER 15 YEARS

AIAC 2015-037

MISTAKES MADE (AND LESSONS LEARNED) IN THE LAST 50 YEARS OF STORE SEPARATION

AIAC 2013-028

MACH SWEEP TECHNIQUE FOR STORE SEPARATION WIND TUNNEL TESTING

AIAC 2011-060

A NEW APPROACH TO EVALUATING STORE TRAJECTORIES

AIAC 2011-061

UNDERGRADUATE EDUCATION AND RESEARCH IN COMPUTATIONAL FLUID DYNAMICS

AIAC 2005-003

ONE CFD CALCULATION TO END POINT TESTING (HAS CFD FINALLY REPLACED THE WIND TUNNEL)

Most of the material presented today is explained in AIAC papers above and can be downloaded from the AIAC website

Store Separation

1. Initial Conditions 2. Aircraft Flowfield 3. Freestream

Disclaimer

- All material in this presentation has been acquired from open sources, previously cleared for public release, downloaded from the internet or based on memory
- AIAC, ICAS and RTO free downloads – AIAA papers cost $15
- The problem with getting old is that you not only lose short term memory, you also lose long term memory.
- Memories tend to be self serving
- Apologies for some of the figures. Excel was not around in the 1980's and Harvard Graphics doesn't work on windows.
- No apologies for the high "Augustine Acronym Index (AAI)." That's a requirement to survive in the military-industrial complex.

"Augustine Law Number IX: Acronyms and abbreviations should be used to the maximum extent possible to make trivial ideas profound...Q.E.D."

Air Force SEEK EAGLE Office (AFSEO)

Applied Computation Fluid Dynamics (ACFD) was part of the Weapons Modeling and Simulation Capability (WMASC) from 1991 to 2000. It was a tri-service (Air Force, Army and Navy) program to improve store separation techniques. This program arranged two AIAA invited store separation sessions, ACFD Challenge I (1996 F-16/Generic Store) and ACFD Challenge II (F-18C/JDAM 1999)

Captive Trajectory System (CTS) wind tunnel quasi-steady simulation of store trajectories

Guided Bomb Unit (GBU)

High Performance Computing (HPC)

Influence Function Method (IFM) aircraft flowfields converted to store grid loads (AIAC-2017-049)

Institute for (HPC) Applications to Air Armament (IHAAA) was a tri-service program funded by HPC to improve the application of computational techniques to aircraft/weapon integration. It replaced WMASC from 2000-2007. AIAA invited session for the B-1B/GBU-38 in 2008

Joint Direct Attack Munition (JDAM)

Naval Air Development Center (NADC) Research and Engineering

Naval Air Systems Command (NAVAIR) Program Management

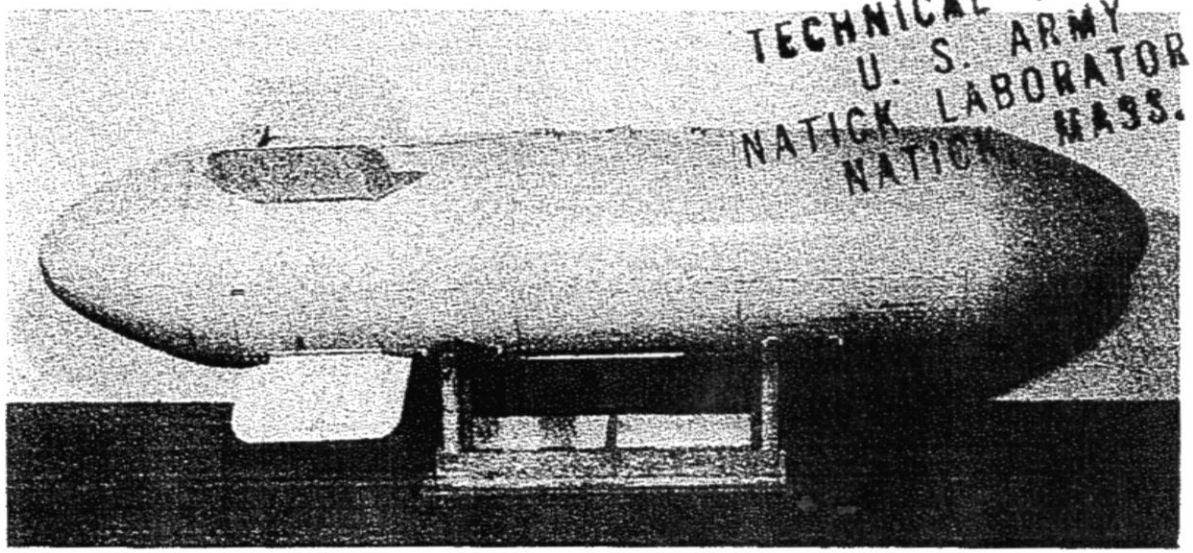
Six Degree of Freedom (SDoF) off line quasi-steady trajectory simulation program

The Technical Cooperative Program (TTCP) is a cooperative agreement between Australia, Canada, Great Britain and the US to share technical information.

What Affects Store Separation

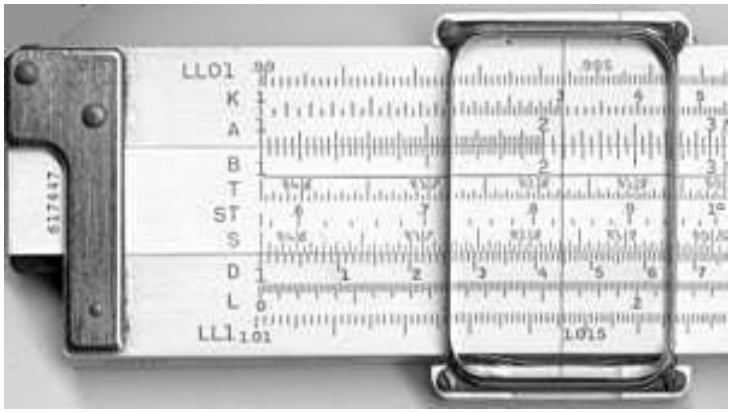
- Initial Conditions
- Aircraft flowfield
- Freestream
- Aircraft Flowfield effects usually extend for only about 20-30 ft, **BUT**

M-4A High Speed Delivery Container (1964)



The Marine Corps' M-4A high speed aerial delivery container is being tested for use in supply of dispersed forces anticipated in nuclear and missile warfare. The container is made from aluminum and weighs 104 pounds.

Store Separation Tools in 1964



First Trajectory Prediction

- Six Degree of Freedom (SDoF) written in Fortran IV
- Freestream aerodynamics based on DATCOM
- Mass properties and ejector forces simulated
- Aircraft flowfield effects unknown. Release from centerline.
- Pitching Moment (CLM) input as 0.0 and +/- 1.00. Normal Force (CN) had little impact.
- +/-1 CLM predicted container would tumble
- 0 CLM predicted a safe trajectory
- M-4A container designed to deploy parachute after release
- Container tumbled, parachute failed to deploy, hit airfield
- Base commander and local dignitaries present, close to impact location

M-21/D-21 Incident July 30, 1966 M = 3.0

The first three flight tests were done in a .9g dive. Flight four was be in level flight. At release the D-21 did not separate for 2-3 seconds, then hit the M-21 (Blackbird).

Could Six Degree of Freedom (SDoF) simulations have predicted this?

Captive Trajectory System (CTS) wind tunnel testing not possible at M = 3.0.

https://www.youtube.com/watch?v=GMyC2urCl_4#t=30.196051

Computational Aerodynamics

- Hess sources (1967)
- Woodward (sources/vortices 100 panels matrix inversion, design - 1967)
- Nielsen (panel method coupled with SDoF code - 1976)
- PanAir (doublets 1,000 panels, 24 hours CDC 6600 1978)

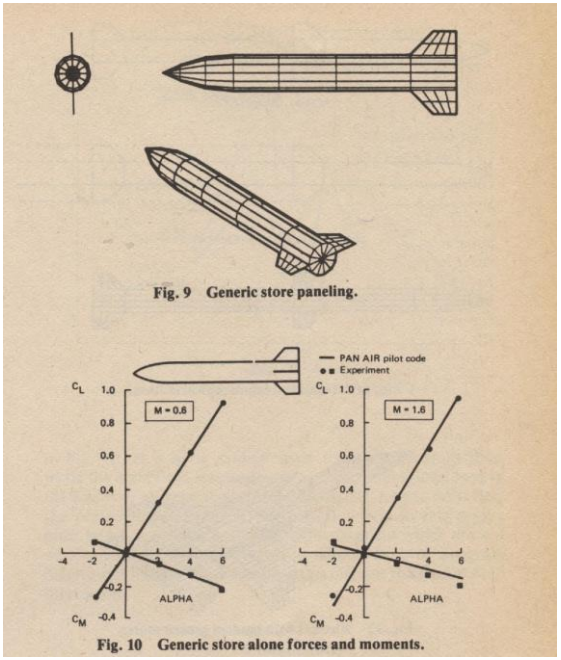


Fig. 9 Generic store paneling.

Fig. 10 Generic store alone forces and moments.

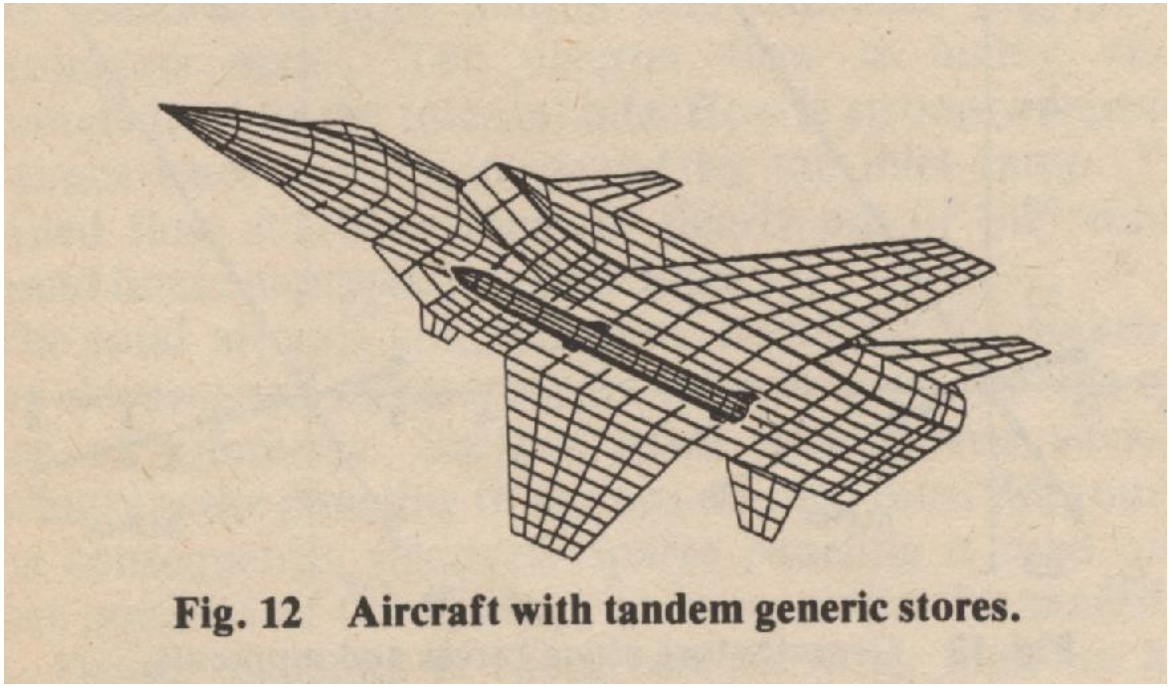


Fig. 12 Aircraft with tandem generic stores.

- Influence Function Method (1980) AIAC-2017-049
- Full Potential - TranAir (1987)

Favorite Contractor Lies , Wing Commander Malcolm Tutty

RTO MP-16, paper 15, Sept. 1998

1. **It's only a software change.**
2. **It's the same as a MK-XX / GBU-XX / AGM-XX / AIM-XX*.**
3. **Only secondary structure was modified.**
4. **Boeing / Lockheed / McDonald / Northrop / EADS* say its OK.**
5. **The Army / Navy / USAF / Australia / Canada / UK * do it all the time ...**
6. **The test starts today, we don't need a Clearance ...**
7. **It's just a "one-time" flight, we don't need a Clearance ...**
8. **This Program has Programs Manager's top priority, we don't need a ...**
9. **Of course the mass properties, inertias, geometries haven't changed...**
10. **I will still respect you after he flight!**
11. **You will save money**

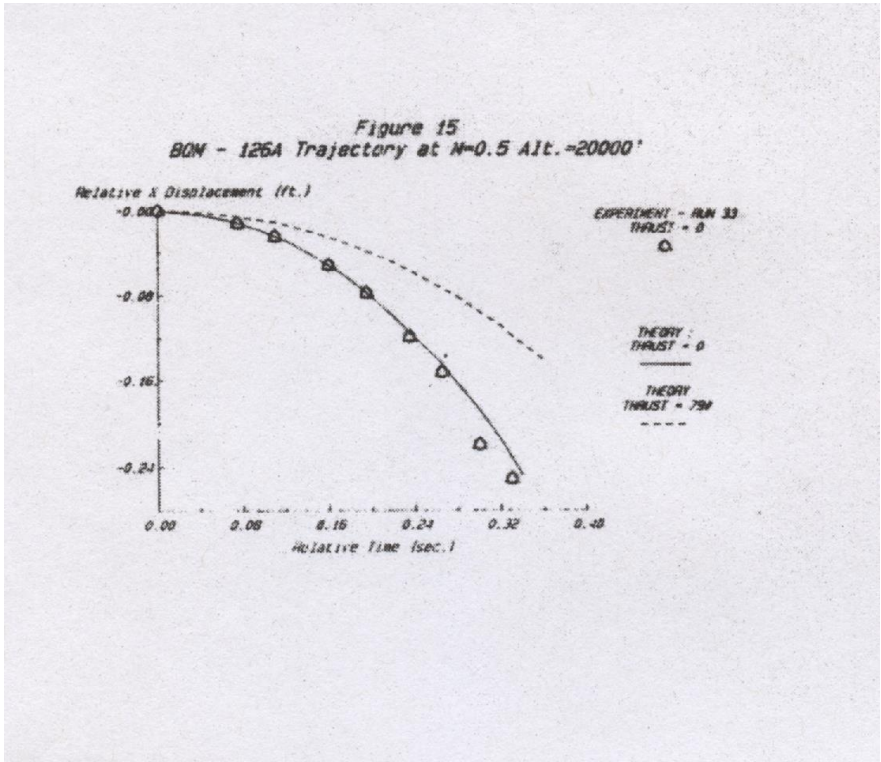
F-18C/BQM-126A

4. Boeing/Grumman /Lockheed/McDonald/EADS* say its OK

- BQM-126A was a powered UAV
- CTS only wind tunnel test
- Engine effects for 0, 75 and 150#, no effects seen in CTS trajectories
- CTS indicated store would move aft and safely clear the aircraft
- Store flew forward and rolled, almost hitting the aircraft
- PanAir and IFM used to generate SDoF aero inputs to match test results (AIAC-2017-049)
- Program cancelled

Image: Raytheon

BQM-126A



CTS vs Grid Wind Tunnel Testing

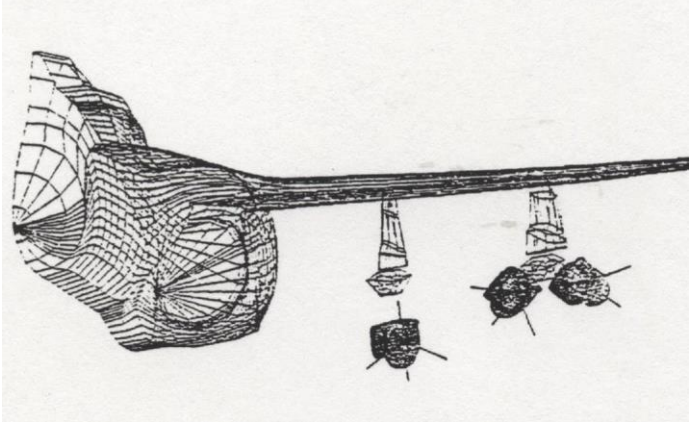
- 1 Mach
- 1 Aircraft AOA
- 1 Ejection force
- 1 Ejection line of action
- 1 store cg
- 1 store Ixx, Iyy, Izz
- 1 g

- 1 Mach
- 1 Aircraft AOA
- ∞ Ejection forces
- ∞ Ejection var.
- ∞ store cg
- ∞ store Ixx, Iyy, Izz
- ∞ g
- Replace CTS with large scale freestream data
- Grid testing will always give better match with flight test

Improved Tactical Air Launched Decoy

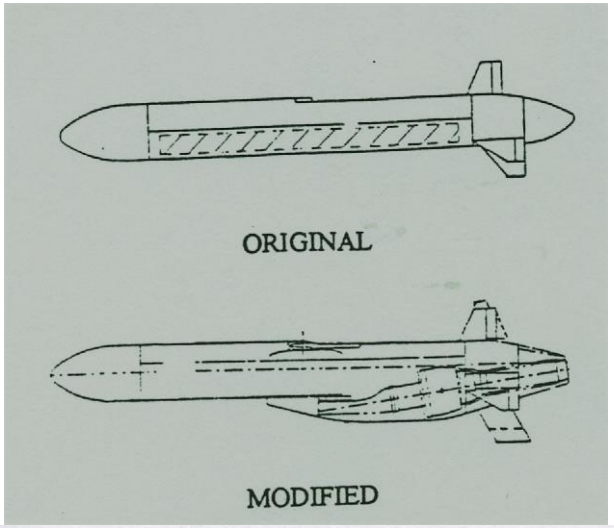
1. **It's only a software change.**
2. **It's the same as a MK-XX / GBU-XX / AGM-XX / AIM-XX*.**
3. **Only secondary structure was modified.**
4. **Boeing/Grumman /Lockheed/McDonald/EADS* say its OK**

- ITALD was marketed as a minor modification to TALD
- Modified tail and jet engine
- After **several flight failures** NADC was consulted
- Pan Air predicted failure was caused by changes in Yawing (CLN) and Rolling Moments (CLL)
- Contractor disagreed, redesigned autopilot
- Result was another **flight test failure**



Freestream Data is Important

- A **6%** freestream and grid wind tunnel test was conducted
- Contractor provided **40%** freestream data that was used in NADC SDoF simulations
- Result was **another flight test failure**
- Failure could be matched in SDoF by changing freestream
- Contractor used increments to 40% TALD freestream to account for engine and tail
- New 40% freestream wind tunnel test, autopilot redesigned, **successful test**
- Contractor went bankrupt – each store cost $250,000



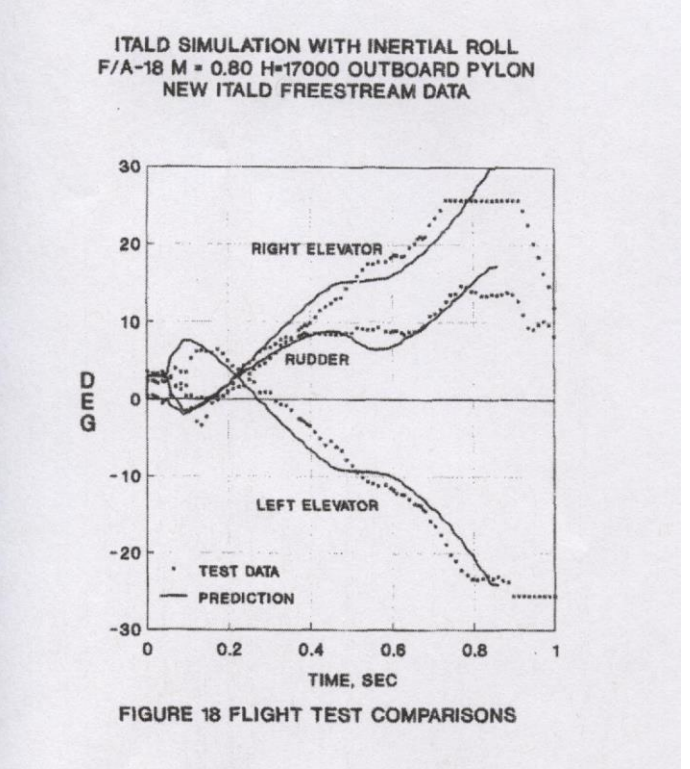


FIGURE 18 FLIGHT TEST COMPARISONS

JSOW AGM-154

- Started in 1988 as the Advanced Interdiction Weapon System (AIWS)
- Designed to fit into the A-12 weapons bay. This restricted the tail size, reducing stability
- Series of F-18 wind tunnel tests used to determine store separation characteristics
- Program became joint Air Force and Navy, renamed JSOW

Flight Test Program

- Original flight test plan was to drop **24 weapons**
- Mach numbers 0.6, 0.7, 0.8, 0.85, 0.9, 0.95 and 0.95 in a dive
- Three different aircraft configuration; inboard tank critical
- SDoF predictions done at Naval Air Development Center PA.
- Excellent match with pre-flight predictions in first two flights, NADC recommended to reduce the flight test program to 10

"The engineers and I had several conversations for the need to believe SDoF predictions and reduce the flight test matrix …"If I were to develop another weapon like JSOW I would stress the test community to complete the full test envelope with 8-10 tests"

J.. Chenevey (JSOW Program Manager)
RTO MP-16, Keynote Address, Sep. 1998

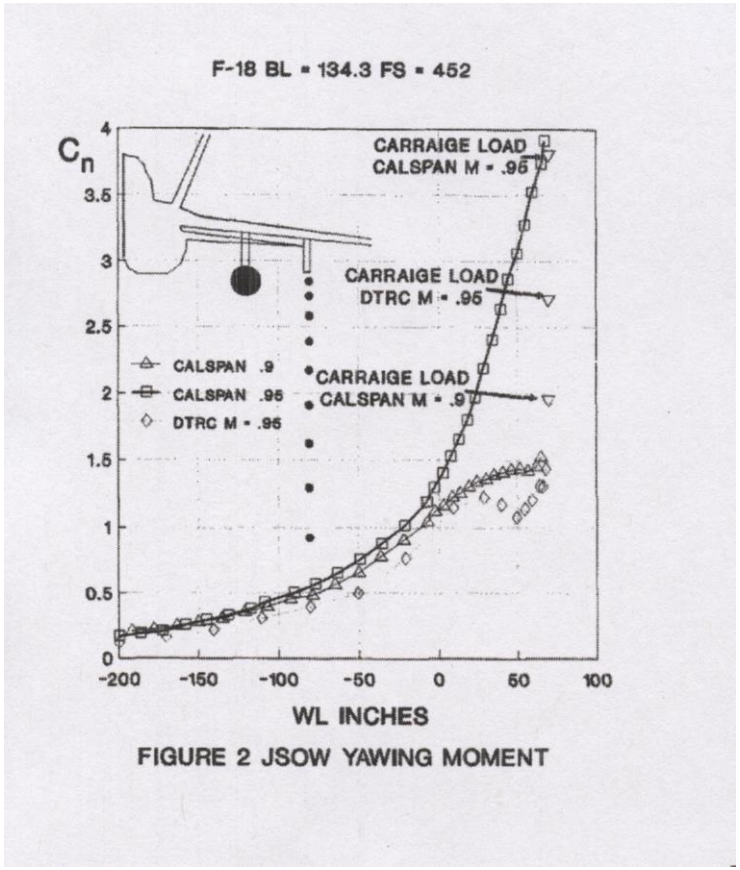


FIGURE 2 JSOW YAWING MOMENT

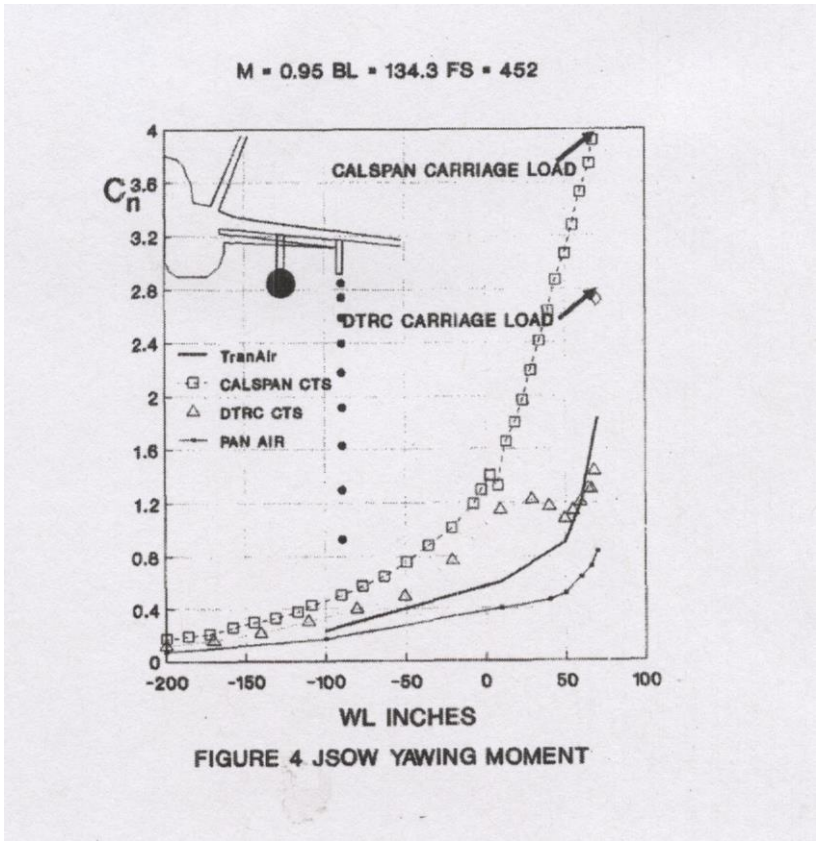
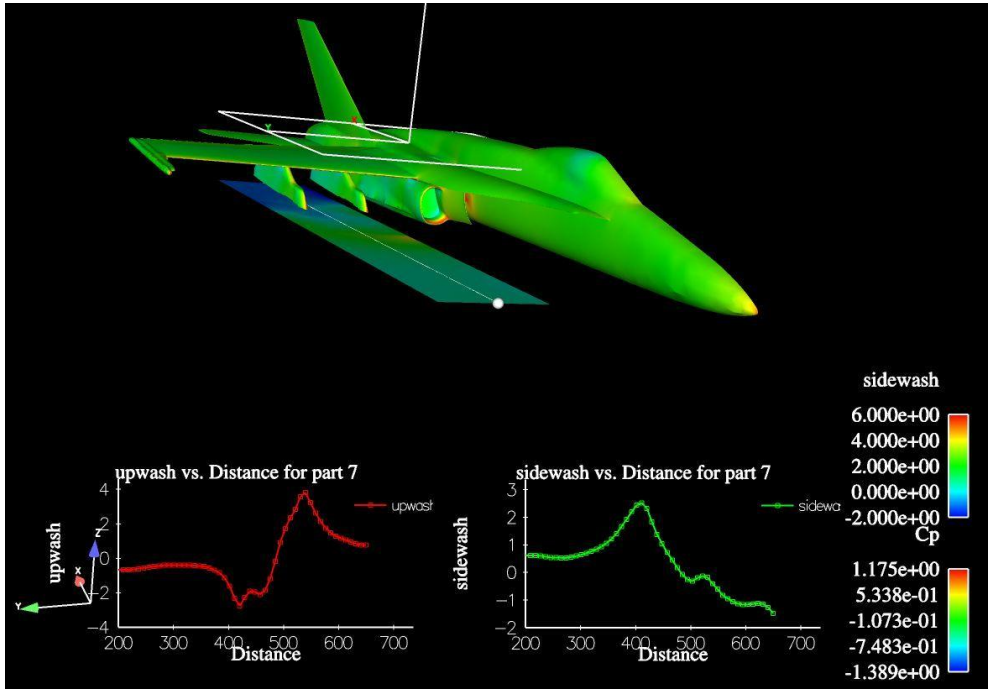


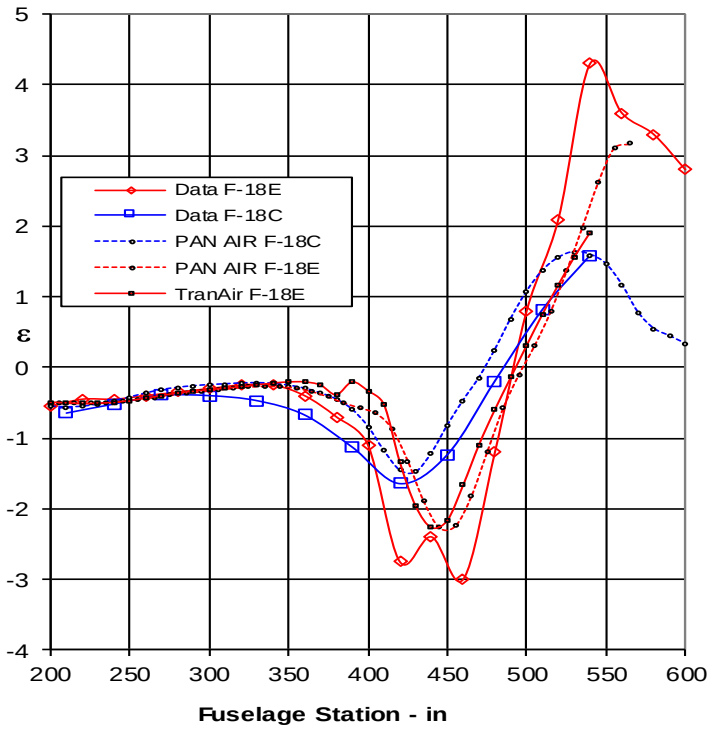
FIGURE 4 JSOW YAWING MOMENT

F-18C & F-18E Flowfields

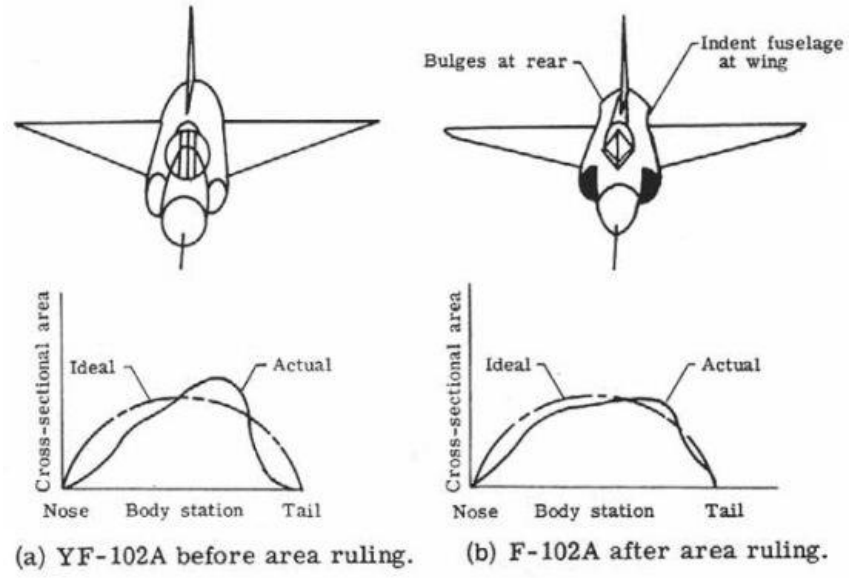
2. It's the same as a MK-XX / GBU-XX / AGM-XX / AIM-XX*.
3. Only secondary structure was modified.
4. Boeing / Lockheed / McDonald / Northrop / EADS* say its OK.

- Early in the program, Pan Air predicted F-18E flowfields were worse than the F-18C
- Warnings ignored "It's only CFD"
- Flowfield predictions later validated by wind tunnel testing





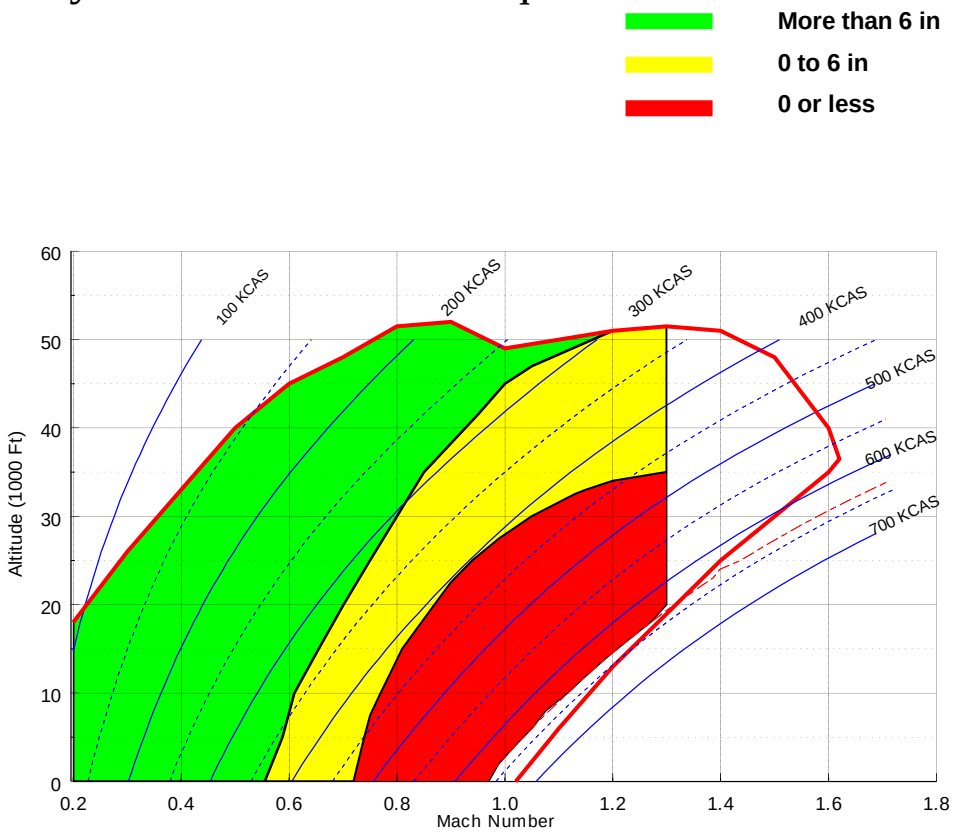
Area Rule



(a) YF-102A before area ruling. (b) F-102A after area ruling.

F-18E/F Store Separation
RTO MP-16 Paper 14

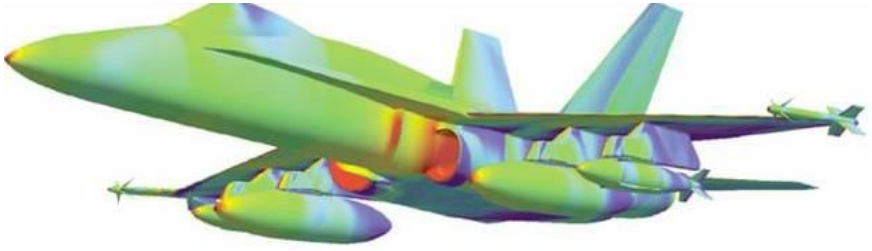
- Wind tunnel test confirmed CFD predictions
- Several aircraft modifications considered to
- Pylon toe and release sequence selected



•Straight Pylons
•Wind Tunnel CTS, Grid and Analysis

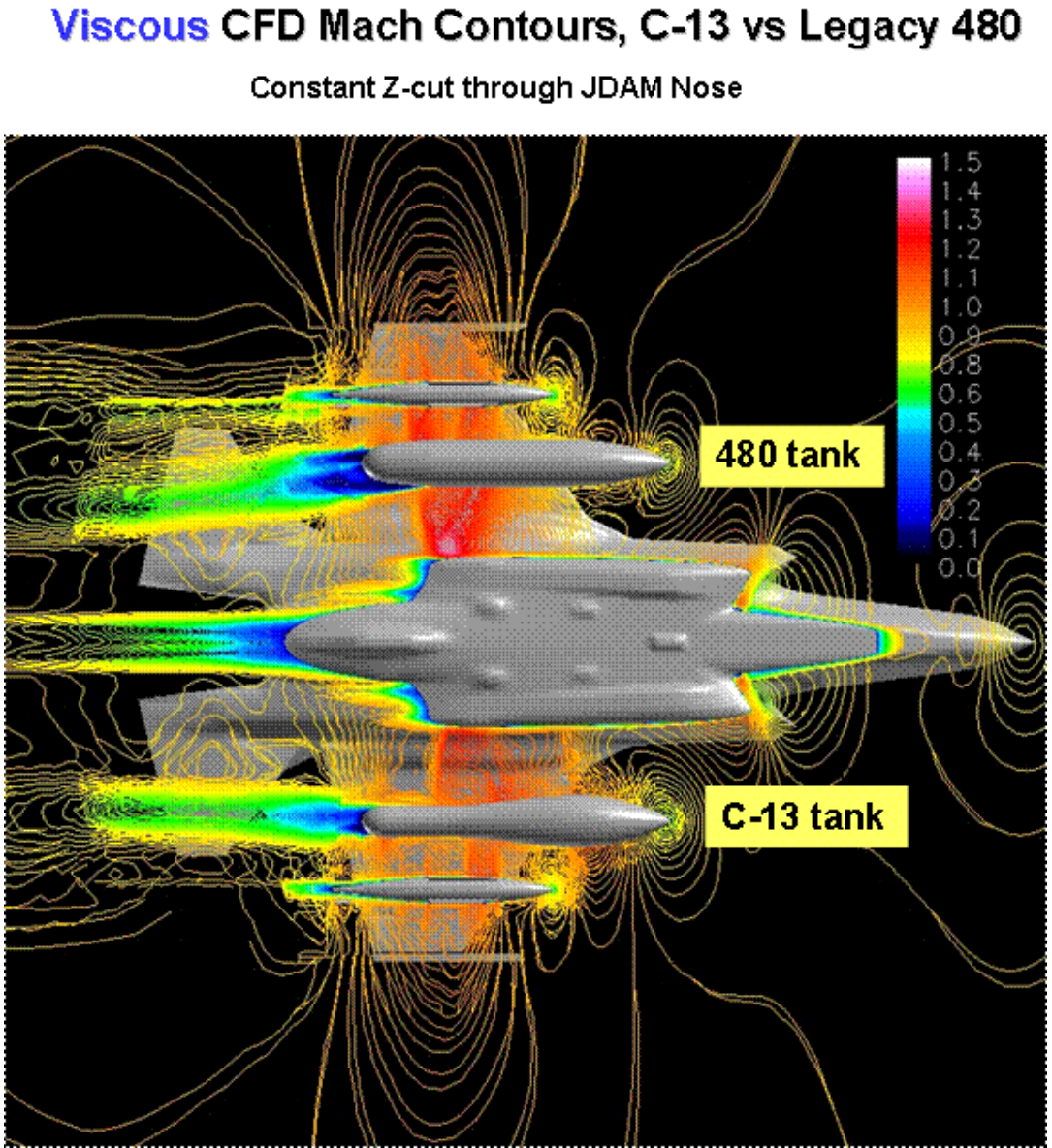
•Toed Pylon

ACFD Challenge II (AIAC 2015-022)



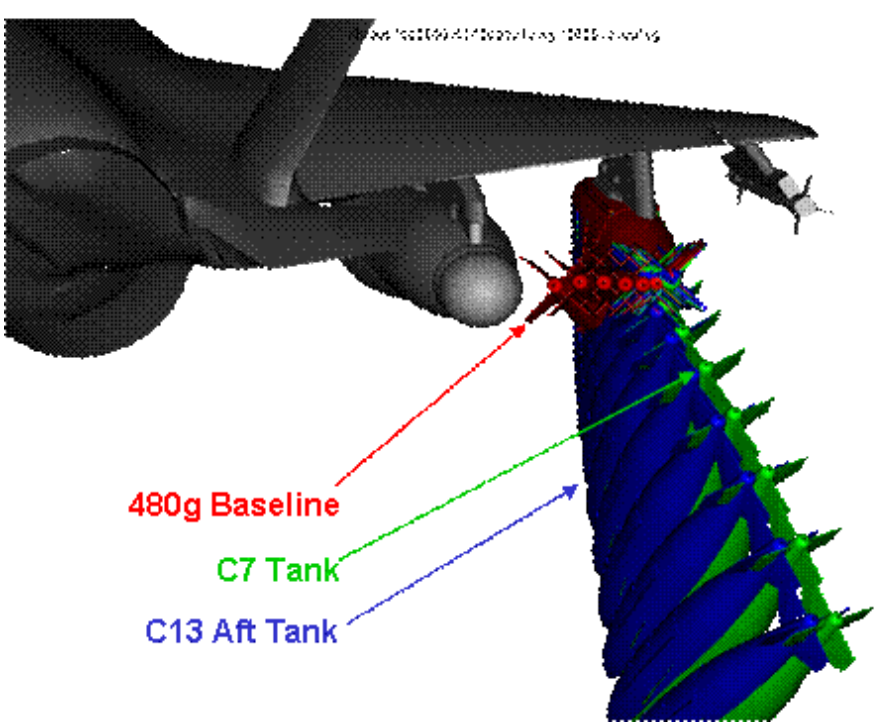
- FTP distribution of aircraft and store geometries and flight test data
- Representative of state of the art for current CFD-based tools for store carriage and release.
- Wind tunnels will still be relied on for the provision of the major part of the aerodynamic data on which stores certification are to be based.
- CFD solutions were within the error range of the wind tunnel and flight test data.
- Time required to produce a solution needs to be decreased significantly.
- CFD-based tools should now become far more prevalent in use during Requirements Definition and Systems Engineering trade-off studies.

Aircraft/Store Integration
Sometimes the Contractors do it Right

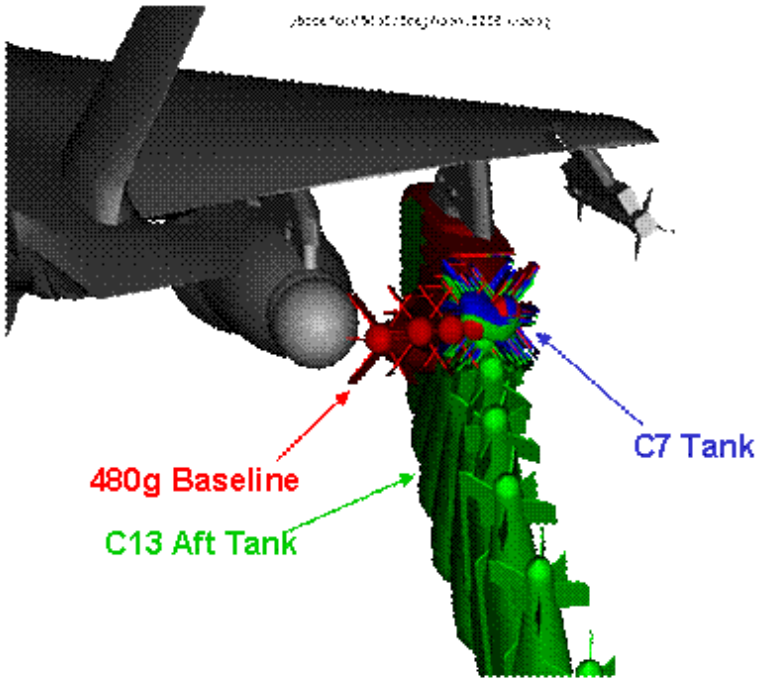


Improved Trajectories of 2K JDAM & JSOW Adjacent to Various Tank Designs

2K JDAM



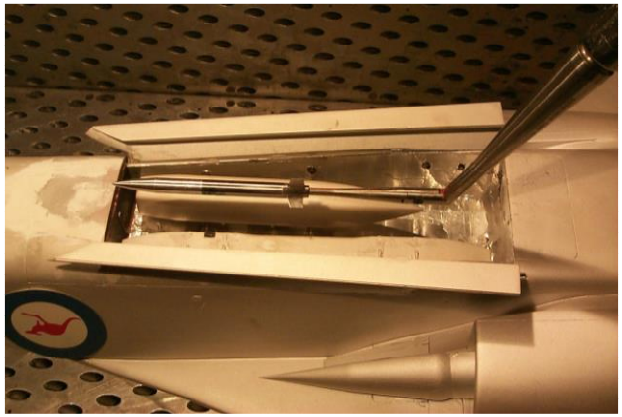
JSOW



F-111G/SSB

RTO-AVT-108

- The separation of a Small Smart Bomb (SSB) from the Royal Australian Air Force (RAAF) F-111G weapons bay provided data to validate computational trajectory simulations codes.
- A total of 16 weapons were released in 8 different sorties. Weapons were released at a variety of Mach numbers and altitudes starting at 0.8, 20K – 1.3, 30K
- Neither the wind tunnel nor CFD came close to matching the flight test results.



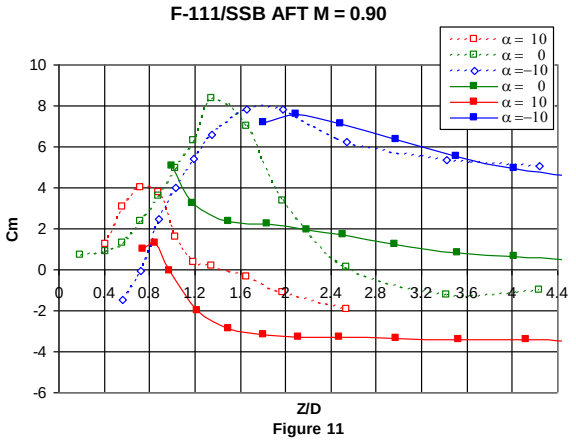
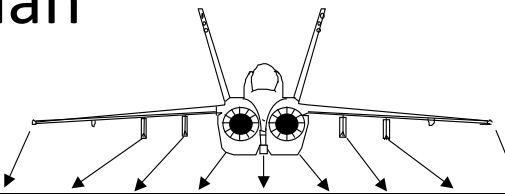


Figure 11

- "Hence it is Aircraft Research and Development Unit's (ARDU) opinion that the pitch anomaly during flight test was not due to the flexing of the (SMER), as the anomaly would have been observed consistently across Mach number."

Wind Tunnel Test Plan

- ***17 Test configurations***
- ***3 Aircraft angles of attack***
- ***2 Aircraft yaw angles***
- ***3 Store pitch angles***
- ***2 Store yaw angles***
- ***20 Z grid points***
- ***12,240 test points per Mach #***



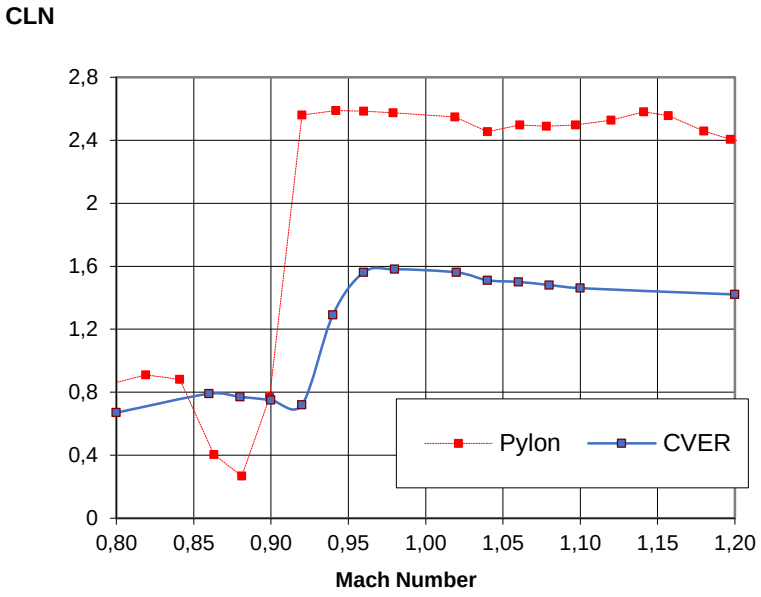
Configuration	1	2	3	4	5	6	7	8	9
300		No Store						No Store	
301		No Store	No Store						
302		No Store			No Store			No Store	
303		No Store	No Store					No Store	
304			No Store				No Store	No Store	
305							No Store		
306		No Store							
307									
308									
309									
310									
311 Sharp Nose JDAM									
312									
313									
314									
315									
316									

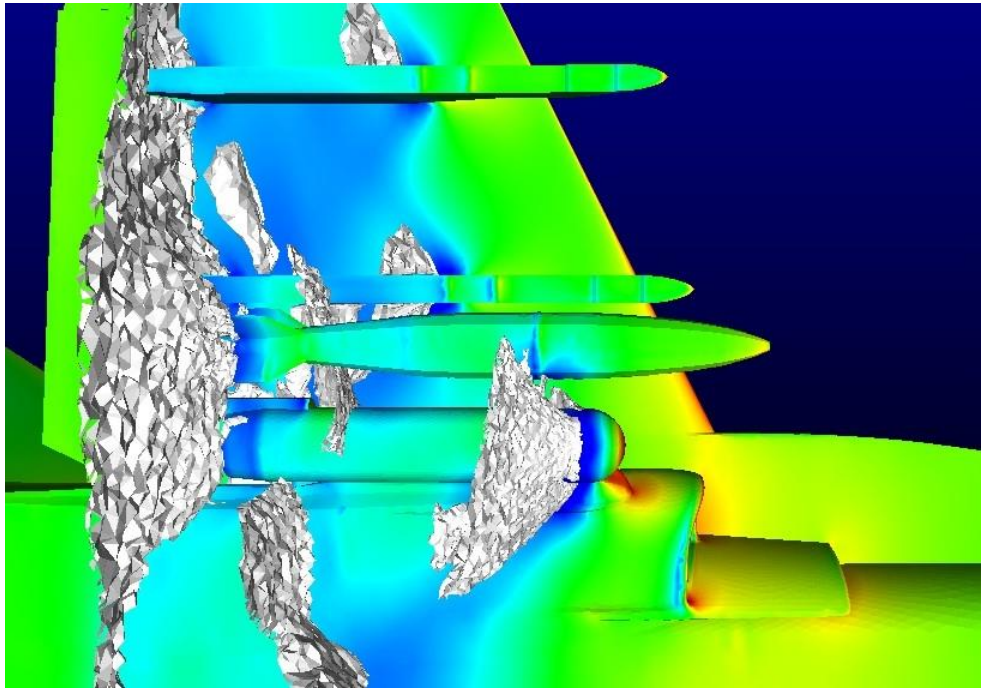
AIM-9L · AIM-7 · ATFLIR · 330 Tank · LAU-118 HARM · No Store Only Pylon · MK-83JDAM Dummy · MK-82JDAM Dummy · MK-83JDAM Metric · MK-82JDAM Metric · Dual AIM-120 · CVER

Traditional Store Separation Wind Tunnel Testing

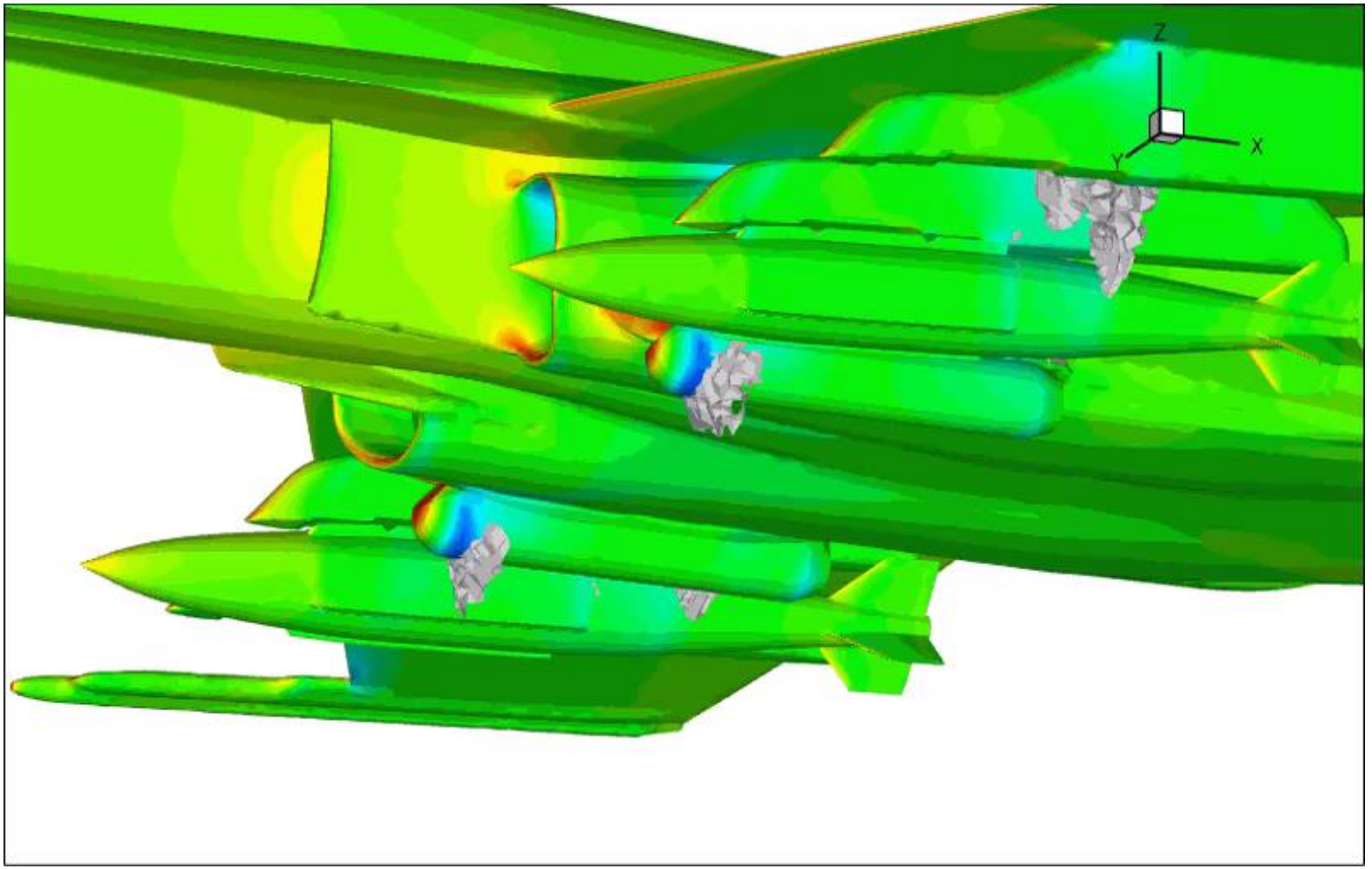
- Store Separation Wind Tunnel Tests Provide Store Forces and Moments in Proximity to the Aircraft
- These Forces and Moments are Then Used to Simulate the Store Trajectories Under Various Conditions
- The Store Separation Engineer Attempts to Determine What Would be the Worst Case Trajectory Under Various Conditions
- The Flight Tests are Conducted for the Worst Cases; However Flight Test Conditions **Can Not Be Determined Prior to the Flight**
- Store Separation Wind Tunnel Tests Were Conducted at Several Aircraft Attitudes with the Store Positioned at +/- 20 Degree Intervals Relative to the Aircraft
- Tests Conducted at Set Mach Numbers (0.80, 0.85, 0.90, 0.95, 1.05, 1.2)
- The Assumption Made was that these Mach Numbers Would Bracket the Worst Case

Mach Sweep Positions the Store at Carriage Position and Measures the Forces and Moments Change with Mach

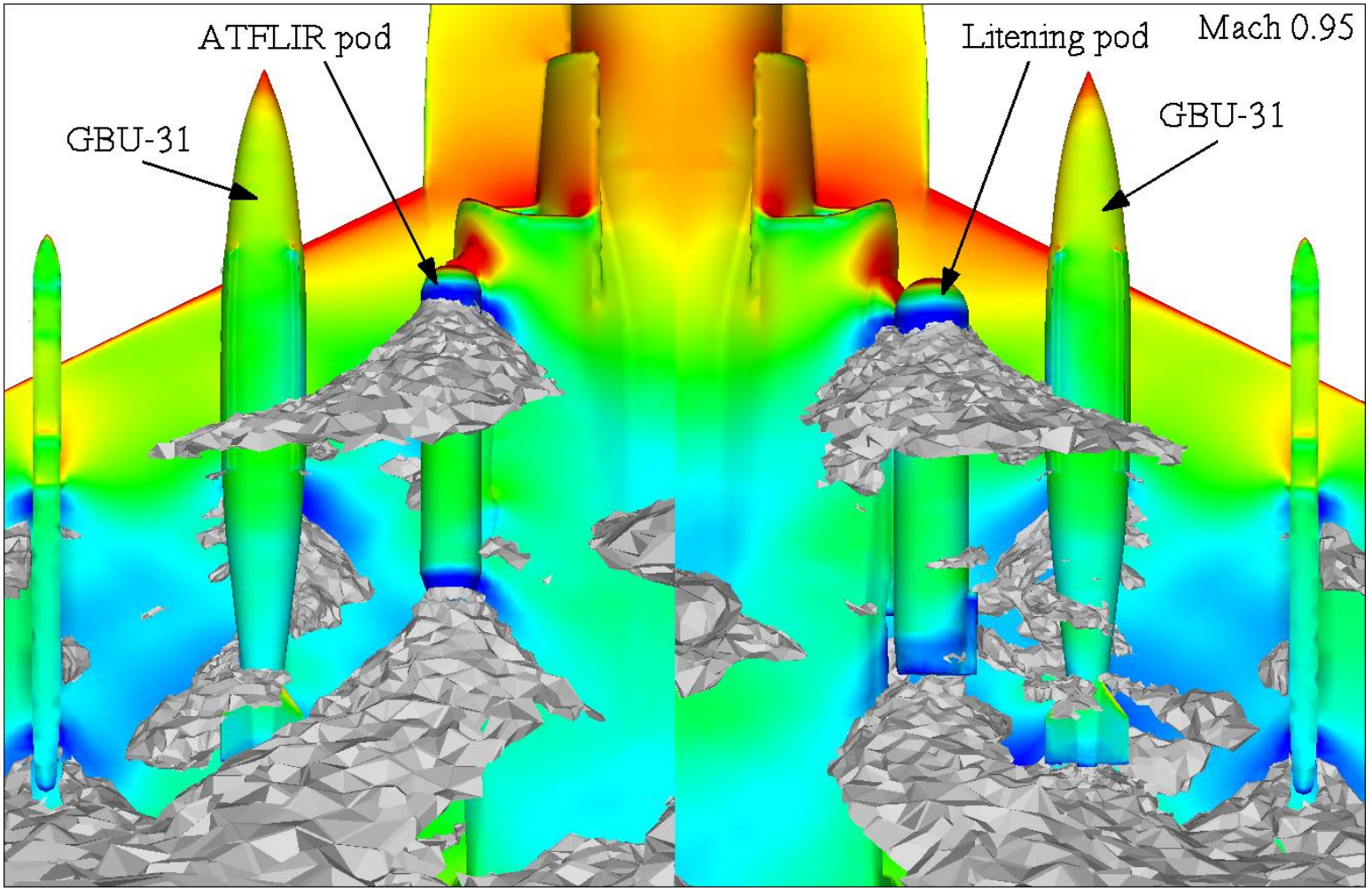




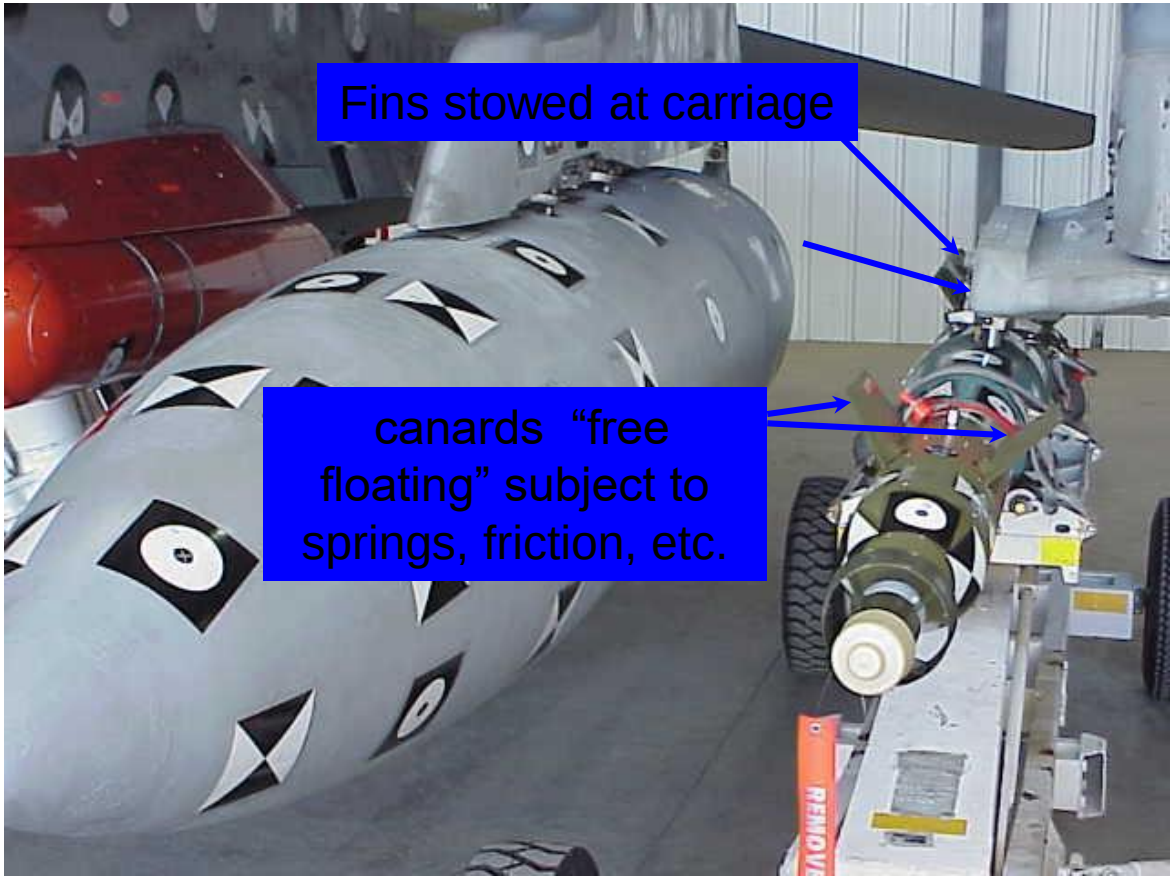
Shock Wave Behavior – Remember Area Rule



ATFLIR/Litening Pod Shocks

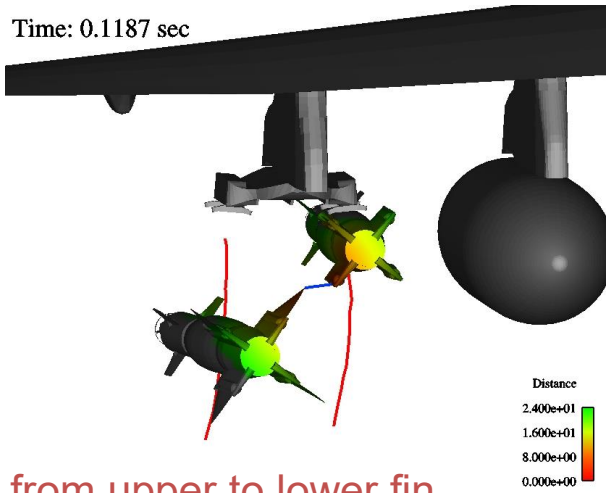


F/A-18C/GBU-12 Adjacent Tank

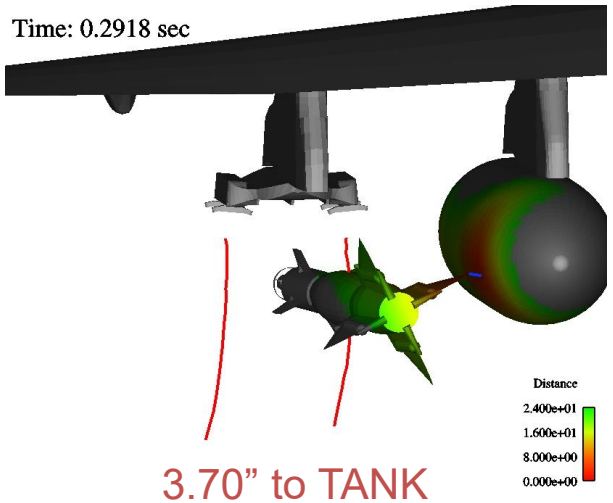


Flight Clearance

- Operation Iraqi Freedom (1st Iraq war) required flight clearance of CVER mounted GBU-12's next to a 330 gallon tank
- Wind tunnel test would have required a minimum of 6 months
- Navy did not have a computational model of the GBU-12 store
- The "hit-or-miss" method was be employed.
- The first flight (M = 0.88, 5000') raised flight safety issues.
- Air Force SEEK EAGLE Office (AFSEO) had the F-18C/D (**ACFD Challenge II**) and GBU-12 grids available
- AFSEO provided the Navy with two time-accurate trajectories predictions in less than two weeks
  - Validation with the first flight
  - End point verification of clearance which allowed continuation of flight test program



5.17" from upper to lower fin



3.70" to TANK

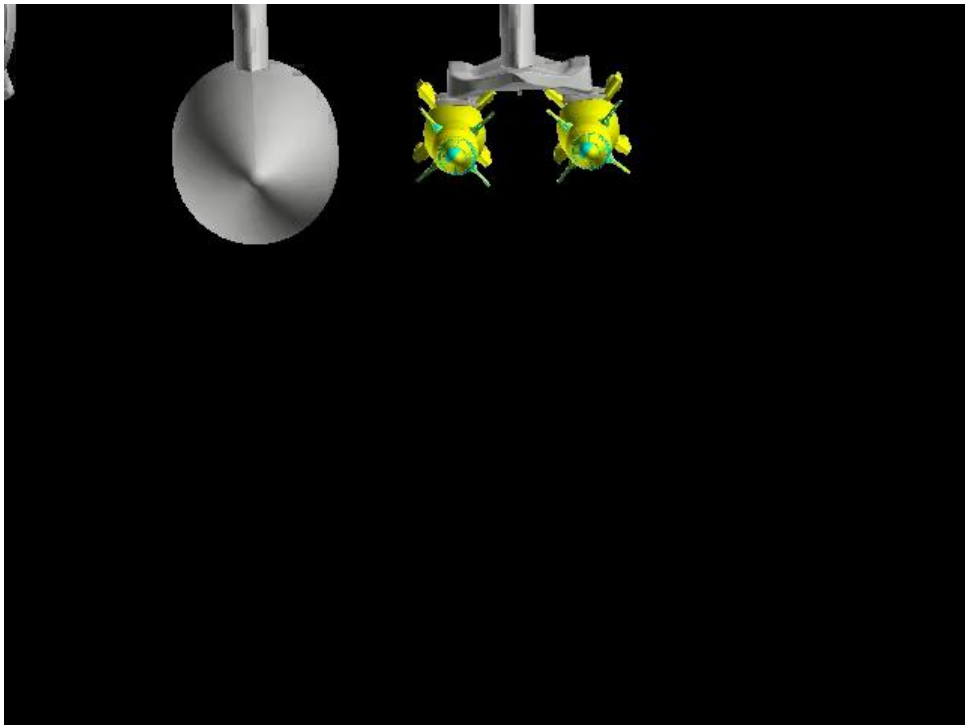
Time Accurate Trajectory Simulations

" the best way to waste computer time is to couple a transonic small disturbance code (Boppe) with a design optimization," P. Adiala, Grumman, 1981.

"Alex, you can't participate in the in the Wing/Pylon/Generic Store CDF challenge because you don't do CFD," Davy Belk, Nov. 1991

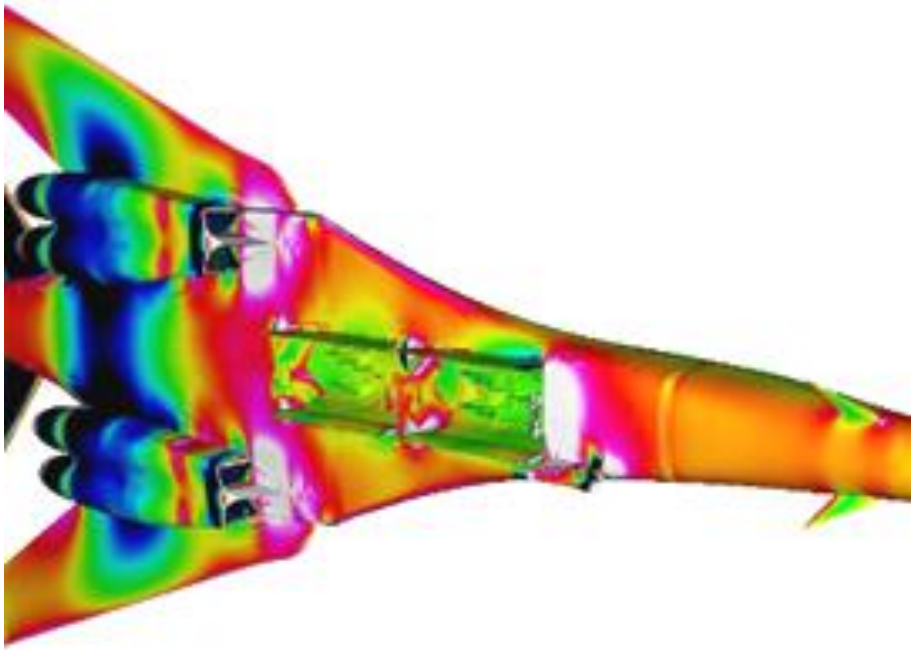
"the best way to waste computer time is to run an overset grid code (OVERFLOW) time accurate to calculate store trajectories (Beggar)," A. Cenko, 1995.

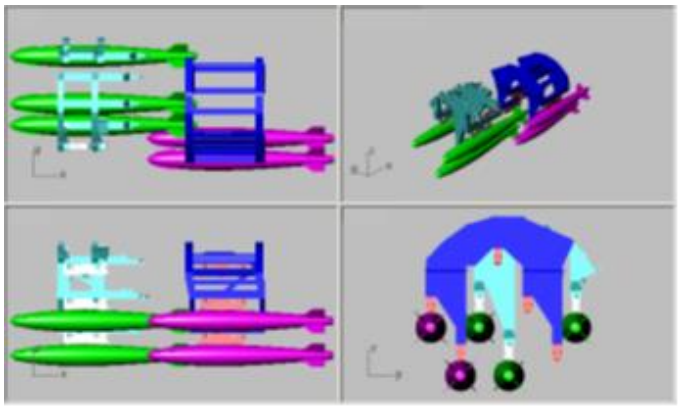
"Time accurate has it's uses," A. Cenko, 2003



B-1B/GBU-38

- CFD blind challenge
- Geometry and test conditions provided
- Flight test results released after predictions submitted
- Poor match with flight test
- Initial ejector forces provided were incorrect; telemetry data provided corrections
- Quasi-steady trajectory simulation did not require any further computations.
- Time accurate had to be repeated.





Store Separation Cook Book

- Start by using a SDoF code
- Ejector forces will dominate the trajectory
- Wind tunnel test plan should be at least 2-3 times time allocated

(if you have money for 200 User Occupancy Hours (UOH), plan for 600)

- No wind tunnel test plan should survive the first CTS run
- SDoF simulations should be done after each model change
- CTS trajectories are useless for flight testing
- Wind tunnel tests occur at different Mach numbers than in flight
- Each change in aircraft configuration should be examined (CFD)
- Each change in store geometry should be accounted for (CFD)
- Mass properties and inertias must be measured before flight
- Every wind tunnel test costs more than expected
- No flight test plan should survive the first flight

Conclusions

- There have been numerous improvements in store separation capabilities over the past 50 years
- Store Separation is a complex process.
- The likelihood of an engineer reading a SDoF user manual and then correctly calculating a trajectory is similar to someone reading an aircraft manual and successfully taking off, and then landing the airplane.
- Mistakes will be made. That is how the process can be improved.
- Documenting mistakes will make further improvements possible.
- Success has hundreds of parents, one admitted mistake may lead to thousands successes.
- I have been very fortunate to be in the right place at the right time.

This lecture is dedicated to Richard Whitcomb, who invented the area rule, supercritical airfoils and winglets.

Questions to the Audience

- There have been incredible changes in CFD capabilities for store separation in the past 5 decades.
- Why have there been no improvements in flight testing? SDoF telemetry still uses 1980's technology.
- Why have there been no improvements in wind tunnel testing since the 1960's?