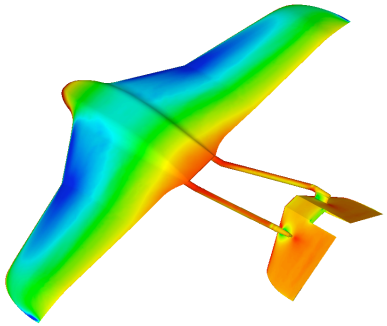
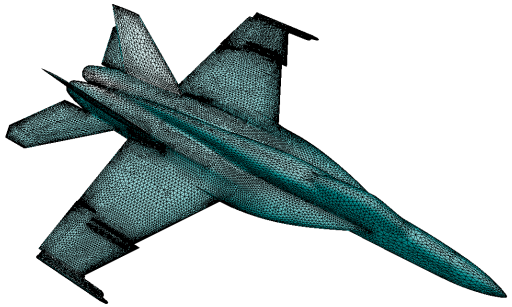
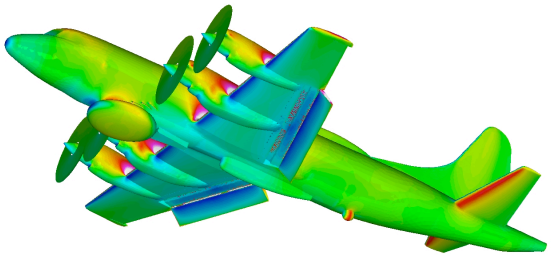
NASA LANGLEY RESEARCH CENTER

TetrUSS

Award-winning Navier-Stokes CFD software
for complex real-world aerodynamics problems

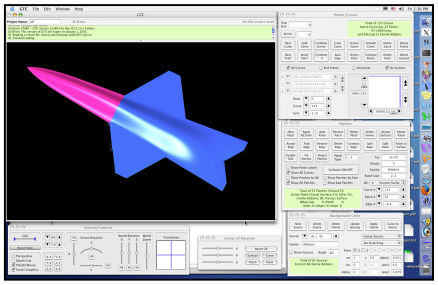




Apple Design Award
Best Mac OS X
Scientific Computing Solution
2004 Winner

NASA
Software of the Year
1996 and 2004

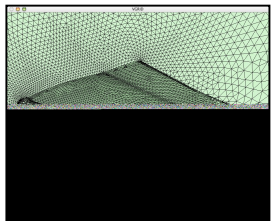
TetrUSS Tetrahedral Unstructured Software System

*A **proven, stable, and reliable** multi-platform system for unstructured Euler and Navier-Stokes CFD analysis.*

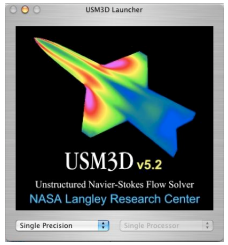


Geometry Setup
GridTool

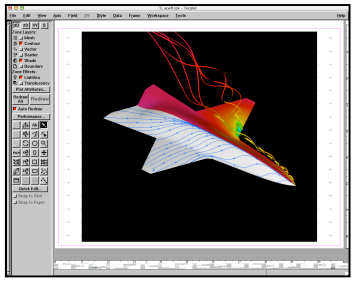
- Complete flow analysis system
- Well developed and validated
- In-house experts
- Broad outside collaborations
- Large experience/confidence base
- Responsive to needs and applications of NASA and external users



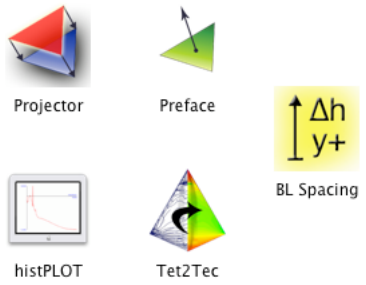
Grid Generation
VGRID



Flow Solver
USM3D



Visualization
ViGPLOT, Tecplot, EnSight, FieldView



Tools & Utilities

The TetrUSS Team

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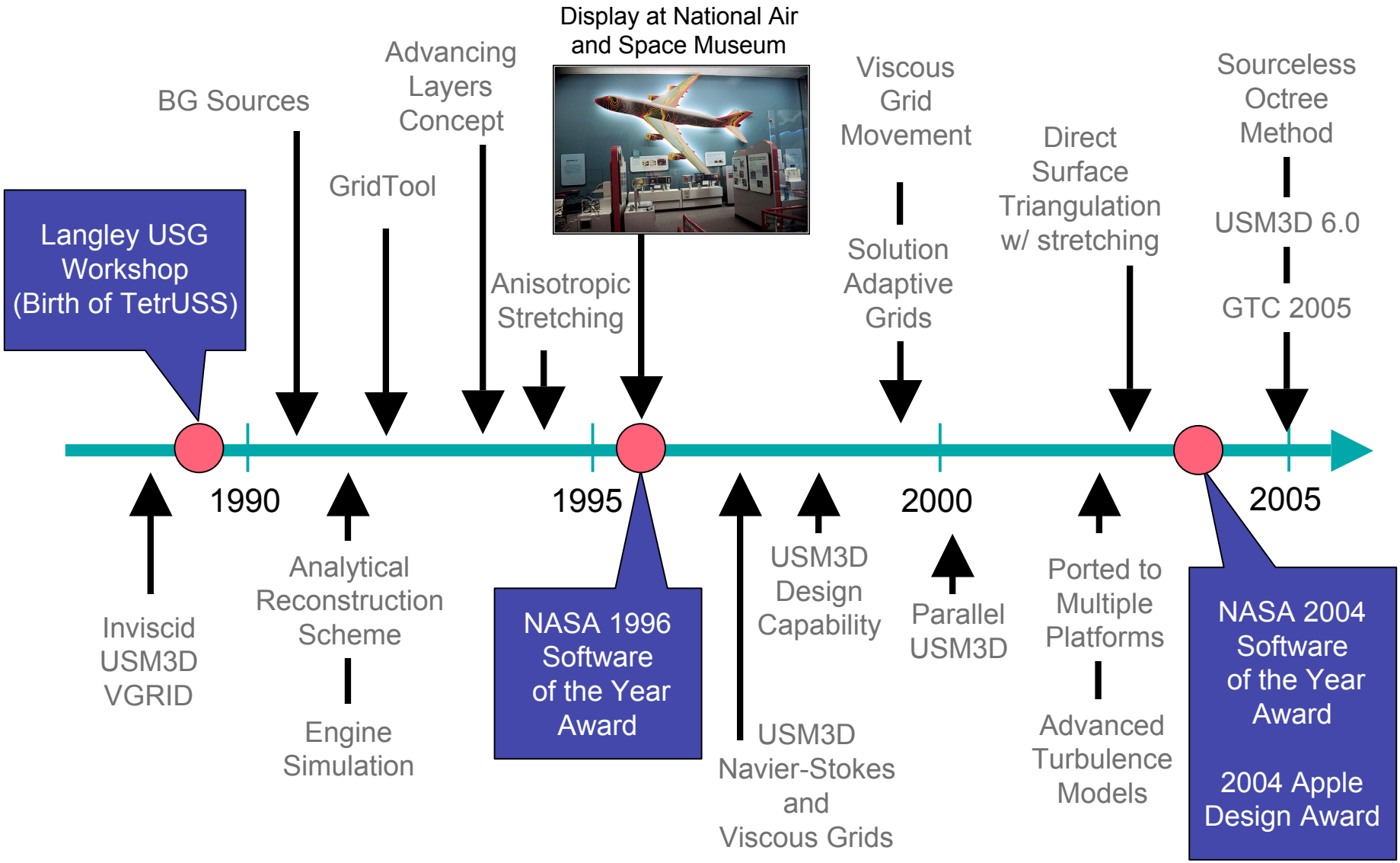
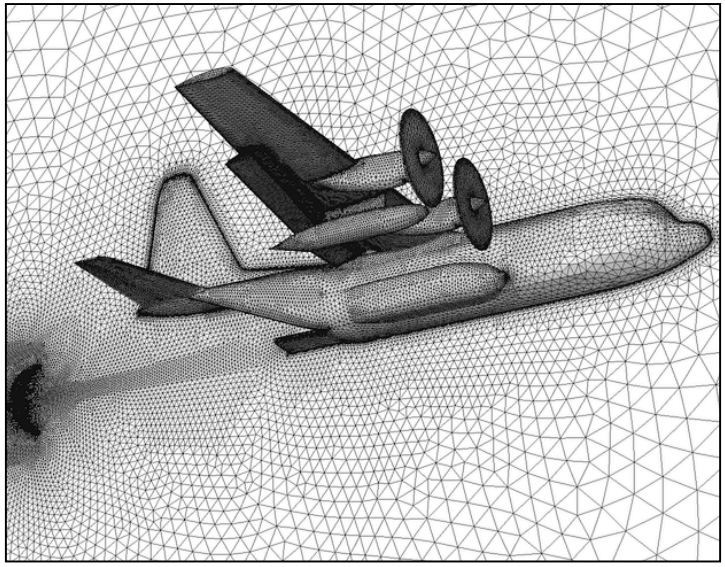
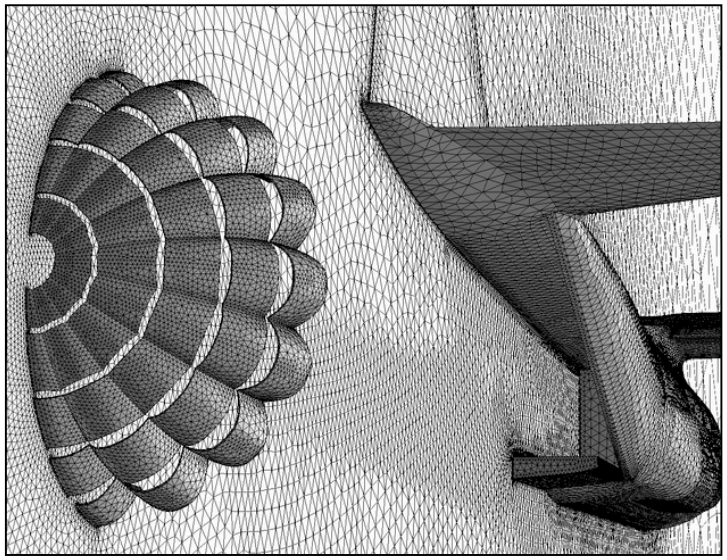
An Award-winning History of Innovation



VGRID: Tetrahedral Grid Generator



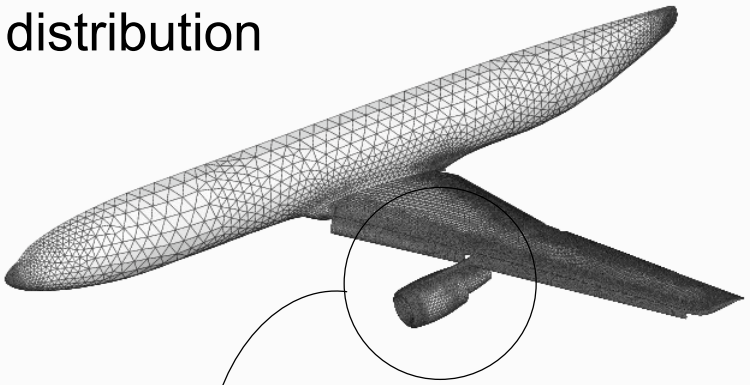


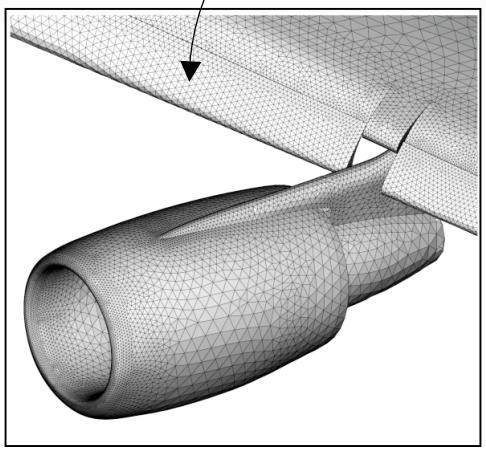
- Thin-layer viscous tetrahedra
- Elliptically smooth grids
- Anisotropic grid stretching on Computer-Aided Design (CAD) surfaces
- Robust viscous grid movement
- Solution adaptive inviscid grid
- Easy control of grid spacing
- Robust, easy to use

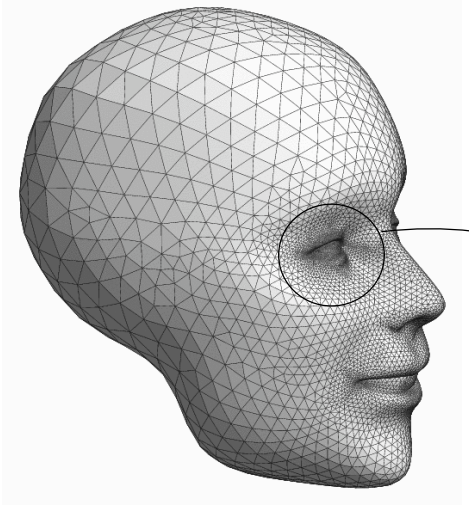
Sample Navier-Stokes Grid
C-130 with Cargo Release Parachute (grid independently generated by student at U.S. Air Force Academy)

Advanced Grid Generation Capabilities

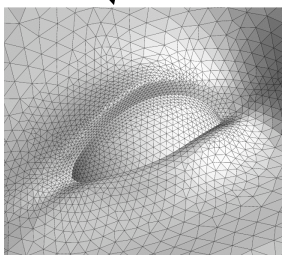
Geometrically-derived background function for **automated** grid point distribution



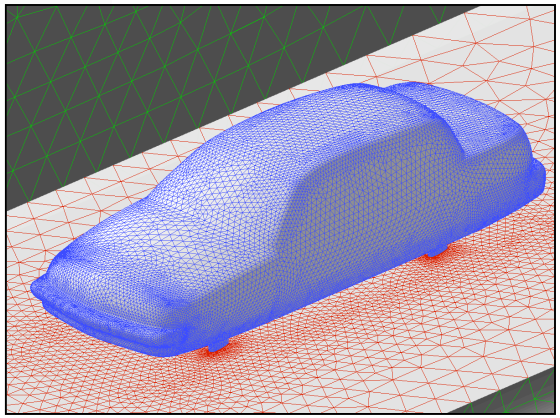




Smooth transition in mesh length scale ensures high quality meshes



Mesh length scales are sensitive to local curvature

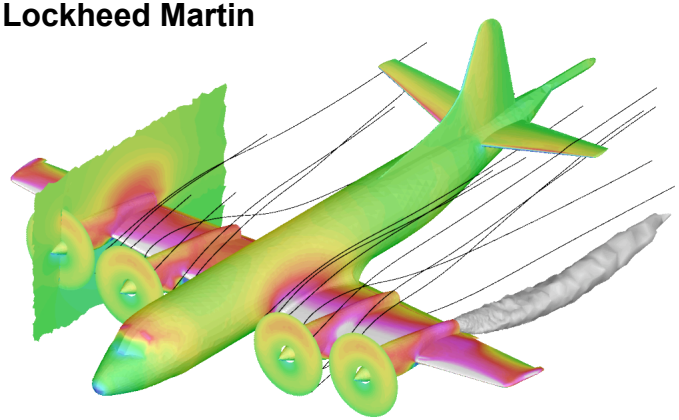


Optional background grid “sources” can be placed by the user for **easy local control** of grid distribution and anisotropic stretching

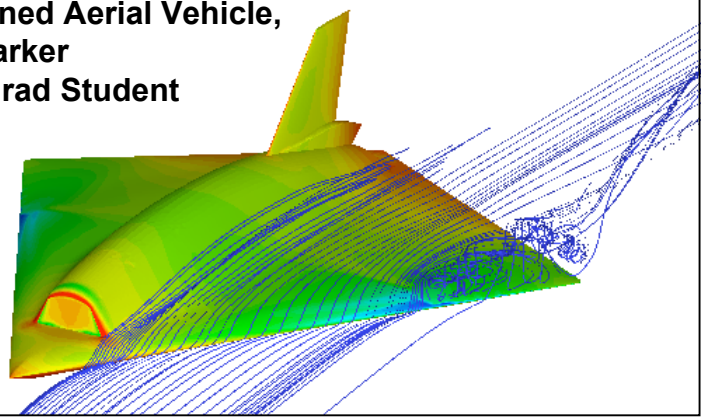
USM3D: Unstructured Flow Solver

- Tetrahedral cell-centered, finite volume
- Euler and Navier-Stokes
- Several 1- and 2-equation turbulence models
- Time Integration: Local and 2nd order time step
- Upwind spatial discretization: FDS, AUSM, FVS
- Preconditioning for low speed flows
- Standard and special BC's
- Runs on multiple platforms:
  Cray, SGI, Sun, PC, Alpha, Mac, IBM, HP
- Parallelized for clusters

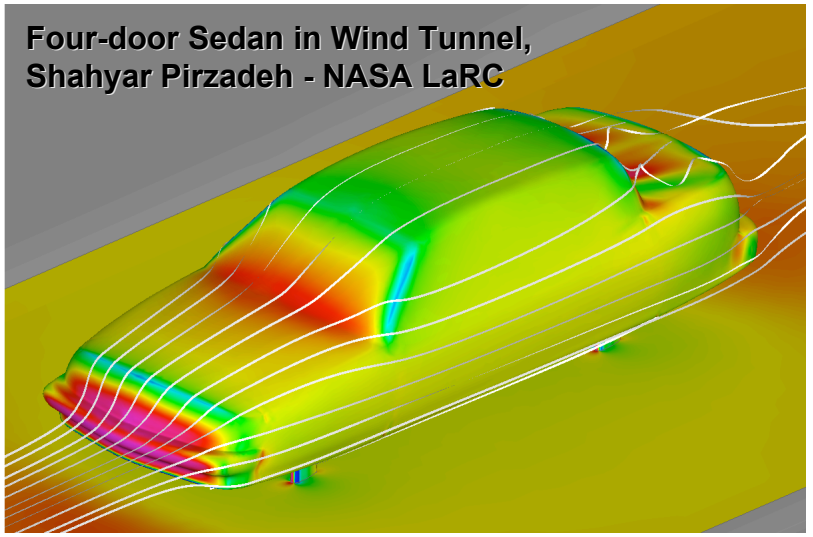
P3-C, Brian Goble and Rick Hooker
Lockheed Martin



Unmanned Aerial Vehicle,
Mike Parker
GWU Grad Student



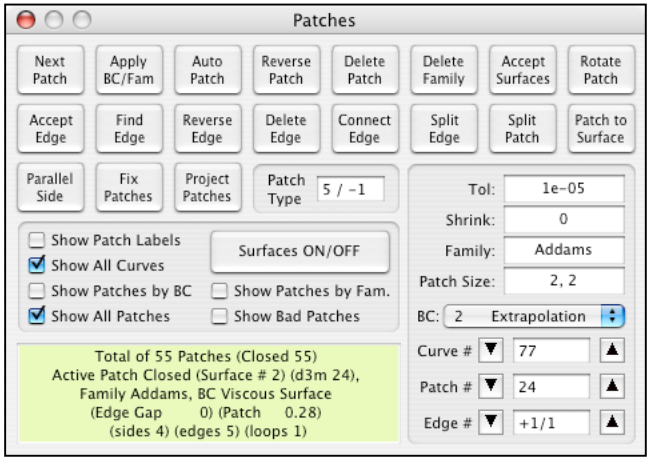
Four-door Sedan in Wind Tunnel,
Shahyar Pirzadeh - NASA LaRC



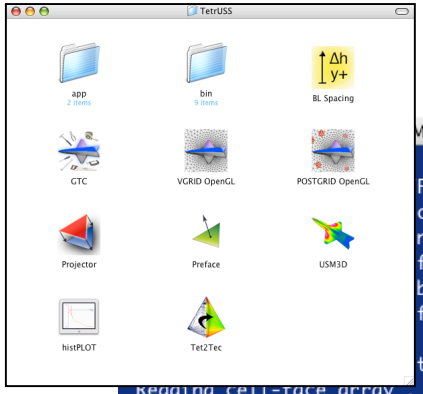
TetrUSS Features - Usability

- **Ease of Grid Generation on Complex Configurations**
  - Less than one week for Euler
  - 1-2 weeks or less for Navier-Stokes
- **Quick turn-around**
  - Lockheed-Martin runs 10 N-S solutions per day on 128 node P4 cluster
- **Phone support and on-site training offered by ViGYAN in Hampton, VA**
  - http://www.vigyan.com/tetruss_training/
- **Online Documentation, Training Materials, Downloads**
- **Collaboration with the TetrUSS team**

Ease of Use: Mac OS X TetrUSS



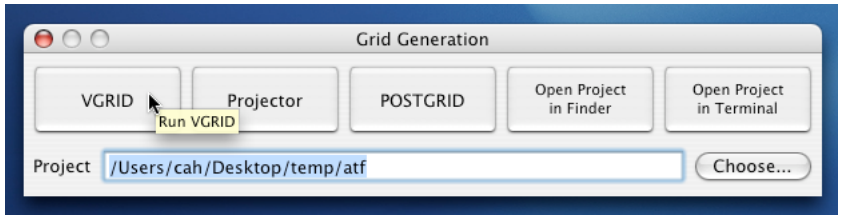
Highly refined GUI design



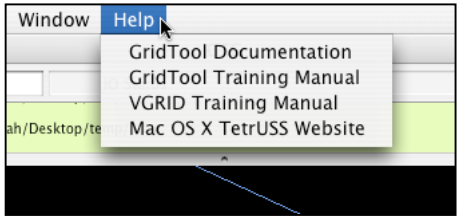
Applications can be run with a mouse click…

or from the UNIX command line

Use of scripted droplets for automation and productivity



“Tool Tip” popups



Help Menus

Software Quality

- TetrUSS has been verified and validated in over a decade of comparison with ground and flight test data
- Continuous quality control and testing through internal use on NASA projects
- Performance optimization and scripting for fast turnaround time and productivity
- Use of open standards like OpenGL, GLUT, MPI, Metis, CVS
- Languages: F77, F90, C, Obj-C, AppleScript
- Cross platform: full TetrUSS suite on SGI, Mac OS X, and soon Linux. USM3D flow solver runs on SGI, Mac, Intel/Linux, HP, IBM, Origin, Cray, Sun, and Alpha/Linux systems.

Innovation

- Several “firsts” in the field of unstructured CFD
  - Novel finite volume algorithms in USM3D
  - Advancing front and advancing layer grid generation techniques
  - Multi-directional anisotropic stretching
  - Viscous grid movement
  - Direct surface triangulation on CAD
- Advanced features
  - Propulsion simulation
  - Moving grids and adaptive grids
  - Higher-order turbulence models
- Many more innovations under development:
  - Time-accurate / unsteady simulations / S&C capability
  - Overset grids
- **Capabilities and functionality are continually driven by the needs and applications of NASA and external users**

Some Organizations that have received TetrUSS

Industry

Achates Power LLC (M)
ADAPCO (S)
Aerodyne Research (S)
Aerospace Corp. (S)
AeroVironment Inc. (M)
Allison (S)
Alpha Star Corp. (S)
American Airlines (S)
Apple Computer (M)
Aurora Flight Sciences (M)
Avid LLC (M)
Beech Aircraft (S)
Bell Automation (M)
BMW Design Works USA (M)
Boeing (S) (M)
Boeing Helocopters (S)
Bosch (S)
CALSPAN (S)
Carleton Technologies (M)
Carrier Corp. (S)
CEI (S)
Ceramatec (S) (M)
Cessna (S)
CFD Research Corp. (S)
Cleaver-Brooks (M)
Cobalt Solutions (S)
Coleman (S)
CRAFT Tech. (S)
Cray Research (S)
CrossFiber Inc. (M)
DH West Aviation (M)
Draper Lab (S)
Dupont (S)
Dynacs Engr. (S)
Eagle Aeronautics (S) (M)
Eaton Corp. (S)
Electrical Geodesics (M)
Energy System Assoc. (M)
Engineering Sciences (S)
Flow Sciences (S)
Ford Motor Co. (S)
General Electric (S)
General Motors (S)
Gulfstream (S)
Hughes (S)
ICEM CFD (S)
Intelligent Light (S)
Kaman Aerospace (S)
Lockheed-Martin (S)
Lucasfilm (M)
Maxtor (S)
MEDAL (M)
Medical Acoustics Inc. (M)
MicroCraft (S)
Miramar Design (M)
MitoSystems Inc. (M)
MSC (S)
Nichols Research (S)
Nielsen Engr. (S)
NN Shipbuilding (S)
Noesis Inc. (M)
Nordam Group (S)
Northrop-Grumman (S)
NYMA (S)
Orbital Sciences (S)
Pioneer Rocketplane (M)
Piper Aircraft (S)
Pratt + Whitney (M)
Precision Stunt Safety Specialists (M)
Raytheon Aircraft (S)
Raytheon Electronics (S)
Raytheon Missile (S) (M)
Raytheon Systems (S)
Reynolds Metal (S)
Rockwell Intl. (S)
Safire Aircraft (S)
SAIC (S)
SGI (S)
Sino Swearingen (S)
Southwest Research Institute (S)
Spectral Sciences (S)
Sverdrup Tech. (S)
Swales (S)
Synaps (S)
The Dow Chemical Co. (M)
Thiokol Propulsion (S)
Transmotive (S)
Universal Space Lines LLC (M)
Veracity Racing Data LLC (M)
Vibro-Acoustic Sciences (M)
Westinghouse (M)
X2 Aeronautics (M)
XCOR Aerospace (M)
Xunami Corp. (M)

NASA Centers

Ames (S) (M)
Dryden (S)
Glenn (S)
Goddard (S)
Johnson (S)
Kennedy (S)
Langley (S) (M)
Marshall (S) (M)

Government

Aberdeen Proving Grounds (S)
AEDC (S)
AFRL (S) (M)
Argonne Natl. Lab (M)
Army (S)
China Lake (S)
CIA (S)
Edwards AFB (S)
Eglin AFB (S)
Hanscom AFB (S)
Idaho National Engr. And Env. Lab (M)
Kirtland AFB (S) (M)
Lawrence Livermore Natl. Lab (S) (M)
Los Alamos Natl. Lab (S) (M)
NADC (S)
NAVAIR - Pax River (S)
Naval Research Lab (S)
NAWC (S)
NCAR (S)
NIST (S)
NSF (S)
NSWC (S)
Office of Naval Research (M)
Sandia Natl. Lab (S)
Tyndall AFB (M)
US Army Missile Command (S)
US Nuc. Reg. Commission (M)
USGS (S)
Wright Pat AFB (S) (M)

Academia

Air Force Institute of Tech. (S) (M)
Arizona State (S)
Boston Univ. (S)
Brown (S)
Cal Poly (S) (M)
Clarkson Univ. (M)
Cleveland State (S)
CMU (S)
Cornell (M)
Drexel (M)
Duke (M)
Embry-Riddle (S)
FSU (S) (M)
Georgia Tech (S) (M)
Harvard (M)
Harvard Medical School (M)
ICASE (S)
Iowa State (S)
Johns Hopkins (S)
Marquette (M)
Michigan State (S)
Mississippi State (S)
MIT (M)
Naval Postgraduate School (S) (M)
NC State (S)
Northwestern Univ. (S)
ODU (S) (M)
Ohio Northern (S) (M)
Ohio State (S)
Penn State (S) (M)
Princeton (M)
Purdue (S)
Rice Univ. (M)
RIT (M)
Rose Hulman Inst. Tech. (M)
Rutgers (S)
San Diego Supercomputer Ctr. (S) (M)
Scripps Institute of Oceanography (M)
Sierra College (M)
Stanford (S) (M)
SUNY (S)
Temple (S)
Texas A&M (S) (M)
Texas Tech Univ. (M)
UC Berkley (S) (M)
UC Davis (S) (M)
UNC (M)
Univ. Alaska (M)
Univ. Central Florida (M)
Univ. Chicago (M)
Univ. Colorado (S) (M)
Univ. Dayton (M)
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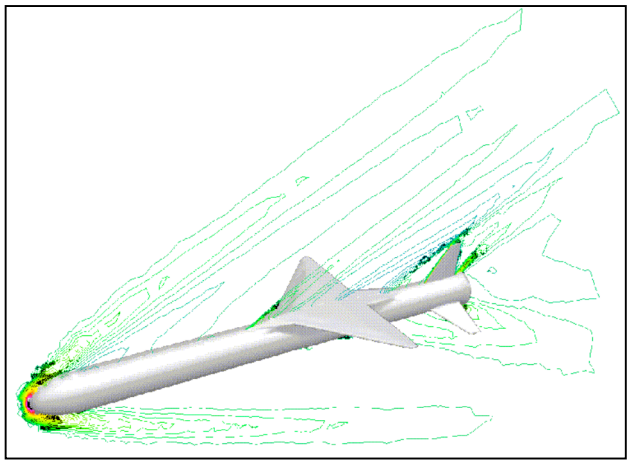
Univ. Kentucky (S) (M)
Univ. Louisville (S)
Univ. Maryland (M)
Univ. Miami (S) (M)
Univ. Michigan (S) (M)
Univ. Minnesota (S) (M)
Univ. Mississippi (M)
Univ. Missouri (S)
Univ. Nevada (M)
Univ. Penn. (S) (M)
Univ. Pittsburgh Med. Ctr. (S)
Univ. S. Maine (M)
Univ. Texas (S)
Univ. Washington (S) (M)
Univ. West Florida (M)
US Naval Academy (S)
USAF Academy (S)
UTSI (S)
VA Tech (S) (M)
Vanderbilt (M)
Washington Univ. (S)
West Chester Univ. (M)
Wichita State (S) (M)
Wright State (S) (M)

Notes: (S) = SGI TetrUSS, (M) = Mac TetrUSS

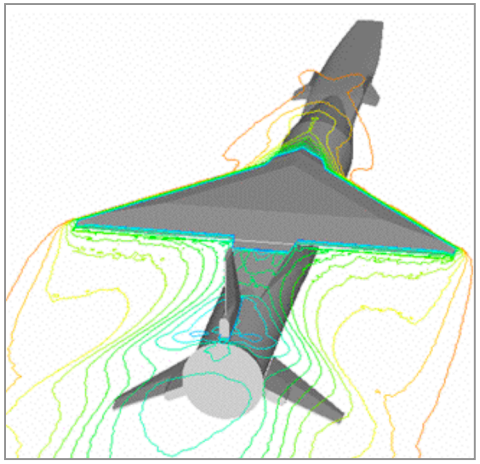
Significance of TetrUSS to NASA's Mission

- **Major impact on critical NASA projects**
  - X-43A/HYPER-X Mishap Investigation and Return to Flight
  - Mars Scout, Mars Smart Lander
  - Joint Strike Fighter Design Team
  - AA Flight 587 Accident Investigation (with NTSB)
- **Manpower and time savings**
  - Ability to tackle complex problems in days or weeks instead of weeks or months
- **Risk reduction**
  - Comprehensive aerodynamic analysis prior to ground or flight testing
- **Direct cost savings to NASA are substantial**
  - **$2.5M over last 8 years** compared to equivalent COTS software licenses
  - Availability of Mac/Linux software saves $20-45K per workstation over comparable legacy hardware (total **more than $400K from 2002-2005**)
  - Parallel software provides an **order of magnitude reduction in supercomputing costs**, from $0.50-$1.00 per hour (supercomputers) to $0.02-0.05 per hour (PC/Linux clusters).

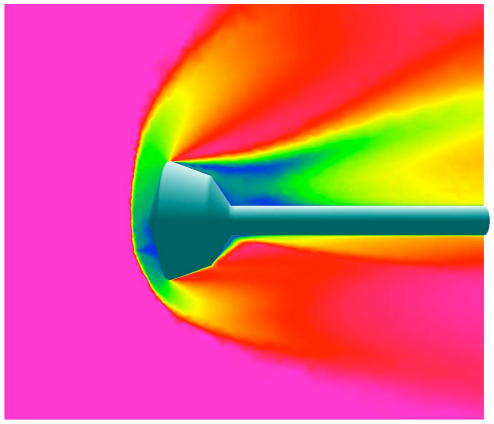
TetrUSS Applications in NASA Projects



Pegasus XL RTF

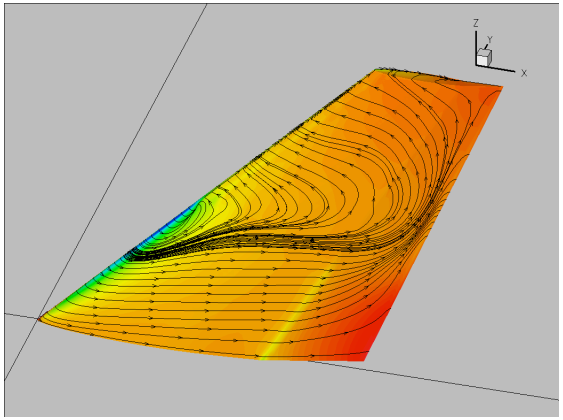


X-43A (HYPER-X)
Mishap & RTF

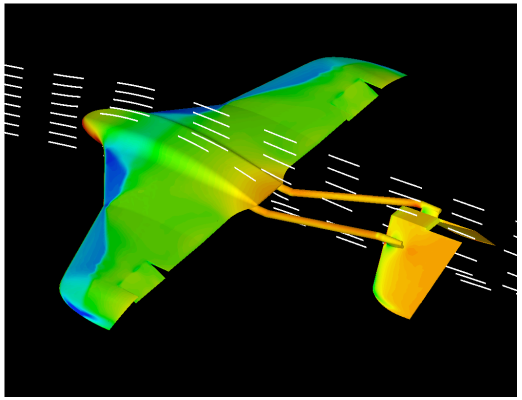


Mars Smart Lander

JSF Design Team



AA Flight 587 Accident
Investigation (with NTSB)



Mars Scout / ARES

X-43A (HYPER-X)

Mishap Investigation

- Over 60 N-S solutions on 8 separate grids in a 3 month period
- **TetrUSS used for:**
  - Filling in “gaps” in exp. data
  - Resolve discrepancies in exp. data
  - Evaluate effect of Thermal Protection Sys. (TPS) on S&C
  - Component loads
  - Aeroelastic studies

Return to Flight (RTF)

- Over 100 N-S solutions on 16 different grids of full stack configuration with TPS in 3 months
- Mach range from 1.4 to 7.0
- **Additional TetrUSS uses:**
  - Trajectory design
  - Loads and hinge moments for mechanical design of spindle & gears for the control surfaces

“The TetrUSS package was utilized extensively during the Hyper-X / X-43A Return-to-Flight activities. Over 100 Navier-Stokes solutions were obtained on the Hyper-X Launch Vehicle over a large Mach number, angle-of-attack, and control configuration range, in order to assess the effects of a variety of complex aerodynamic phenomena. ***This effort proved invaluable during the Return-to-Flight activity, and was possible due in large part to the seamless integration of a rapid grid generation capability, the efficient parallel processor flow solver, and post processing software tools.”***

Walt Engelund, NASA Langley - Hyper-X Aerodynamics Group Leader

AA Flight 587 Accident Investigation

- Nov. 12, 2001: American Airlines flight 587 (Airbus A300-600) enroute to Santo Domingo crashed in Belle Harbor NY shortly after takeoff from JFK.
- All 260 persons aboard and 5 persons on the ground were killed -- second deadliest airline accident in U.S. history.
- Vertical tail and rudder and both engines separated from the aircraft before it impacted the ground.
- TetrUSS team members asked to compute and analyze aerodynamic loads on the vertical tail and rudder.
- CFD team examines and measures tail and rudder wreckage, generates geometry model with GridTool and viscous grid with VGRID, and runs three N-S solutions **in 40 man-hours effort**.
- **Able to respond to critical need in less than one week.**

"I would like to commend the developers of the TetrUSS software for their efforts in support of the NTSB's accident investigation of the crash of American Airlines Flight 587. The group performed CFD computations […] which provided the accident investigation with an improved understanding of the aerodynamic loadings on the tail during the accident."

John Edwards, NASA Langley - AA 587 Investigator

Application: Mars Scout / ARES

Role: TetrUSS leveraged throughout the design process as an aerodynamic analysis tool, used to evolve the design of ARES from concept to flight.

TetrUSS allowed credible, detailed examination of flow characteristics and aerodynamic performance before wind tunnel or flight hardware were built.

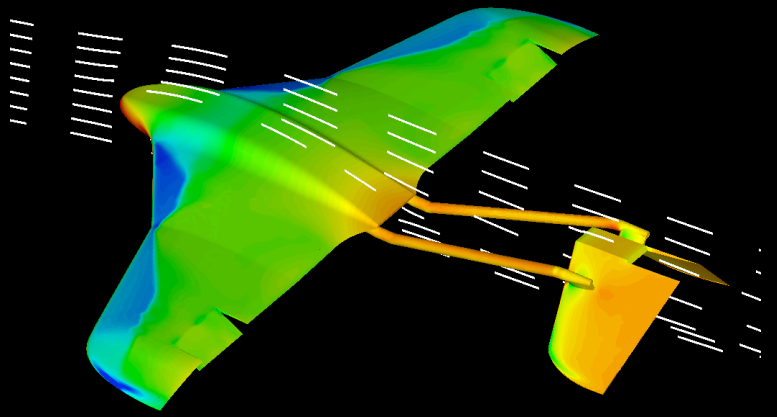
In one man-year's worth of effort:

3 different airplane configurations analyzed

Over 30 different grids developed

Over 120 CFD solutions run

Turnaround: **CAD to N-S solution in 4 days**



"Being able to perform detailed assessments of aerodynamic performance reduced our design cycle time from months to weeks allowing us to define the optimum configuration with time to spare. Operating in a niche aerodynamic regime (low Reynolds number and high subsonic Mach number) where tools are few and far between and testing is very expensive, ***we have found TetrUSS to be the tool of choice."***

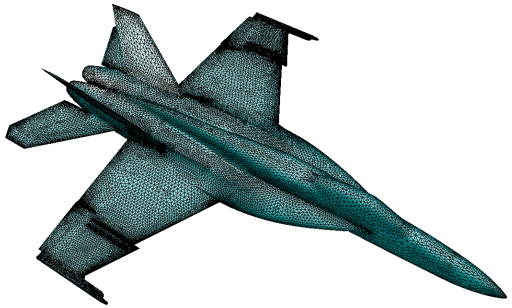
Henry Wright, NASA Langley - Chief Engineer of ARES

Significance of TetrUSS to Science & Technology

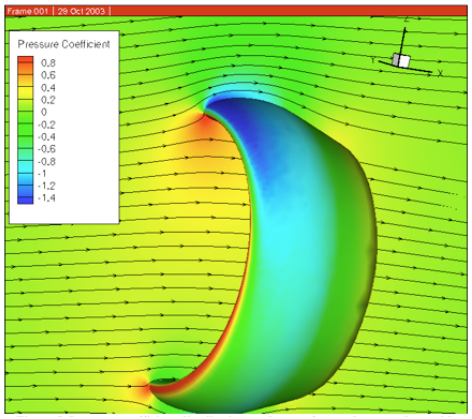
- **Extensive use in Government and Industry, including:**
  - Piper Aircraft
  - Raytheon Aircraft Company
  - Lockheed-Martin
  - Cobalt Solutions LLC
  - AVID LLC
  - Central Intelligence Agency (CIA)
  - Naval Air Systems Command (NAVAIR)
  - Air Force Research Lab (AFRL)
- **Extensive use in Academia**
  - Software released to over 80 colleges/universities across the nation

TetrUSS Applications in Gov. & Industry

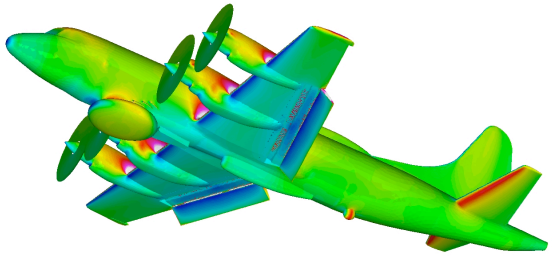
MD-11 Pylon Fairing Redesign (MDA)



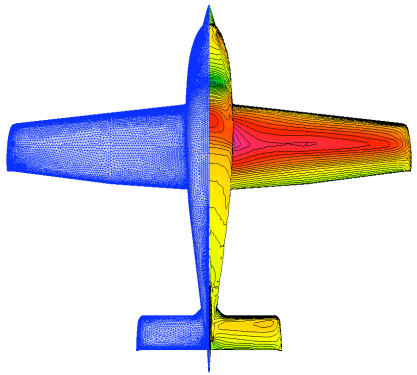
F/A-18 Abrupt Wing Stall (NAVAIR)



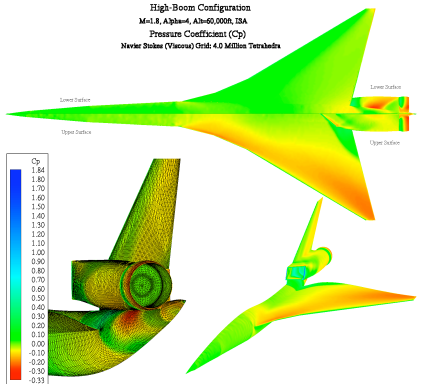
Ducted Fan UAV (AVID LLC)



P-3 Loads Database (Lockheed-Martin)



FAA Recertification of Reengineering (Piper)



Civil Transport Concept Study (Raytheon)

External Customer Comments

"We have developed a high level of confidence in TetrUSS and, indeed, have matched wind tunnel results with surprising accuracy. We have used it to provide aerodynamic estimates for many foreign weapon systems. ***TetrUSS represents a huge increase in our ability to provide quality answers."***
M.L. Bangham -- Central Intelligence Agency

"What we like about the software is its ease of use, which allows us to generate very detailed viscous unstructured grids over extremely complex geometries in a short time frame (on the order of a week once one has become proficient), the continuous upgrades that reduce user-required actions and also speed up hands-off grid generation time, the quality of the mesh produced, the accuracy of the CFD results we achieve with that mesh, and most importantly, the support." **John Clark, Division Chief -- NAVAIR**

"No other grid package, commercial or otherwise, was able to suit our needs as well as NASA's tools. The software tools are reliable and robust, and coupled with the excellent support provided by NASA personnel, allow us to satisfy the needs of our Air Force Customers."
Doug Blake, Branch Head -- Air Force Research Laboratory

External Customer Comments

Raytheon Aircraft Company

"The TetrUSS system is an outstanding tool for industrial strength problems. Its strengths are magnified by the support of a responsive and professional team. ***TetrUSS is now among our preferred CFD tools at Raytheon."***
C. Venkatasubban -- Raytheon Aircraft Company

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cobalt solutions
first time ... every time™

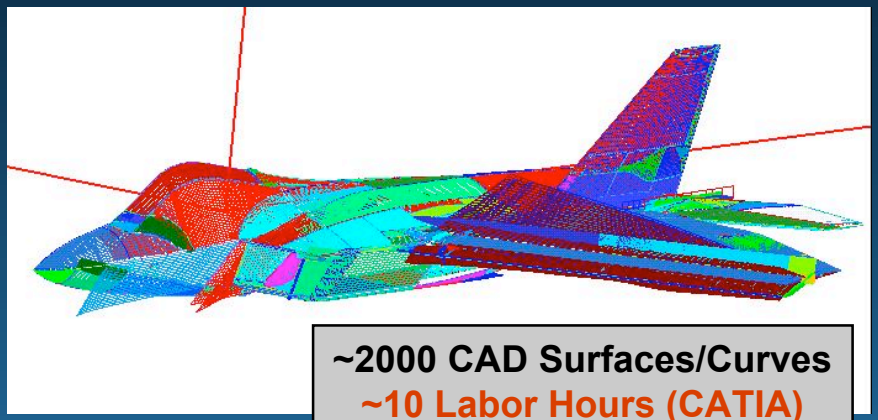
"These software packages have been crucial to full-aircraft research that my company and our customers have performed." **Jim Forsythe -- Cobalt Solutions LLC**

LOCKHEED MARTIN

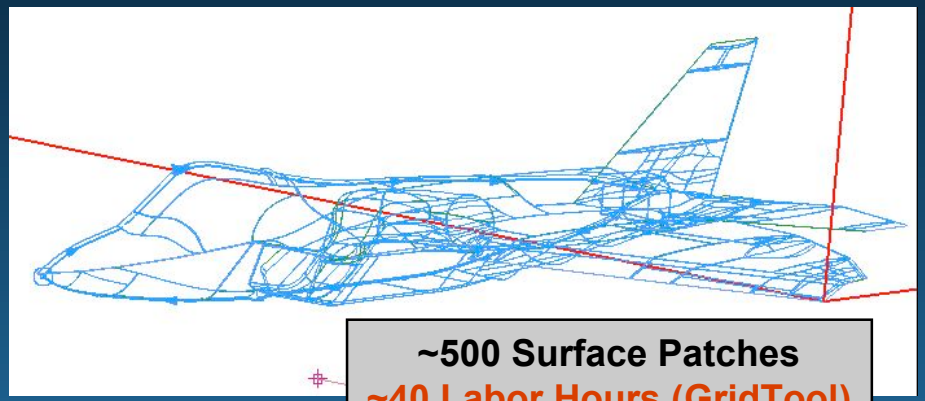
"Lockheed-Martin has relied heavily on the TetrUSS system for aerodynamic analysis of complex configurations. This system has proven very reliable and robust and provides critical capabilities not available in other packages. Of equal importance to Lockheed-Martin is the continued support of the NASA researchers. Their shared expertise coupled with their willingness to incorporate enhancements based on our needs has proven critical in solving several time-critical tasks and has made TetrUSS an invaluable asset."
Rick Hooker -- Lockheed-Martin Aeronautics Company

TetrUSS Capabilities - Grid Generation Examples

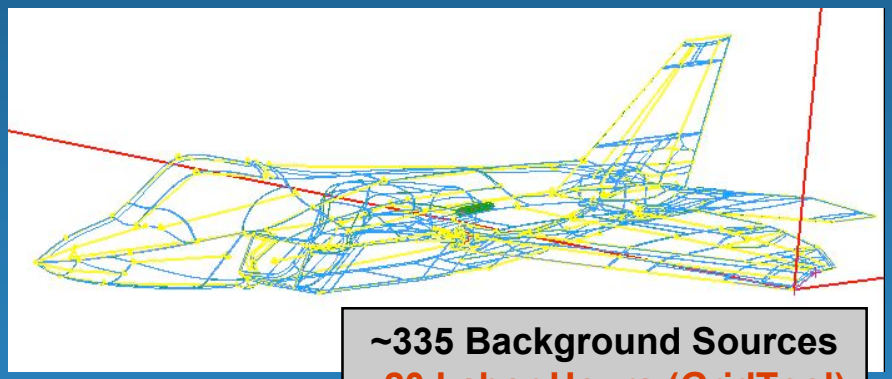
F-22 Viscous Grid Generation Example



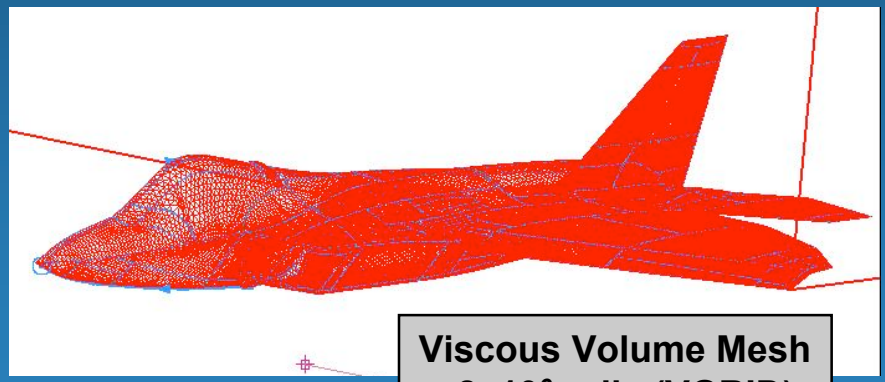
~2000 CAD Surfaces/Curves
~10 Labor Hours (CATIA)



~500 Surface Patches
~40 Labor Hours (GridTool)



~335 Background Sources
~20 Labor Hours (GridTool)



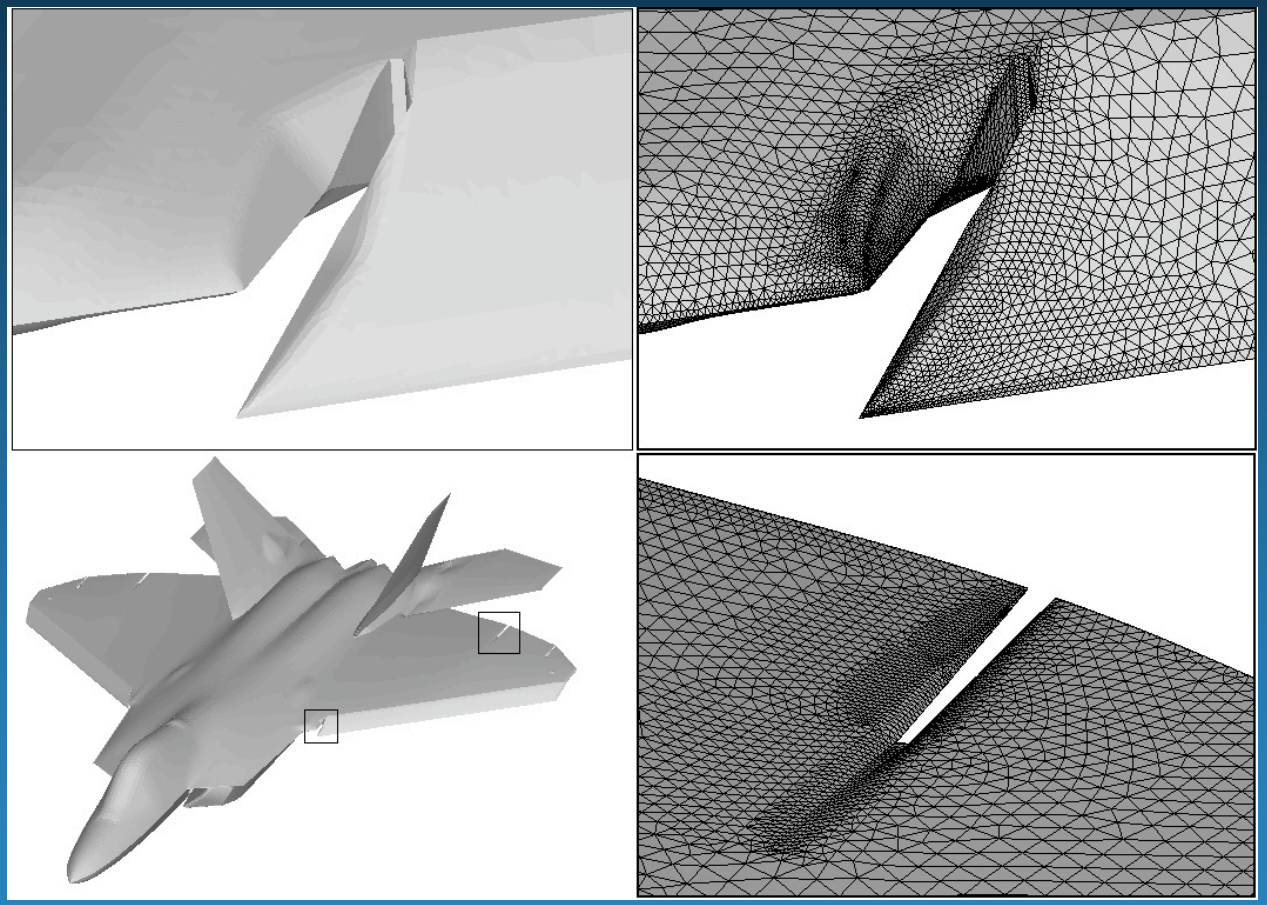
Viscous Volume Mesh
~8×10^6 cells (VGRID)

~60 – 70 Total Labor Hours
(1 Week Time)

The following charts contributed by Rick Hooker show how Lockheed-Martin is using TetrUSS to solve complex real-world aerospace design and analysis problems.

TetrUSS Capabilities
- Grid Generation Examples

F-22 Viscous Grid Generation Example

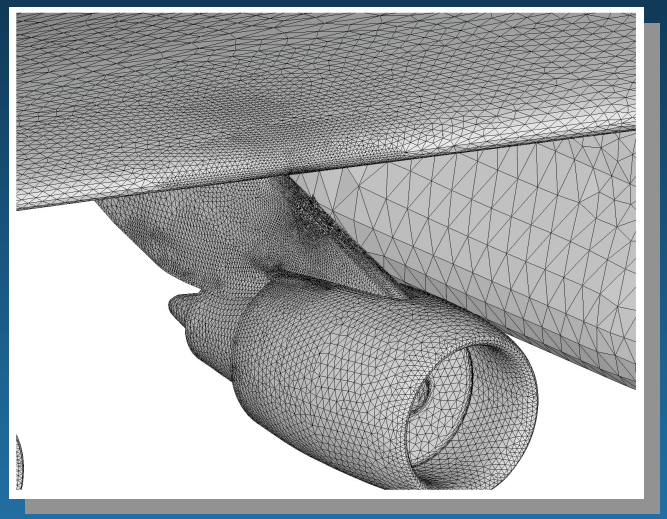


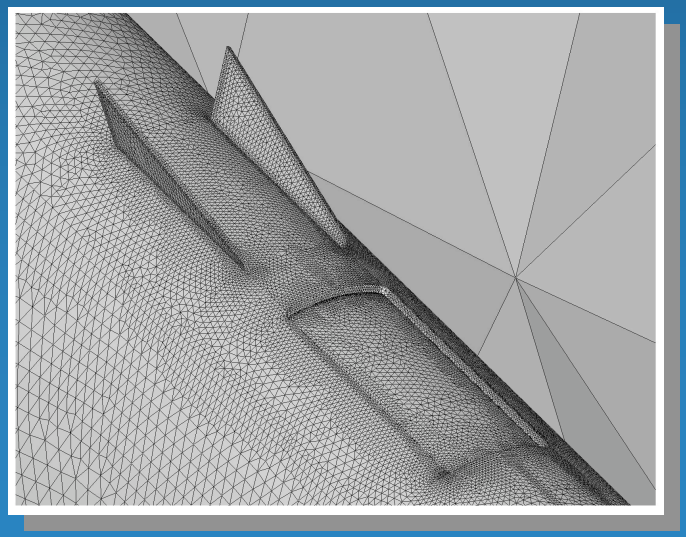
Traditional Problem Areas

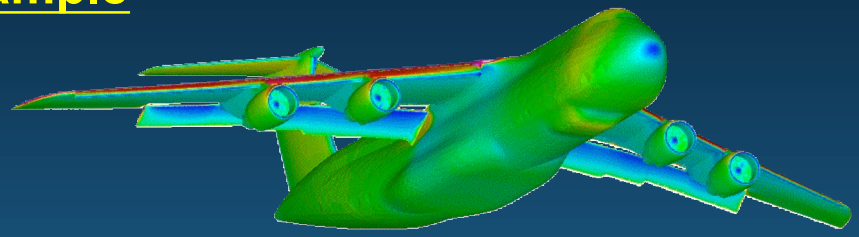
- **Cat's eyes**
  - *High geometric fidelity*
  - *Multiple viscous layers growing together*
- **VGRID handles well**
  - *Requires adequate grid resolution*
  - *Viscous layers prevented from running into/through each other*

TetrUSS Capabilities - Grid Generation Examples

C-5 Viscous Grid Generation Example







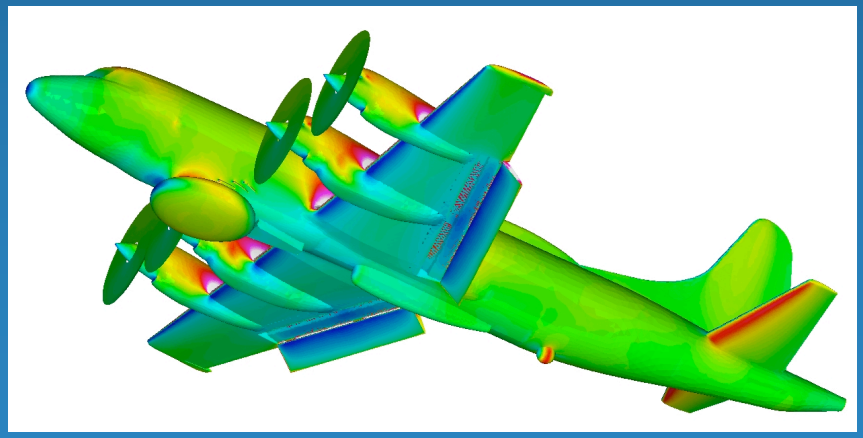
Model Specifics

- 77k surface points
- 7.5×10^6 cells
- Baseline C-5 viscous volume mesh generated in 40 LABOR HOURS
  - Various flap/slat settings modeled
  - 4 different engine installations modeled
- Pre-Cooler exhaust effort grid modifications
  - Spatial adaptation used to resolve pre-cooler exhaust plume

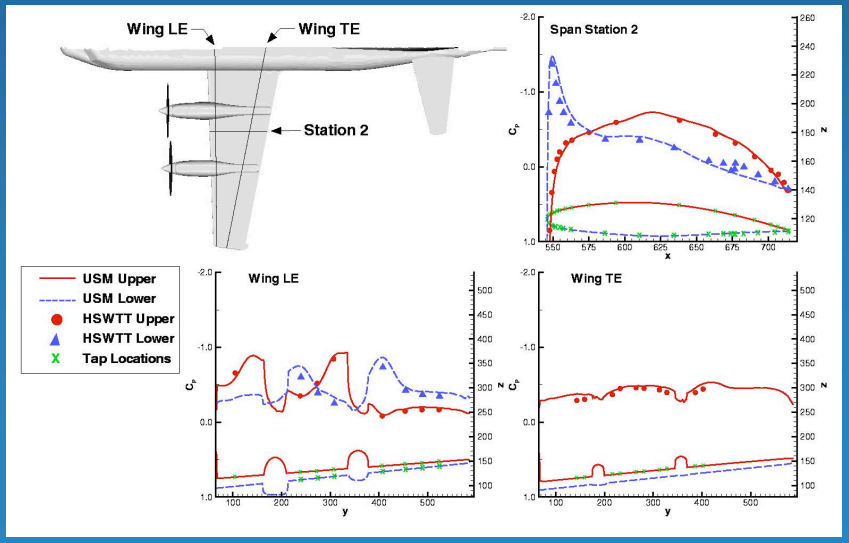
P-3C/EP-3E Aerodynamics Support

- **Overview:**
  - *Develop structural upgrades to the P-3 for extended airframe service life*
  - *Support re-engining efforts (Multi-Mission Maritime Aircraft – MMA Program)*
- **Objectives:**
  - *Develop aerodynamic loads database used for structural analyses*
  - *Evaluate any adverse propulsion airframe integration effects due to integration of a new propulsion system*
- **252 Euler/Navier-Stokes Solutions for P-3C, 128 Navier-Stokes Solutions for EP-3E**

Capability to Model Complex Configurations for VISCOUS Analyses

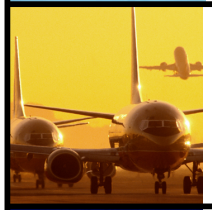


Correlation with Wind Tunnel Data
M = 0.250, AOA = -2.75º, h = 500'



Significance of TetrUSS and ties to NASA Vision

NASA/industry programs use TetrUSS to develop safe, quiet, efficient, and environmentally-friendly aircraft.



TetrUSS used by NASA/NTSB to investigate aircraft accidents and to help prevent future accidents and loss of life from occurring.

The CIA uses TetrUSS to provide aerodynamic estimates of foreign weapon systems, aiding in national defense and counter-terrorism activities.

To Understand and Protect Our Home Planet

TetrUSS is used in planetary exploration programs like Mars Scout to aid in the search for and understanding of life on other planets.

To Explore the Universe and Search for Life

TetrUSS is a valuable teaching and learning tool used in K-12, undergraduate, and graduate education across the country.

To Inspire the Next Generation of Explorers

Summary: TetrUSS

- A complete “workhorse” CFD software system
- Innovations have advanced the state-of-the-art
- Proven, reliable, easy to use, productive
- Responsive to user needs
- Reduces costs and risk
- Significant impact on critical projects
- “Tool-of-choice” for many organizations and projects

The TetrUSS Team is ready to work with you!
Contact us for more info, collaborations, custom software development, and CFD applications.