Enabling Multidisciplinary Design Exploration and Optimization for Hypersonic Flight Systems & Applications

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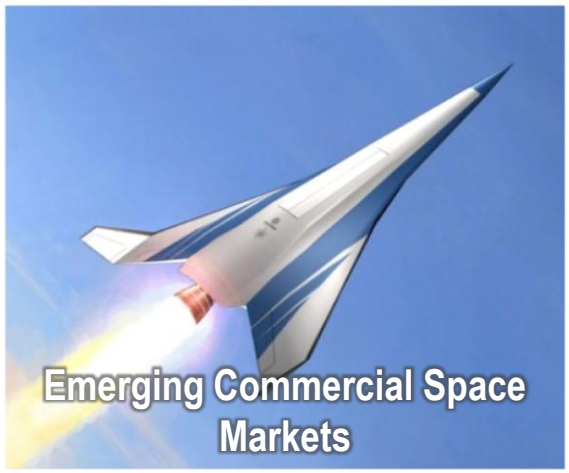
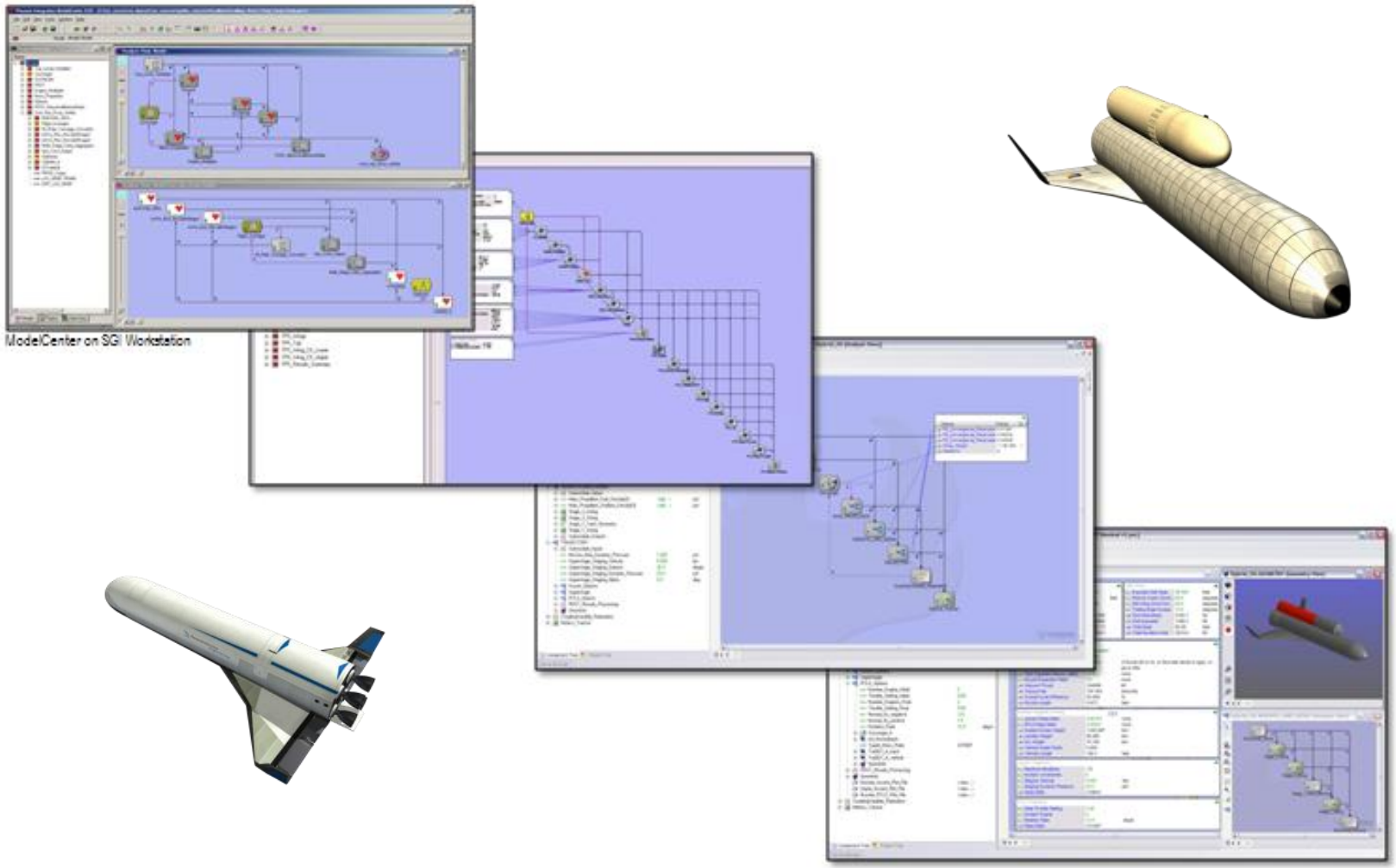
Engineering Focus Areas



SpaceWorks' PHX ModelCenter History

- Corporate use of PHX Products since ~2003



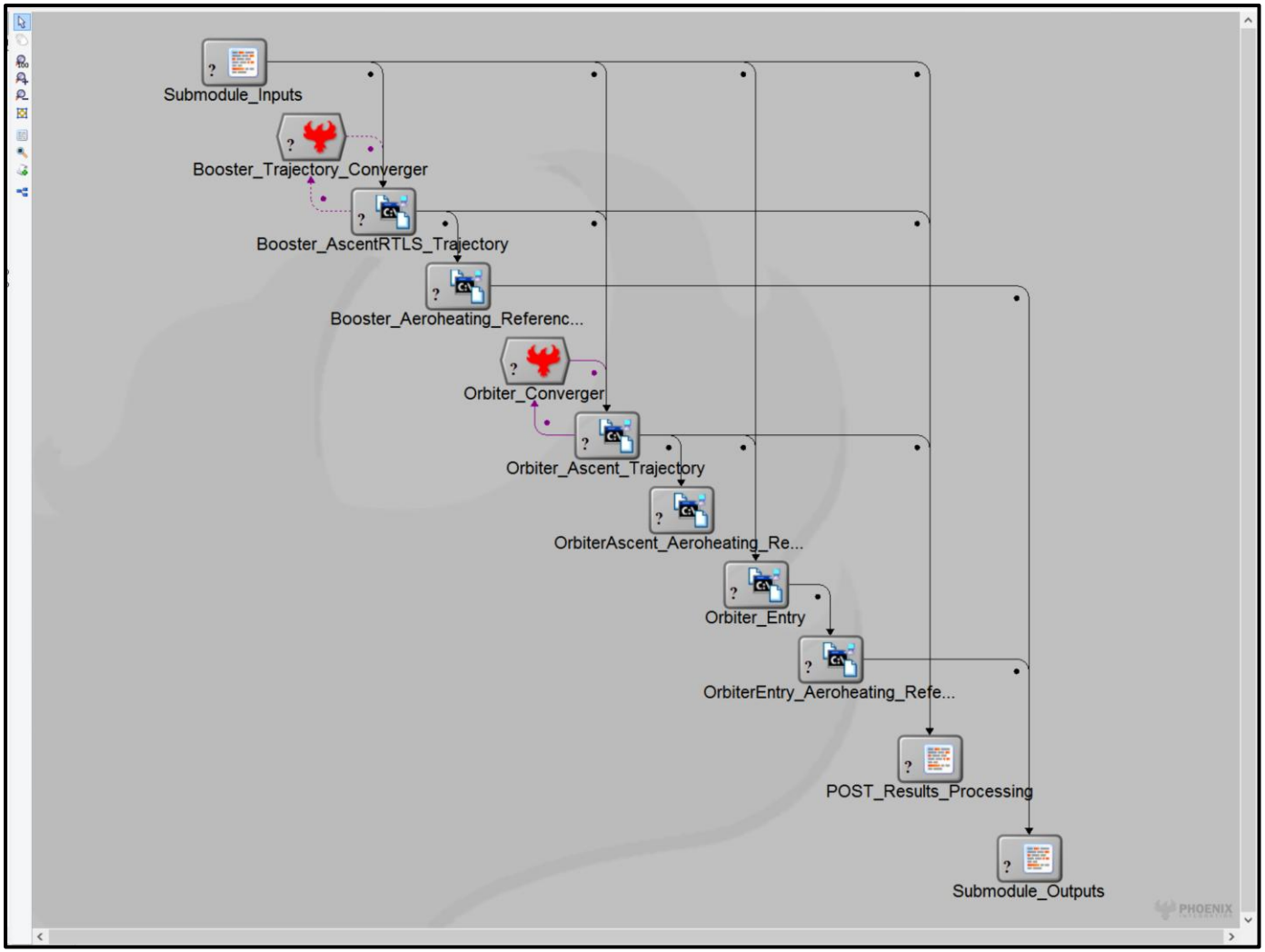
The Challenges of Hypersonic Systems Analysis

- **PHYSICS**
  - Operating environments are expansive, pushing current technology limits structurally and thermally
  - Complex chemical reactions, shock waves, and transient flows
  - Many phenomenon still not understood well
- **ECONOMICS**
  - (very) Sparse data points of historical systems to use as basis
  - High development costs, poorly understood impact of design choices to operability
  - Large uncertainty in markets and therefore revenue
- **COMPUTATIONAL**
  - Software tools often created by non-CS engineers
  - Many legacy programs originally created 30+ years old
  - General lack of willingness to replace dated software applications
  - Despite significant increases in computing power, still a limitation

Single Discipline Analysis : Trajectory Simulation

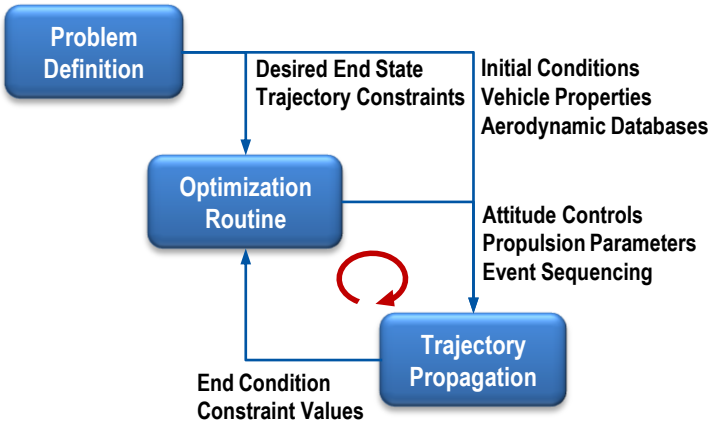
Branching Trajectory Problem

- Multiple instances of POST trajectory tool : Booster Ascent/RTLS, Orbiter Ascent, Orbiter Entry
- Typical problem: Maximize payload subject to fixed total gross weight for two-stage system



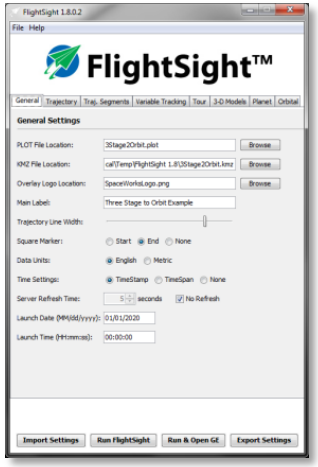
QuickShot™ Trajectory Tool

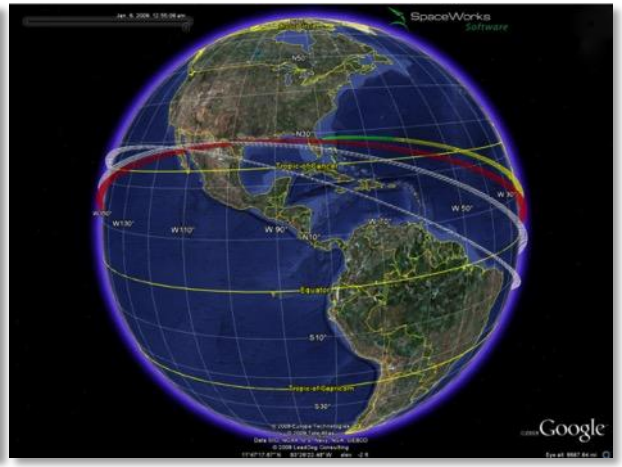
- **SpaceWorks has been developing *QuickShot* since May 2011**
  - Written in Java for cross-platform compatibility and multi-threaded for full scalability (including computing clusters)
  - Minimizes the customization per problem, allowing for quick problem setup
- **Minimizes and simplifies the user inputs**
  - Inputs include initial position, velocity, attitude, propulsion characteristics, weights, and tabular aerodynamic data files
  - Attitude control type (Euler, aerodynamic, etc.) is specified by bounds (no initial guess required)
- **Leverages recent advances in computing power to increase robustness**
  - Typically completes 200 – 1,000 simulations per second on a single 8-processor machine
  - Optimization process trades user setup time for computer runtime
  - Optimization is scalable if a "quick-and-dirty" solution is required
- **Verification**
  - Numerous examples validated against NASA POST tool

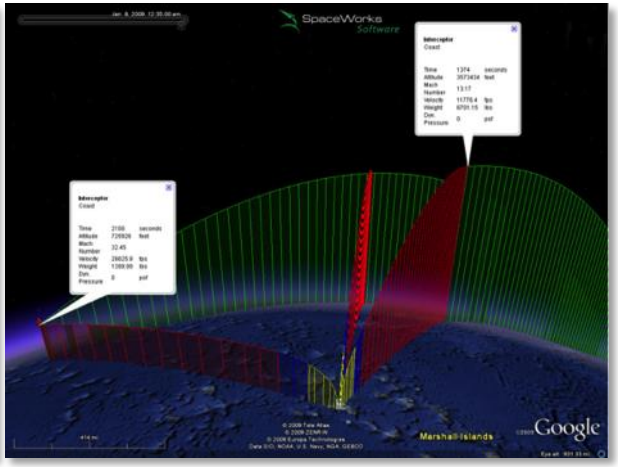


FlightSight™ Visualization Tool

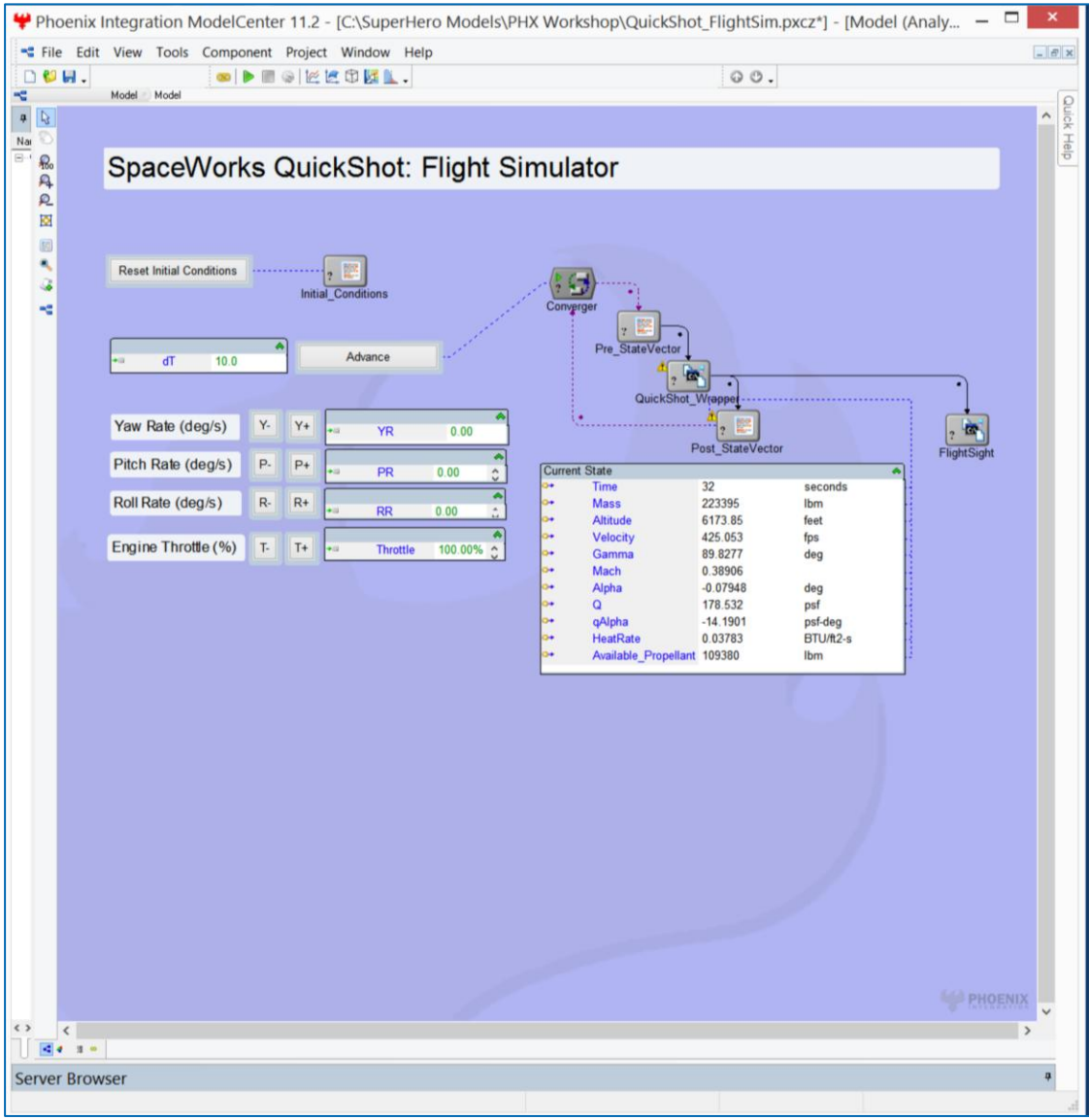
- FlightSight enables production of striking 3-D visualizations and dynamic animations that bring trajectory data to life
- FlightSight accepts trajectory plot data from virtually any source, as long as formatting guidelines are observed
- Intuitive Graphical User Interface makes it easy to control appearance, content, and behavior of a visualization - vary the colors, data overlays, integrated 3D models, camera angles, and more
- Data visualization can be viewed in Google Earth® or one of several other KML viewing utilities

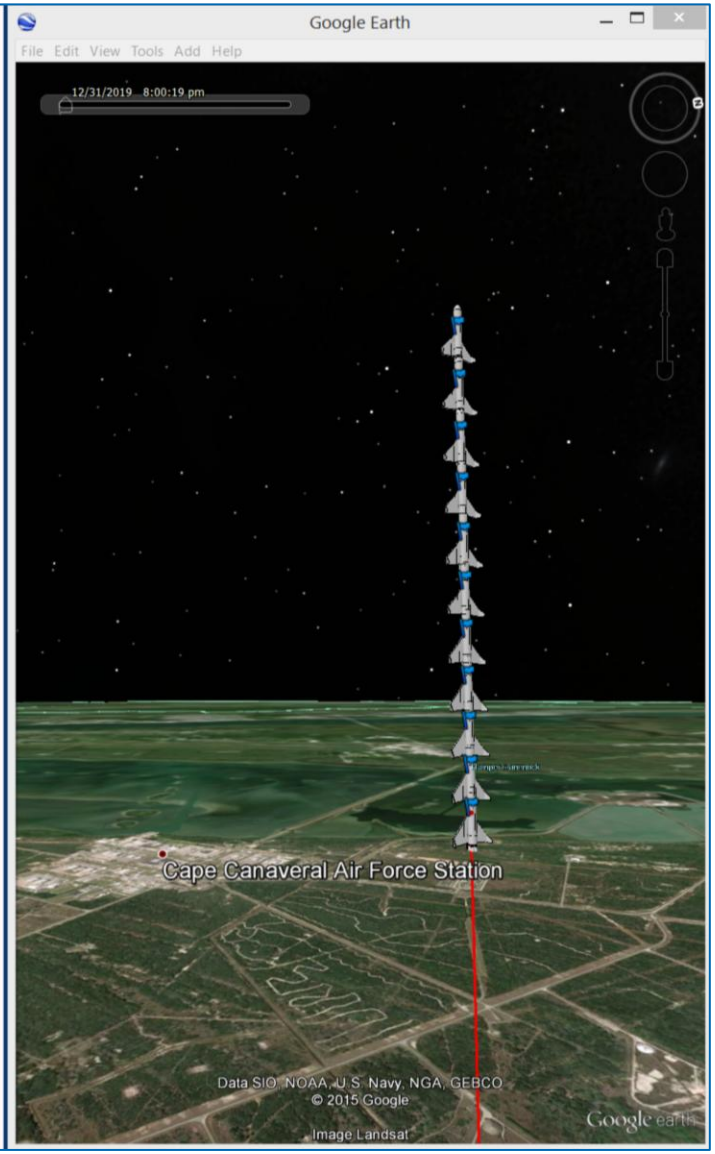






Flight Simulator

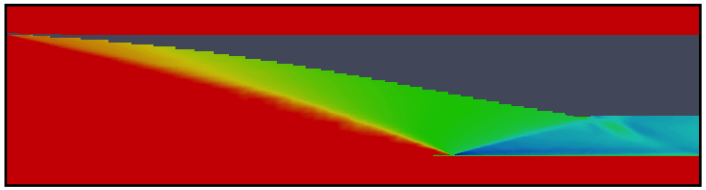


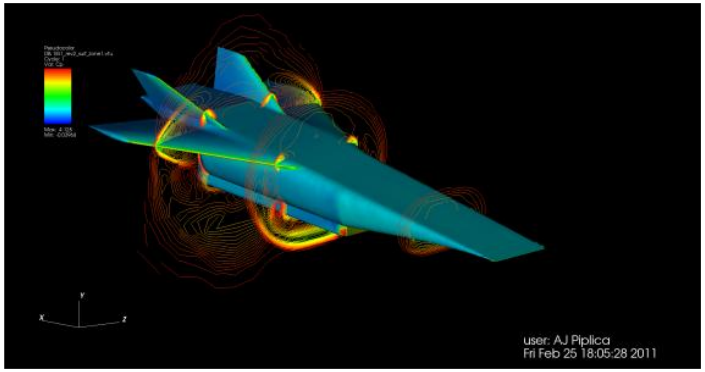


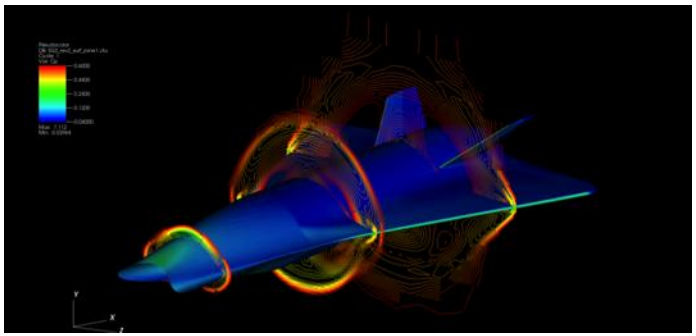
Single Discipline Analysis : Aerodynamics

Aerodynamic Tool Suite

- **Missile DATCOM**
  - AFRL, ITAR-controlled
  - Regime: Mach 0 to 25
  - Enabled with “DATCOM Runner” script
- **S/HABP**
  - AFRL, Unlimited Distribution
  - Regime: Mach 2 to 25
  - Enabled with “SHABP Runner” tool
- **CBAero**
  - NASA Ames, For Non-Commercial Use
  - Regime: Mach 0 to 25
- **Cart3D**
  - NASA Ames, For Non-Commercial Use
  - Euler 3-D CFD code

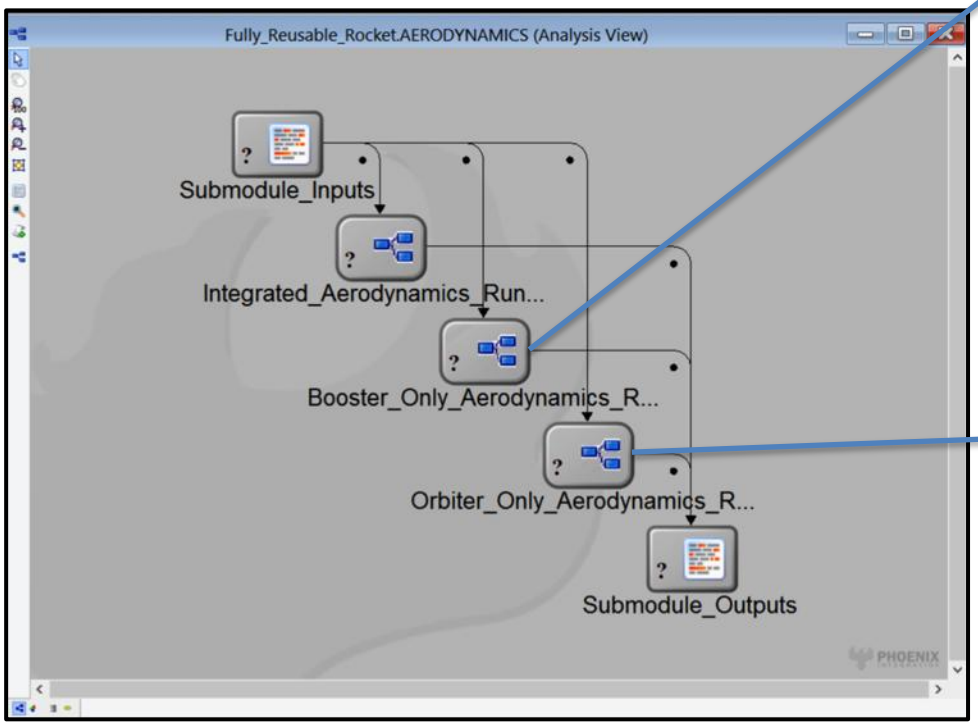


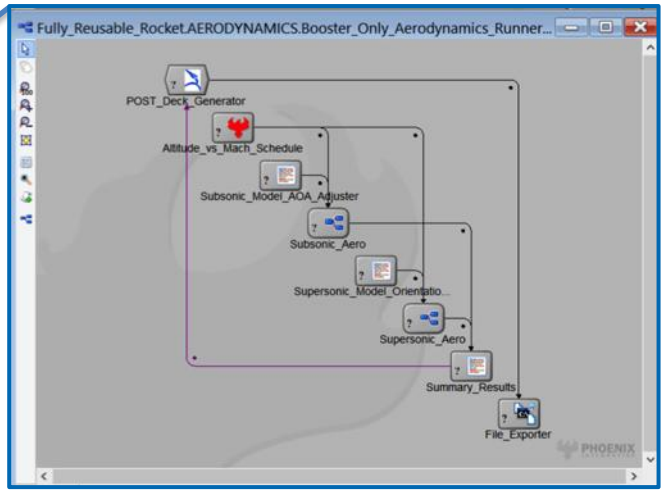


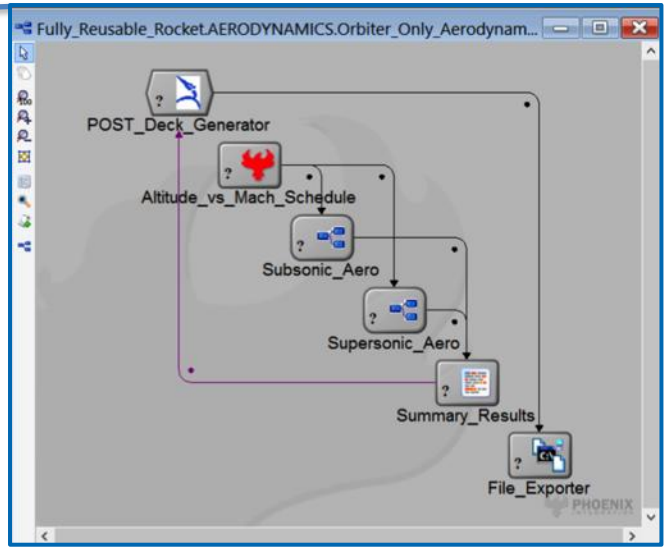


Multi-Stage, Multi-Tool Aerodynamics Assessment

- Quickly generate aerodynamic databases using variety of tools for various system flight configurations (mated, booster, upperstage with engines on/off, etc.)







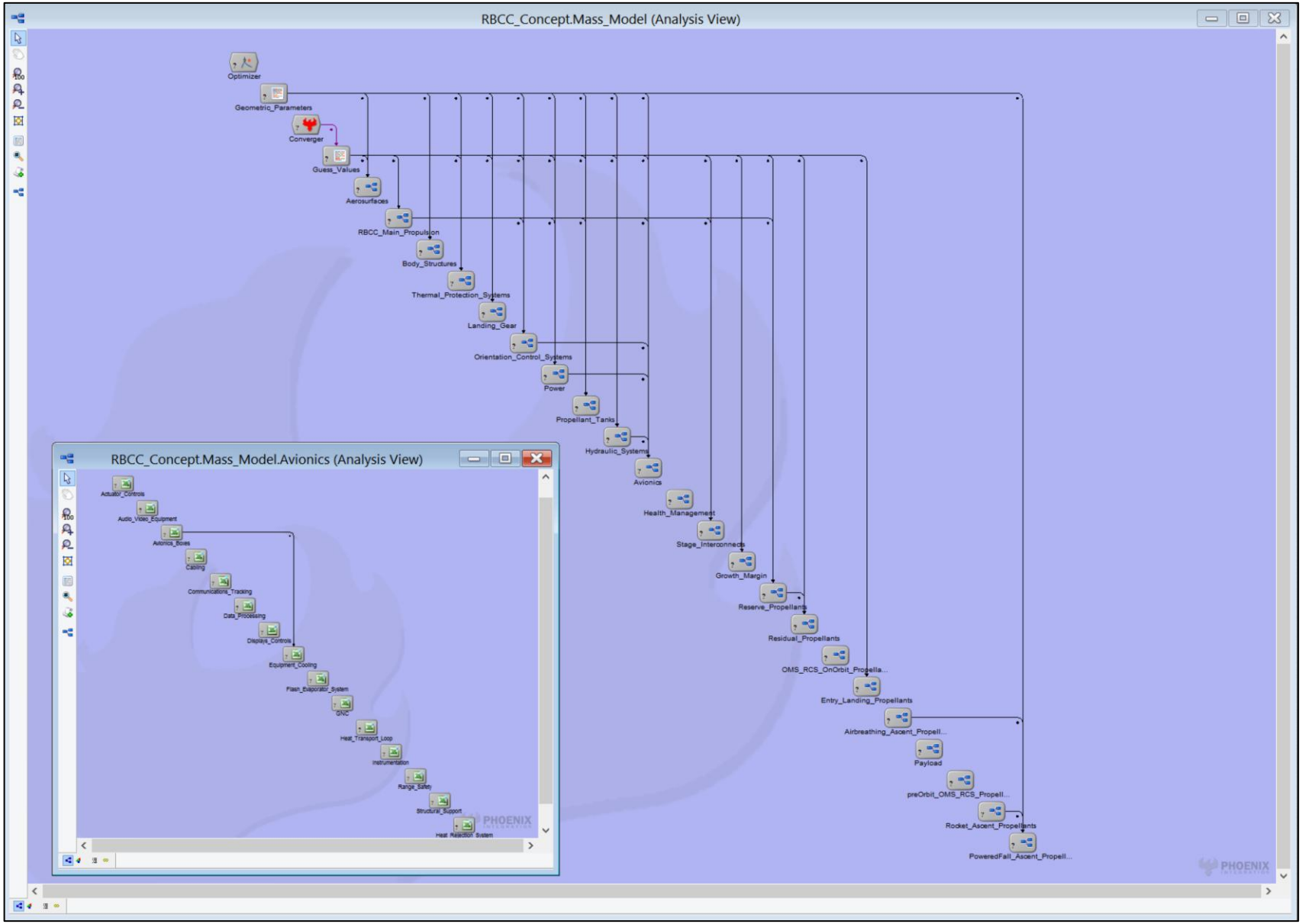
Single Discipline Analysis : Weight & Sizing

Vehicle Closure

- **Weight Estimation**
  - Air Force Weight Analysis Tool (AFWAT) Database
    - Compilation of various industry MERs
  - Component Databases
    - RCS, Payload Fairings, Actuators, Tanks, FTS, etc.
  - Pass-through from higher-fidelity analysis
    - e.g. Finite Element Analysis (FEA) results
- **Sizing**
  - Typically photographic scaling from reference geometry (easiest)
  - Parameterized geometry for in-the-loop geometric variation/optimization
    - openVSP (Veicle Sketch Pad)
    - Custom geometry generators

- **MS Excel is common industry tool for compiling MERs to generate system mass estimates and quickly resize/scale a vehicle to obtain target GLOW, payload, etc.**

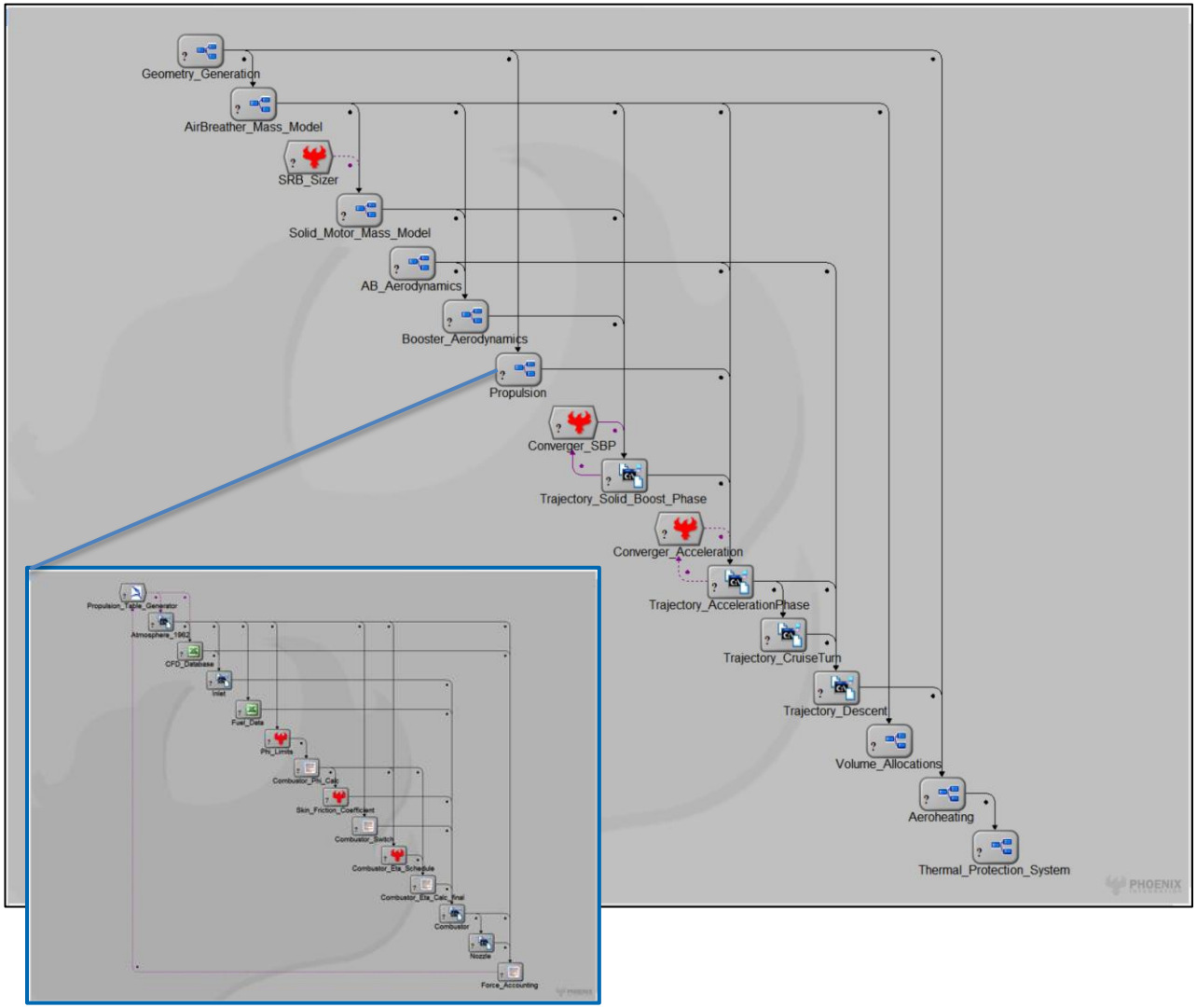
Weight Model Estimation and Parametric Sizing



Multi-Disciplinary Design Analysis/Optimization

MDAO : Hypersonic Flight Research Vehicle (FRV)

- Mach 5+ scramjet-powered cruise vehicle

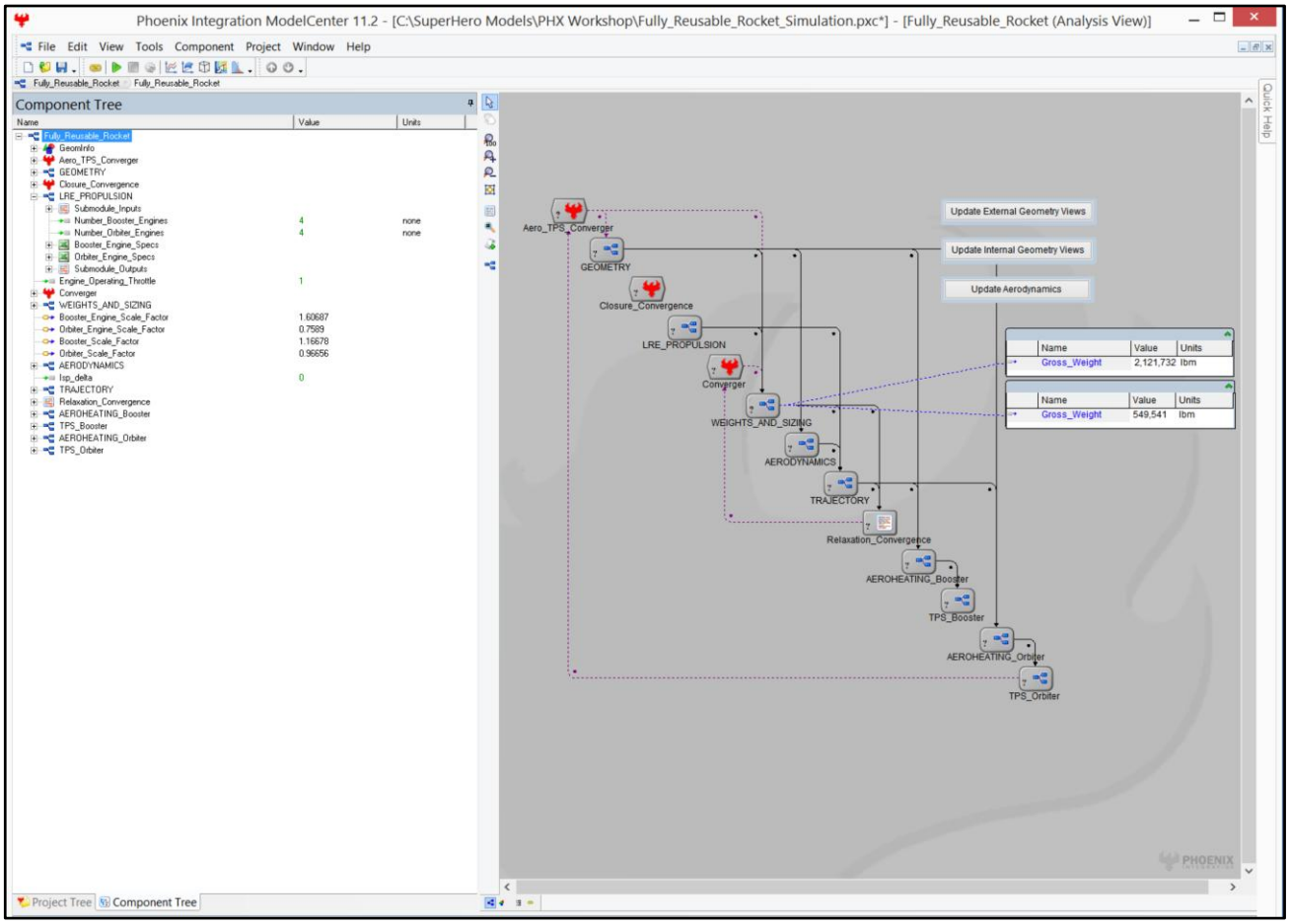


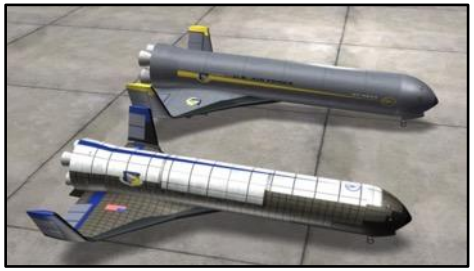
DISCIPLINES

- Geometry
- Aerodynamics
- Air-Breathing Propulsion
- Solid Motor Propulsion
- Weights/Sizing
- Trajectory
- Aeroheating
- TPS

MDAO : Fully-Reusable Two Stage to Orbit (TSTO)

- Nested system convergence loops
- PHX Macros used for quick linking/unlinking and specific analysis updates





DISCIPLINES

- CAD/Geometry
- Rocket Propulsion
- Aerodynamics
- Weights/Sizing
- Trajectory
- Aeroheating
- TPS

Reverse Engineering

Concept of Interest

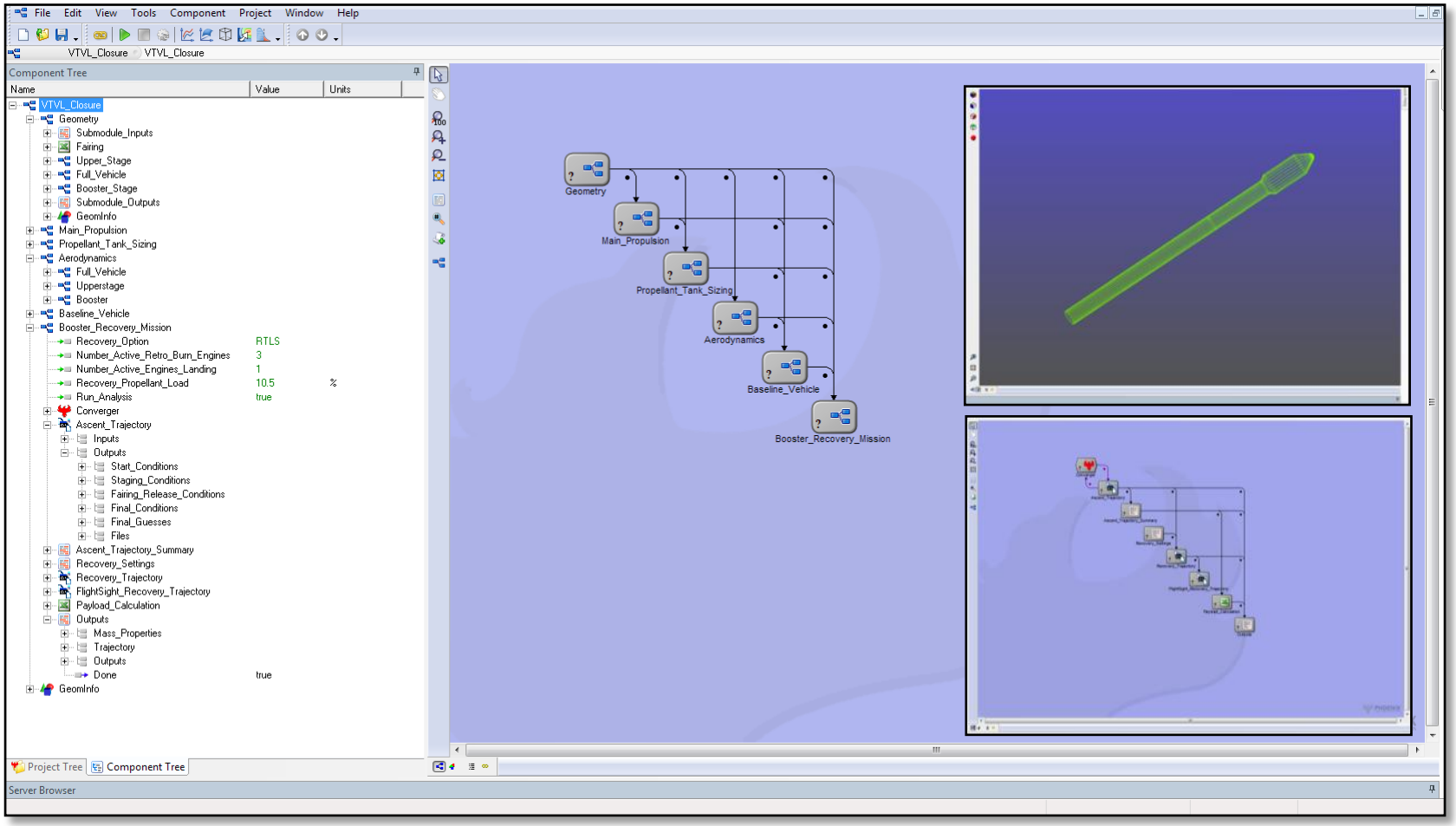
- **SpaceX Falcon 9 v1.1 system**
- **Public data sources and engineering models calibrated for:**
  - Geometry
  - Propellant loads
  - Propulsion
  - Aerodynamics
  - Trajectory
  - Fairing
- **Assumed flight constraints common for expendable launch systems**

Parameter	Value
Gross Liftoff Weight	1,115,200 lbm
Upperstage Gross Weight	246,150 lbm
Total Height	224 feet
Diameter	12 feet
Liftoff T/W	1.2
Reported Payload to LEO	28,990 lbm

Image Credit: SpaceX

VTVL Concept Simulation Model

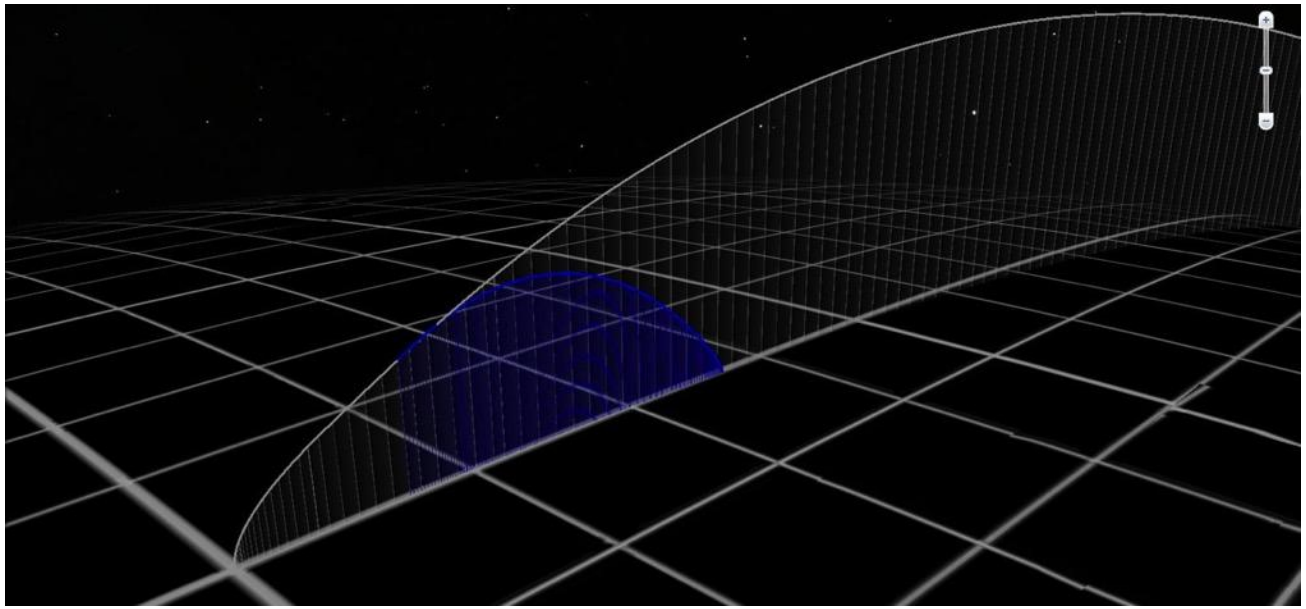
- **Created a multi-disciplinary simulation**
- **ModelCenter permitted fine calibration of secondary parameters to establish reference system**



Results : FlightSight™ Images

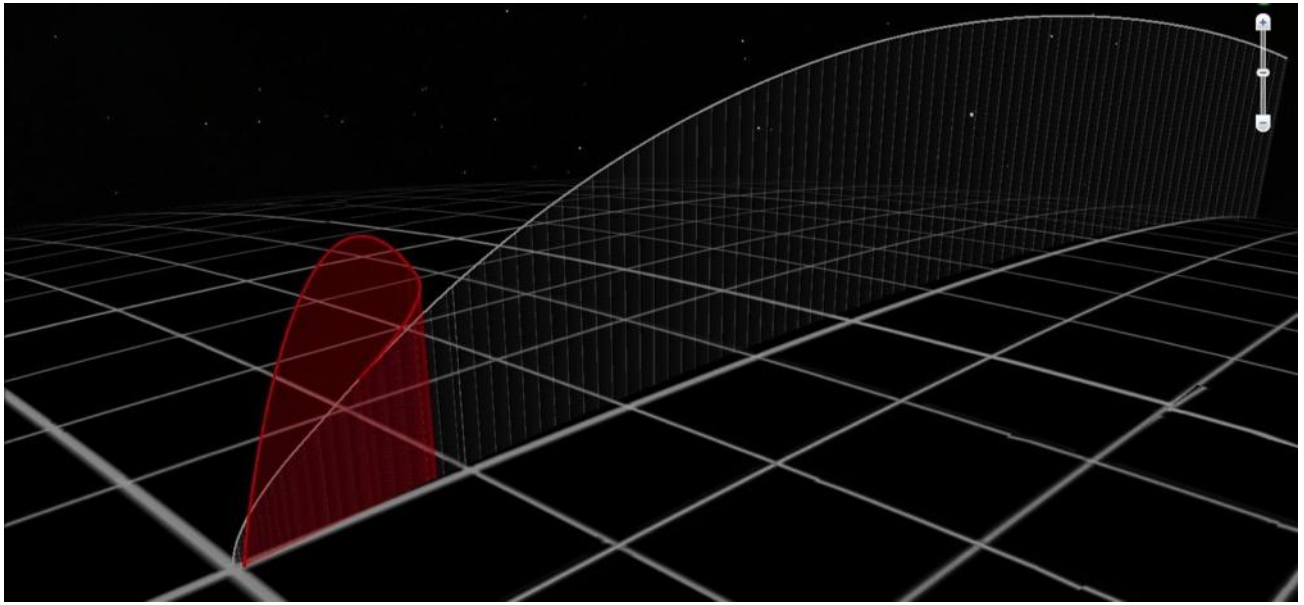
Downrange Landing

Booster Parameter	Value
Flight Time	390 sec
Final Downrange Distance	156 nmi
Max Downrange Distance	156 nmi
Mach Number @ Staging	7.1
Altitude @ Staging	201,500 feet
Peak Altitude	271,500 feet



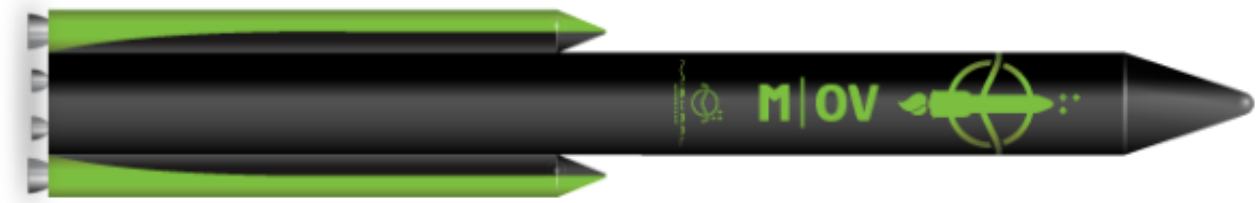
RTLS Maneuver

Booster Parameter	Value
Flight Time	480 sec
Final Downrange Distance	~0 nmi
Max Downrange Distance	57 nmi
Mach Number @ Staging	6.0
Altitude @ Staging	187,000 feet
Peak Altitude	423,500 feet



Market Modeling and Economics

Space is getting to be a crowded place!



All images credit of their respective company.

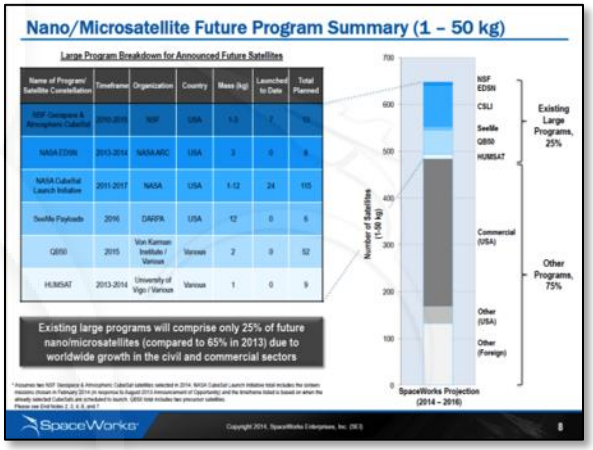
SpaceWorks' Launch Demand Database (LDDB)

- SpaceWorks Satellite Launch Demand Database (LDDB) catalogues all historic and future satellite missions, documenting key mission, program, satellite, and launch characteristics
  - Spacecraft mass ranges are from 0 to over 10,000-kg, with over 3,800 satellites identified
  - Database is updated quarterly with new project announcements, program cancellations, launch successes (and failures)

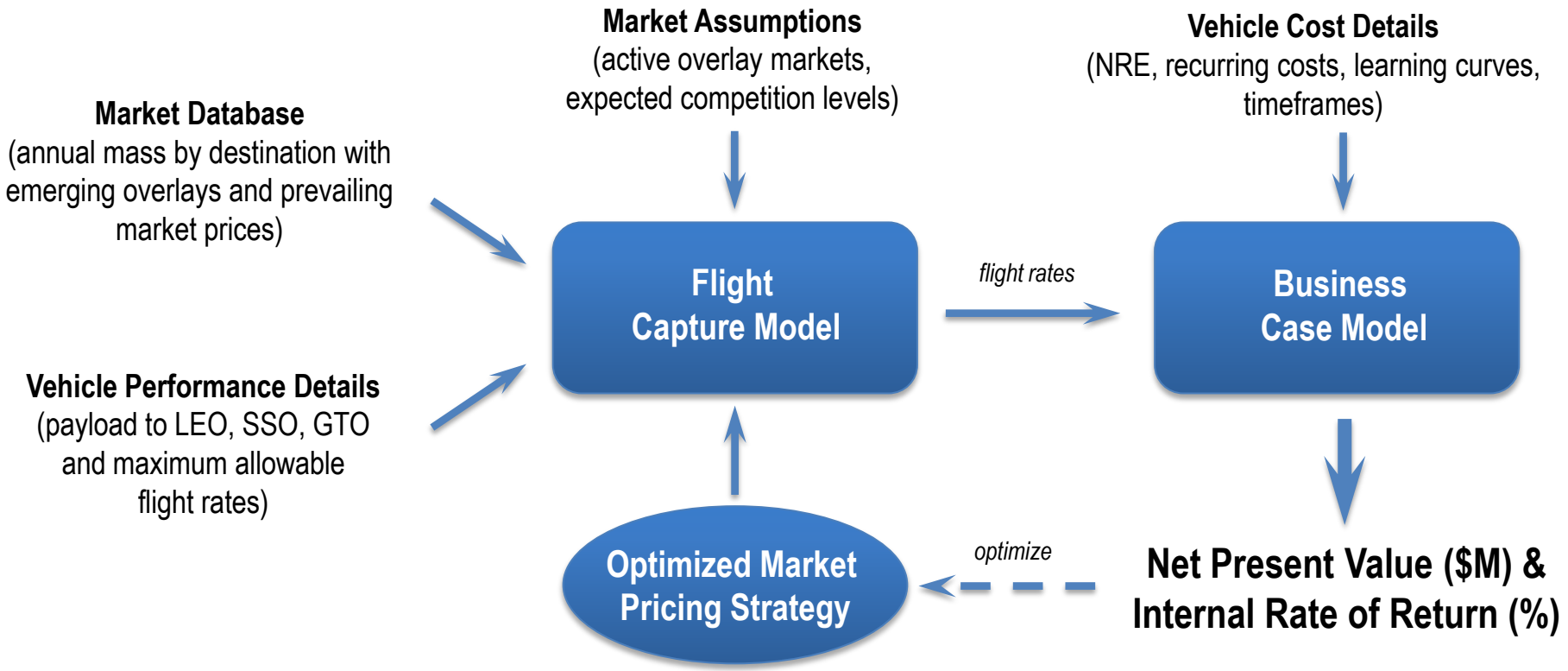
- In additional to the spacecraft name and mass, the LDDB tracks parameters including:
  - Target launch orbit and inclination
  - Application and primary user
  - Country of operator/owner
  - Planned launch year, launch site, and launch vehicle (if selected)
  - Onboard S/C propulsion and type (if present)

- Data is obtained from the following sources:
  - Publicly announced future projects and programs
  - Quantitative and qualitative adjustments to account for the expected sustainment of current projects and programs (e.g. follow-on to EDSN, CubeSat Launch Initiative), and the continued emergence and growth of numerous existing commercial companies
  - Non-public and sensitive information obtained from industry contacts

- Value judgments are made on announced satellites to adjust projections using SpaceWorks' Probabilistic Forecast Model (PFM)

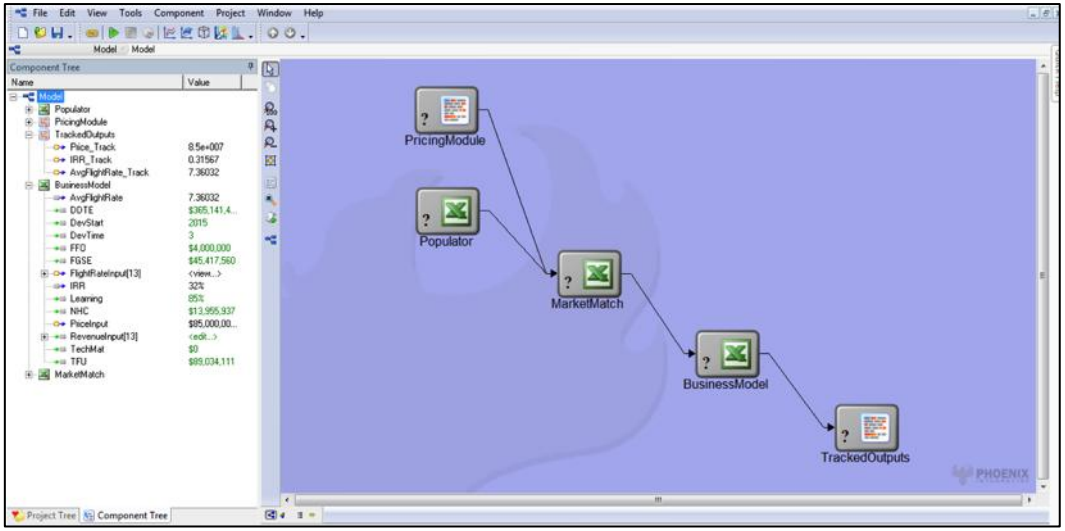


MarketMatch Assessment Model

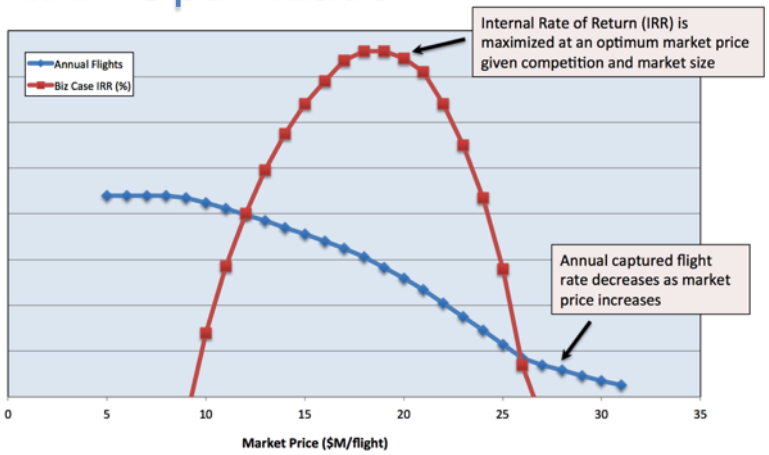


Market prices are optimized to improve NPV. Extremely low prices result in insufficient profits while extremely high prices result in insufficient flight rates

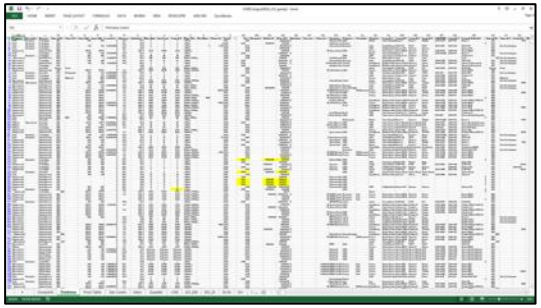
MarketMatch in PHX ModelCenter (under development)



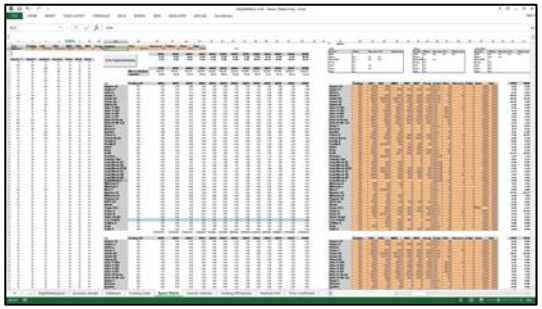
IRR Optimization



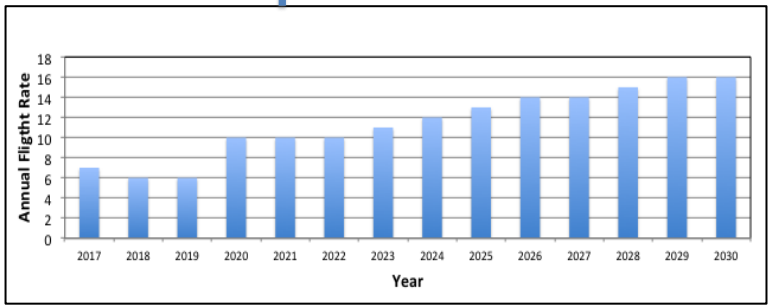
LDDB



Forecast



Market Capture



Wrap-Up

Summary

- **Analysis of hypersonic systems is extremely challenging**
  - After decades of research, community is still working to have basic predictive capability in many areas
  - Tight coupling among multiple disciplines is required given design sensitivity

- **ModelCenter successfully enables a number of enhanced capabilities and novel implementations for various disciplinary-level analysis tools**

- **Created highly-coupled, complex system-closure models for numerous hypersonic applications**
  - Automated execution permitted trade studies and sensitivity analysis
  - Excellent for supporting reverse-engineering analysis

SPACE IS GO

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