Florida Institute of Technology

Florida State University

NM State University

New Mexico Tech
Science • Engineering • Research • University

Leland Stanford Junior University

CU

University of Central Florida

UF University of Florida

utmb Health

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COE CST Center of Excellence for Commercial Space Transportation

Federal Aviation Administration Center of Excellence for Commercial Space Transportation

Year 5 Annual Report

Volume 2. Annual Technical Meeting Presentations

December 31, 2015

COE CST YEAR 5 ANNUAL REPORT – VOLUME 2

This report is produced by the FAA Office of Commercial Space Transportation in fulfillment of FAA Centers of Excellence program requirements.

The full report is broken into an Executive Summary and three volumes:

- The Executive Summary gives an overview of the FAA AST, the FAA COE program and the COE CST. A brief description of the member universities precedes a series of "quad charts," one for each task conducted by the COE CST during the fifth year of operation. The document ends with a listing of the Year 5 students, supporting organizations and technical publications.
- Volume 1 gives a description of the FAA COE CST, its research, structure, member universities and research tasks.
- Volume 2 is a comprehensive set of presentation charts of each research task as presented at the fifth Annual Technical Meeting in October 2015 held in Arlington, VA.
- Volume 3 is a comprehensive set of notes from all FAA COE CST teleconferences and face-to-face meetings.

This is Volume 2 of the full report.

Any questions or comments about the content of this report should be directed to Mr. Ken Davidian, FAA Program Manager for the Center of Excellence for Commercial Space Transportation, or Dr. Patricia Watts, FAA COE Program Director.

Introduction

This report includes a comprehensive set of presentations for each research task as presented at the fifth Annual Technical Meeting in October 2015 held in Arlington, VA.

Below is the order of the non-technical presentations as they appear in this document:

- “COE CST Fifth Annual Technical Meeting (ATM4) Status" presented by Mr. Ken Davidian, FAA Program Manager for the Center of Excellence for Commercial Space Transportation.

Below is the order of the technical presentations as they appear in this document:

- Task 185 “ Near-Elimination of Airspace Disruption from Commercial Space Traffic Using Compact Envelopes” presented by Tom Colvin and Juan Alonso of Stanford University (SU).
- Task 186 “ Space Environment MMOD Modeling and Prediction” presented by Sigrid Close and Alan Li of Stanford University (SU).
- Task 187 “Space Situational Awareness” presented by D.J. Scheeres and In-Kwan Park of University of Colorado, Boulder (CU).
- Task 220 “Update” presented by Patricia C. Hynes, Ph.D. of New Mexico State University (NMSU).
- Task 244 “ Autonomous Rendezvous & Docking for Space Debris Mitigation” presented by Bungo Shiotani and PI: Norman Fitz-Coy of University of Florida (UF).
- Task 244 “ Autonomous Spacecraft Rendezvous and Docking: Rapid Trajectory Generation” presented by Griffin Francis and PI: Emmanuel Collins of Florida State University (FSU).
- Task 329 "Tracking and Monitoring Suborbital Commercial Space Vehicles" presented by Dr. William H. Ryan of New Mexico Tech (NMT).
- Task 331 “ Optimal Aircraft Rerouting During Commercial Space Launches” presented by Rachael Tompa and Mykel Kochenderfer of Stanford University (SU).
- Task 228 “Magneto-Elastic Sensing for Structural Health Monitoring (SHM)” presented by Andrei Zagrai and Warren Ostergren of New Mexico Institute of Mining & Technology (NMT).
- Task 241 “ High Temperature, Optical Sapphire Pressure Sensors for Hypersonic Vehicles” presented by PI: William Oates, PhD Students: Justin Collins, Harman Singh Bal, Peter Woerner of Florida State University (FSU).
- Task 253 “ Ultrahigh Temperature Composites for Thermal Protection Systems (TPS)” presented by Chris Harris, Jay Kapat, Jan Gou of University of Central Florida (UCF).
- Task 293 “ Reduced Order Non-Linear Structural Model” presented by Donghyeon Ryu, Ph.D. of New Mexico Institute of Mining & Technology (NMT).
- Task 299 “Nitrous Oxide Composite Case Testing” presented by PI: Warren Ostergren and Co-PIs: Bin Lim, Andrei Zagrai of New Mexico Institute of Mining & Technology (NMT).
- Task 311 "Fire and Hazard Detection for Space Vehicles Using LEDs" presented by Justin Urso, Michael Villar, Kyle Thurmond, Zachary Loparo, Dr. Jayanta Kapat, Dr.

Subith Vasu of University of Central Florida (UCF) and Dr. Bill Partridge Jr. of Oak Ridge National Laboratory.

- Task 325 "Optical Measurements of Rocket Nozzle Thrust and Noise " presented by PI(s): Rajan Kumar & Farrukh Alvi and Student: Griffin Valentich of Florida State University (FSU).
- Task 308 "Assessment of Screening and Training Requirements for SFPs Regarding Anxiety During Repeated Exposures to Sustained High Acceleration" presented by James Vanderploeg, MD, MPH of University of Texas Medical Branch (UTMB).
- Task 309 " Assessment of Screening and Training Requirements for Pilots with Repeated Exposures to Sustained High Acceleration" presented by James Vanderploeg, MD, MPH of University of Texas Medical Branch (UTMB).
- Task 310 " Assessment of Methods, Procedures, and Technologies Available for Protection of SFPs in Commercial Spaceflight Vehicles" presented by James Vanderploeg, MD, MPH of University of Texas Medical Branch (UTMB).
- Task 320 " Commercial Spaceflight Risk Assessment and Communication" presented by Professor David Klaus and Robert Ocampo of University of Colorado, Boulder (CU).
- Task 193 "Research Roadmapping Workshops" presented by Scott Hubbard, Jonah Zimmermann, and Juan J. Alonso of Stanford University (SU).
- Task 193 " Role of COE CST in EFP " presented by PI: George H. Born and Bradley Cheetham of University of Colorado, Boulder (CU).
- Task 305 "Space Transportation Industry Viability" presented by Dr. Scott Benjamin, Taylor Smith, and Arion Gray of Florida Institute of Technology (Florida Tech).
- Task 324 "Deregulation Lessons from the Internet" presented by Dr. Ward Hanson and Dr. Greg Rosston of Stanford University (SU).
- Task 304 "Insurers as Regulators of Space Safety and Sustainability" presented by Dr. Ram Jakhu and Andrea Harrington of McGill University (MU) and Florida Institute of Technology (Florida Tech).
- Task 306 " UAT ADS-B Research and Demonstration for Commercial Space Applications: Progress Report" presented by Richard S. Stansbury and Students: Brandon Neugebauer, Dominic Tournour, Dylan Rudolph, Richard Day, and Yosvany Alonso of Embry Riddle Aeronautic University (ERAU).
- Task 332 " Assessing Rural Airports for Drone and RLV Use Using the Draper-Santos Projection Methodology" presented by Professor Aaron Santos, Dr. Chris Draper, Kristina Smith, Nick Joslyn, and Mackenzie Finnegan of Simpson College/Stanford University (SIM/SU).
- Evaluating Space Launch Vehicle / Reentry Vehicle (LV/RV) Separation Concepts and Standards presented by Zheng Tao and Ganghuai Wang of MITRE.
- Launch Vehicle/Reentry Vehicle (LV/RV) National Airspace Systems (NAS) Effect Assessment presented by MITRE.

What

- We started COE CST five years ago
- COE CST grew from our collective vision, not based on FAA norm
- We're a little different

But Because We're Different...

- We have to increasingly justify our existence within the FAA
- FAA Bureaucracy
  - Benefits
  - Costs

There's Still Room for Improvement

- Variation – Selection - Retention
- COE PM Meeting
  - Best Practices
  - "Isomorphism"

#1 Benefit of COEs

	INDIVIDUAL RESEARCH GRANTS	COEs
Functional Goals	•Research	**•Research •Training •Outreach**

DIMENSIONS OF NATIONAL SCIENTIFIC INFRASTRUCTURE	EFFECT ON ECONOMIC GROWTH
Scientific Research	**"a substantial negative effect "**
Scientific Labor Force	**"a substantial positive and significant effect"**

Source: Schofer, E., Ramirez, F. O., & Meyer, J. W. (2000). The effects of science on national economic development, 1970 to 1990. *American Sociological Review*, 65(6), 866–887.

COE CST Status Today

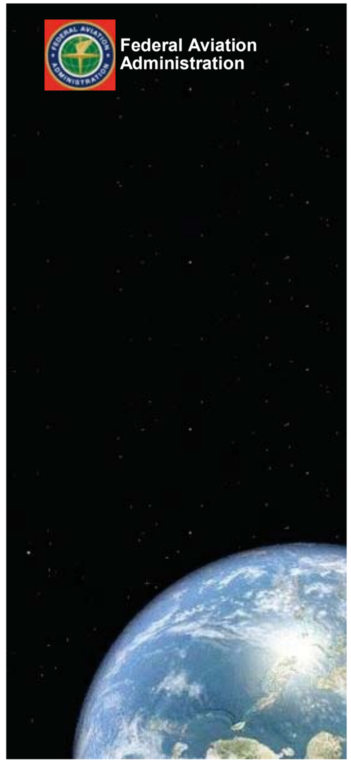
- COE CST is excellent
- The work you do is important

Near-Elimination of Airspace Disruption from Commercial Space Traffic Using Compact Envelopes

Thomas Colvin & Juan Alonso
Stanford University

Task 185

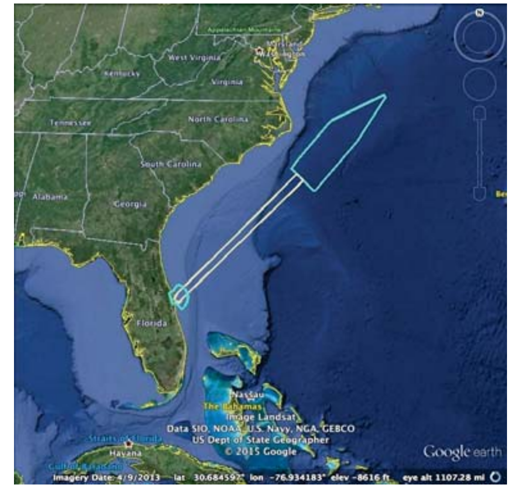
Oct 28, 2015



Space Operations Disrupt The NAS

- Need To Ensure Safety
- Traditional Methods Inefficient
- Large Cost To Airlines
- Commercial Space Traffic Volume Increasing
- New Launch Ranges

March 1st 2013
Falcon9 from Cape Canaveral



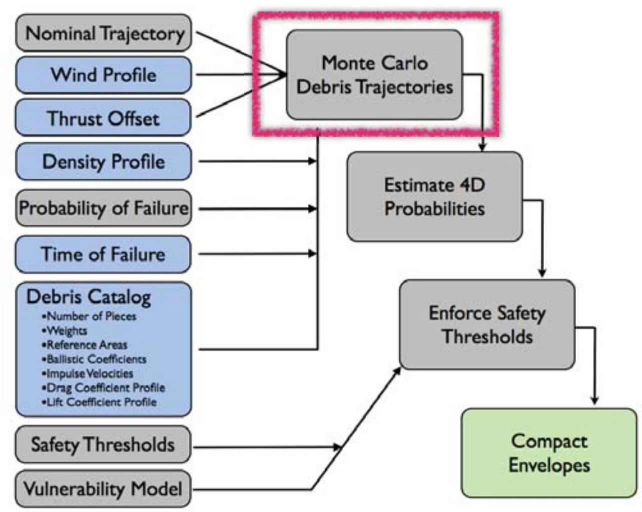
Compact Envelope Assumptions

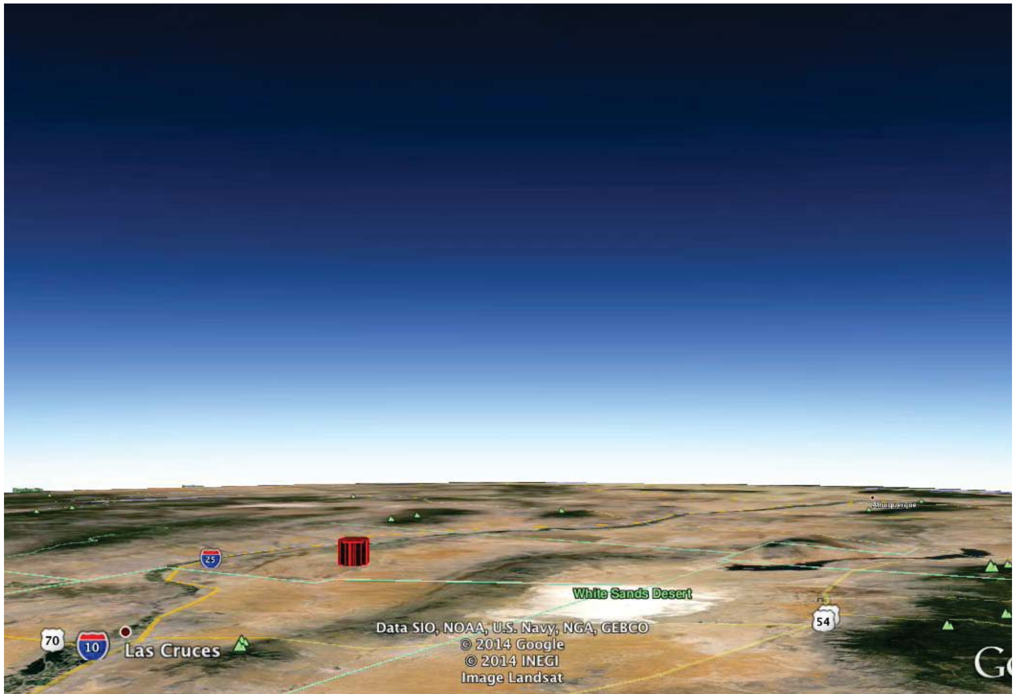
Reaction Time

Vehicle Health Monitoring

Data Comm

Stanford University Framework for Aircraft Risk Management (SU-FARM)





Current State Of Project

- Create Compact Envelopes for arbitrary space vehicles flying from any spaceport.
- Simulate disruption in FACET.
- Have analyzed many vehicles from many spaceports.
- “Near-Elimination of Airspace Disruption from Commercial Space Traffic Using Compact Envelopes”

Near-Elimination of Airspace Disruption...

Paper Simulated:

- 7 vehicles, 10 locations, 14 missions, 90 days
- Traditional Hazard Area vs Compact Envelopes

Key Findings:

- Dramatic reduction in impact near congested airspace.
  - Lynx at Front Range: Average aircraft affected reduced from 90 to 3.
- Completely eliminated disruption for some missions.
  - SpaceShipTwo at Spaceport America, AtlasV at VAFB, ...

Concluding Thoughts

- Surprised by the effectiveness of the Compact Envelope approach.
- FAA Human-In-The-Loop simulations
  - Scenarios based on compact envelope principles
  - Findings support our assumptions and vice-versa
- Compact Envelope ideas are being incorporated into future Space Vehicle Operations ConOps.
- Uploading to github

Thank You

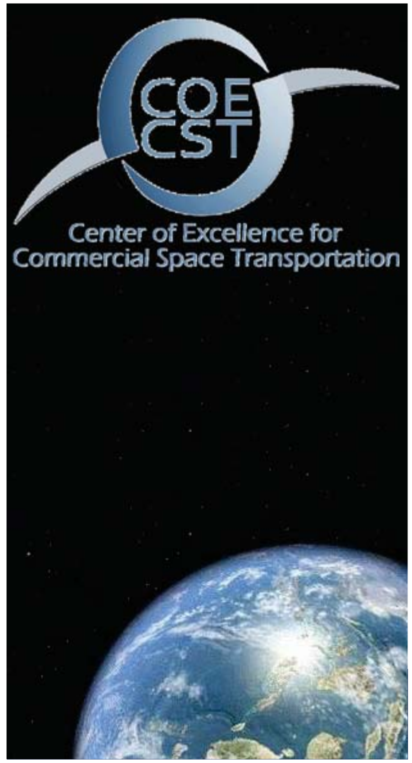
- FAA Center of Excellence in Commercial Space Transportation
- Kevin Hatton, FAA Office of NextGen, Advanced Operational Concepts
- Paul Wilde and Dan Murray, FAA AST
- Francisco Capristán, Mykel Kochenderfer, Rachael Tompa
- FAA Tech Center
- FACET developers, NASA Ames
- MITRE

COE CST Fifth Annual Technical Meeting

Space Environment MMOD Modeling and Prediction

Sigrid Close and Alan Li
Stanford University

October 27-28, 2015
Arlington, VA



Outline

- Team Members
- Task Description and Prior Research
- Goals
- Methodology
- Results
- Conclusions and Future Work

Team Members

- Sigrid Close, Stanford University (PI)
- Alan Li, Stanford University (graduate student)

- Lorenzo Limonta, Stanford University (graduate student supported by NSF)

Purpose of Task

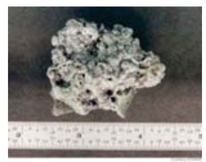
- Spacecraft are routinely impacted by micrometeoroids and orbital debris (MMOD)
  - Mechanical damage: "well-known", larger (> 120 microns), rare
  - Electrical damage: "unknown", smaller/fast, more numerous

- Growing need to characterize MMOD down to smaller sizes and provide predictive threat assessment

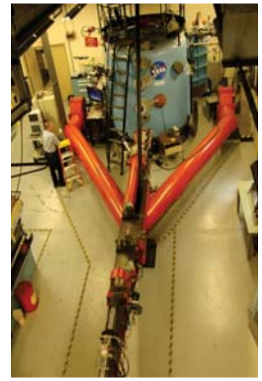
MMOD – Classification

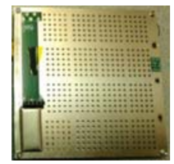
- **Meteoroids**
  - **Speeds**
    - 11 to 72.8 km/s (interplanetary)
    - 30-60 km/s (average)
  - **Densities**
    - ≤1 g/cm³ (icy) or > 1 g/cm³ (rocky/stony)
  - **Sizes**
    - < 0.3 m (meteoroid)
    - < 62 μm (dust)

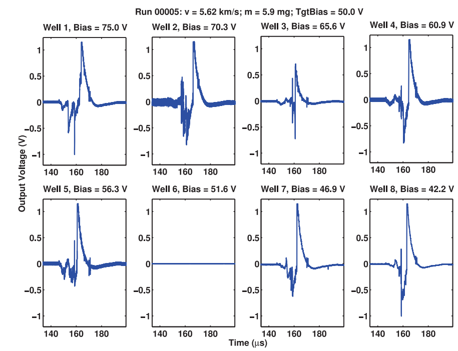
- **Space Debris**
  - **Speeds in LEO**
    - < 12 km/s
    - 7-10 km/s (average)
  - **Densities**
    - > 2 g/cm³
  - **Sizes**
    - < 10 cm (small)



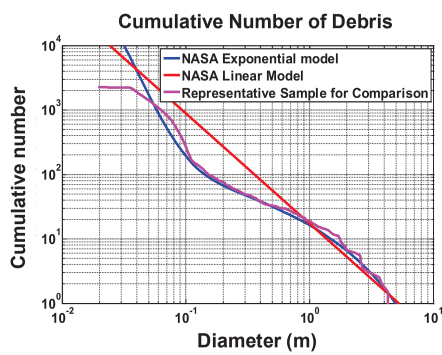
MMOD – Previous Research







MMOD – Previous Research

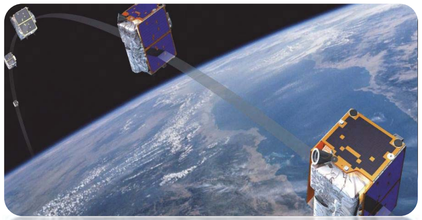


- **EISCAT Svalbard radar**
  - 78.1°N, 16.0°E
  - 500 MHz, 32 m dish, 0.8 MW peak power
  - Data collected March 2007 – March 2009 (following Chinese ASAT test in January 2007)

MMOD and Neutral Densities

- **"Space junk" WT1190F**
  - Approximately 1-2 m long
  - Most likely discarded rocket body "lost" by SSN
  - Reentry on November 13 (point of impact over Indian Ocean?)
- **Can we improve the 15-50% error?**

Goal: Neutral Density Estimation

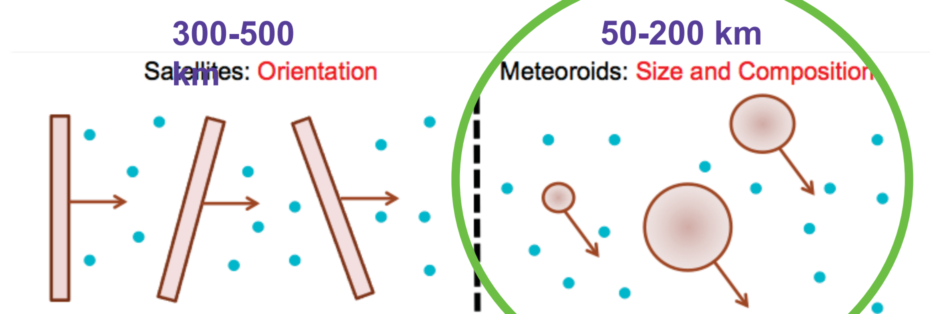


Source: http://eijournal.com/print/articles/entrepreneurial-blueprint-bolsters-satellite-development

Source: http://www.huffingtonpost.com/2014/04/21/lyrid-meteor-shower-2014_n_5186204.html

- Leverage the increasing number of constellations of satellites in orbit
- Leverage the abundance of meteoroids ablating in the atmosphere
- Good temporally and spatially varying profile of neutral density
- Different source of density estimation

Methodology



- Want to measure density from readily available equivalent platforms
- Each of these platforms is slightly different
- Measurements made at a certain time contains certain biases (across all platforms)

Data → Remove Bias → Estimate Variation → Calculate Density

Assumptions and Equations

- **Assumptions**
  - C_D constant (spherical shape)
  - Variation arises from mass/size/bulk density
  - Multiple layers of atmosphere traversed
  - Ablation and mass loss
- **Governing equations**

Drag: $$\frac{dv}{dt} = -\frac{3}{8}\frac{\rho_a}{\rho_m}\frac{C_D}{r}|v|^2$$

Ablation: $$\frac{dr}{dt} = -\frac{1}{8}\frac{C_H}{H^*}\frac{\rho_a}{\rho_m}|v|^3$$

Velocity:	v	Enthalpy of Destruction:	H^*
Radius:	r	Coefficient of Heat Exchange:	C_H
Atmospheric Density:	ρ_a		
Meteoroid Density:	ρ_m		

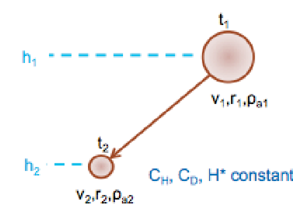
Density Ratios

- **Combine drag and ablation equations and compare ratios of radii at different points in time**

$$\frac{r_1}{r_2} = \exp\left(\frac{1}{6}\frac{C_H}{C_D}\frac{1}{H^*}(v_1^2 - v_2^2)\right)$$

- **For i^th meteoroids at j^th altitude**

$$\underbrace{\ln\left(\frac{dv_{i,j+1}}{dt}\frac{1}{v_{i,j+1}^2}\right) - \ln\left(\frac{dv_{i,j}}{dt}\frac{1}{v_{i,j}^2}\right)}_{LHS_i} = \underbrace{\frac{1}{6}D_i\left(v_{i,j}^2 - v_{i,j+1}^2\right) + \ln(\rho_{rj})}_{RHS_i}$$



- Given data on velocity and deceleration, estimate D_i and ρ_{rj} for each meteoroid and altitude

Minimize: $$\min\left(\sum_{i,j}\left(LHS_{i,j} - RHS_{i,j}\right)^2\right)$$

Subject to: $D_i > 0$

$$D_i = \frac{C_{Hi}}{C_{Di}}\frac{1}{H_i^*}$$

$$\rho_{rj} = \frac{\rho_{a,j+1}}{\rho_{a,j}}$$

Ratio Distribution

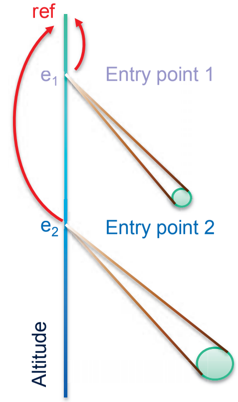
- **Translate point of entry measurement to a reference point in altitude**

$$\frac{dv}{dt}\frac{1}{v^2} \sim \frac{\rho_{a,e}}{r_e \rho_m} \longrightarrow \frac{dv}{dt}\frac{1}{v^2}\frac{\rho_{a,ref}}{\rho_{a,e}} \sim \frac{\rho_{a,ref}}{r_e \rho_m} = K$$

- **Calculate K for each meteoroid and define minimum ratio using order statistics**

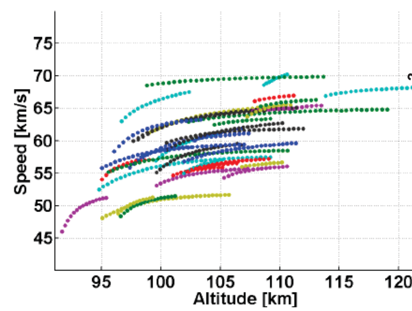
$$\frac{K_j}{K_{mk}} \approx \frac{\left(\frac{1}{r_e \rho_m}\right)_j}{\left(\frac{1}{r_e \rho_m}\right)_{mk}}$$

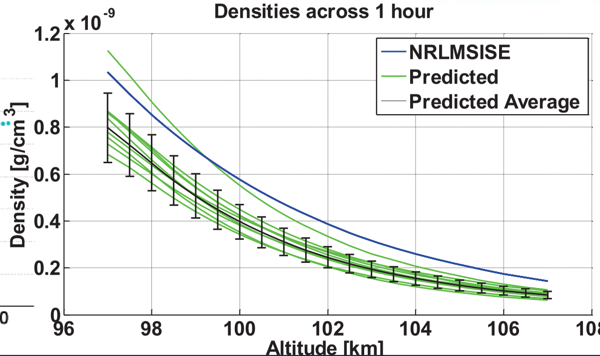
- **Calculate distribution**



Results

- **ALTAIR radar**
  - 9°N, 167°E
  - 160 and 422 MHz, 46 m dish, 6 MW peak power
  - Data collected November 8th 2007 (6 AM local time)





Conclusions and Future Work

- **New method for estimating neutral density from multiple measurements across equivalent platforms**
  - Errors < 10% using CubeSats (not shown), 12% for meteoroids
  - Additional data to modeling community
- **Next steps**
  - Satellites: precision orbit determination
  - Meteoroids: ablation physics
  - Space debris: highly variable C_D

Li, A., and Mason, J. *Optimal Utility of Satellite Constellation Separation with Differential Drag*. 2014 AIAA/AAS Astrodynamics Specialist Conference. AIAA 2014-4112.

Li, A., and Close, S. *Mean Thermospheric Density Estimation derived from Satellite Constellations.* Advances in Space Research 56 (2015),pp. 1645-1657. DOI: 10.1016/j.asr.2015.07.022

Thank you!

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Ballistic Factors

Data → Remove Bias → Estimate Variation → Calculate Density

- θ: Rotation about the satellite spin axis (IID)
- Ballistic factor:

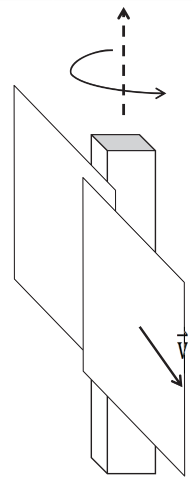
$$B(\theta) = \frac{C_D(\theta)A(\theta)}{m}$$

  - B is IID with some unknown distribution
  - B_{min} defined when θ=0 (absolute minimum)

- Ignore rotations about other axes

$$B_{min} = \frac{C_{D,min}A_{min}}{m}$$

IID = Independent and Identically Distributed



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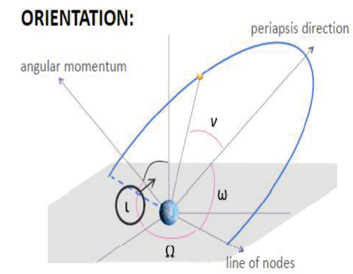
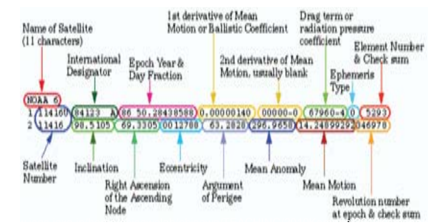
Orbital Elements

Data → Remove Bias → Estimate Variation → Calculate Density



- Kept up to date by NORAD (Space-track)
- Uses Simplified General Perturbations (SGP) model
- Within few km of error over 1 day



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Data

Data → Remove Bias → Estimate Variation → Calculate Density

From TLEs

$$\left.\frac{da}{dt}\right|_D = \frac{2a^2 v}{\mu}\frac{d\vec{v}_D}{dt}\cdot\hat{e}_v = \frac{2a^2 B v^3 F}{\mu}$$

$$\Delta a_{SGP4}(t_i,t_k) = \int_{t_i}^{t_k} \left.\frac{da}{dt}\right|_D + \left.\frac{da}{dt}\right|_G + \left.\frac{da}{dt}\right|_U dt$$

small

$$\Delta\bar{n}_M(t_i,t_k) = \frac{3}{2}\mu^{-\frac{2}{3}}\oint_{t_i}^{t_k} \bar{n}^{\frac{1}{3}}\rho B v^3 F\,dt$$

$$\overline{\rho B} \cong \frac{2\mu^{\frac{2}{3}}\Delta\bar{n}_M(t_i,t_k)}{3\oint_{t_i}^{t_k}\bar{n}^{\frac{1}{3}} v^3 F\,dt} = K$$

From ranging data

$$X = \begin{bmatrix} r \\ v \\ K \end{bmatrix}, X_0 = \begin{bmatrix} r_0 \\ v_0 \\ K_0 \end{bmatrix}$$

$$\dot{X} = F_D(X) + F_g(X) + F_U(X)$$

$$\tilde{b} = R\left(\dot{X}(t_i, X_0)\right) - R_{meas}(t_i)$$

Loop until RMS < Threshold:

$$\delta x = (A^T W A)^{-1} A^T W \tilde{b}$$

$$\rightarrow X_0 = X_0 + \delta x$$

$$RMS = \sqrt{\frac{\tilde{b}^T W \tilde{b}}{n_{obs}}}$$

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How to Remove Bias

- Density estimated as:

$$\bar{\rho} \cong \frac{2\mu^{\frac{2}{3}}\Delta\bar{n}_M(t_i,t_k)}{3\bar{B}\oint_{t_i}^{t_k}\bar{n}^{\frac{1}{3}} v^3 F\,dt} = \frac{K}{\bar{B}} \quad \text{or} \quad \bar{\rho}\bar{B} = K$$

- K can be calculated by:
  - SGP4 in the case of TLEs
  - Ranging or GPS measurements; propagator needs to account for higher order gravity terms, SRP, etc…
- Internal bias within K because K is composed from varying densities

Ballistic factor:	$B = \frac{C_D A}{m}$
Mean motion:	n
Wind Factor:	F
Density:	ρ

The Dilemma: If we have N satellites, we have K_N measurements but need to estimate n+1 values (ρ and B_N), where B_N is randomly distributed

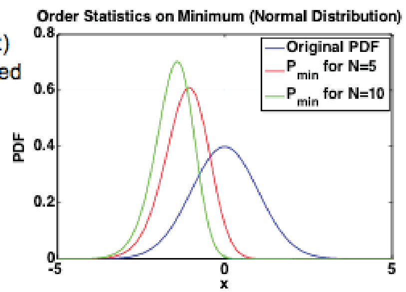
21 Order Statistics

- What is order statistics?
  - Let $X_1, X_2, \ldots, X_N$ be IID with some CDF $C(x)$
  - Then the r^{th} order statistic can be expressed as:

$$C_{(r)}(x) = \sum_{i=r}^{N} \binom{N}{i} C^i(x)\,[1 - C(x)]^{N-i}$$

  - And the minimum as:

$$C_{(1)}(x) = 1 - [1 - C(x)]^N$$



- Why do we use it?
  - We know something about the minimum of C_D from physics
  - We have many satellites
  - Estimation of C_D is difficult due to coupling with ρ

22 Remove Bias

Data → Remove Bias → Estimate Variation → Calculate Density

- Define the minimum of our observations:

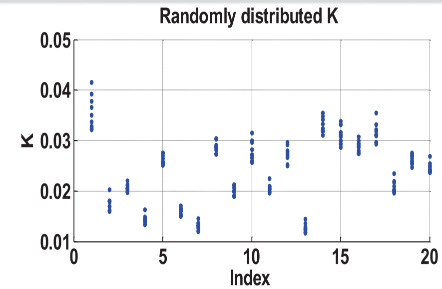
$$K_{mk}(t_k) = \min_j K_j(t_k)$$

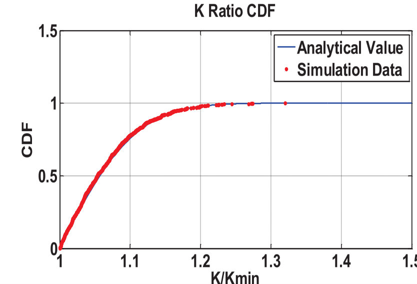
$$\frac{K_j(t_k)}{K_{mk}(t_k)} \approx \frac{B_j(t_k)}{B_{mk}(t_k)}$$

- Amalgamate measurements across all time periods to construct CDF ratio:

- Results in ratio distribution

$$CDF\left(\frac{B}{B_{mk}} \middle| \frac{B}{B_{mk}} > 1\right)$$





23 Ratio Distribution

- Probability of ratios defined as:

$$P(z) = \int_{-\infty}^{+\infty} |y| P_{B,y}(zy, y)\,dy$$

Math

$$C(z) = \frac{N}{N-1}\int_{B_{min}}^{B_{max}} F_B(z \cdot y) \cdot \frac{d\left(F_B^{N-1}(y)\right)}{dy}\,dy + 1$$

Discretize

$$C(z_j) - 1 = \frac{N}{N-1}\sum_{i=1}^{m} F_B(z_j y_i)\left(F_B^{N-1}(y_{i+1}) - F_B^{N-1}(y_i)\right)$$

$$y = B_{mk}$$

$$z = \frac{B}{B_{mk}}$$

N = # of platforms

$$C_B = CDF(B)$$

$$F_B(B) = 1 - C_B(B)$$

- Limits:

$$\lim_{B \to B_{min}} F_B(B) \to 1 \qquad \lim_{B \to B_{max}} F_B(B) \to 0$$

24 Discretization

Data → Remove Bias → Estimate Variation → Calculate Density

- Matrix form:

$$\frac{N-1}{N}\left(\begin{bmatrix} C(z_m) \\ C(z_{m-1}) \\ \vdots \\ C(z_2) \end{bmatrix} - 1\right) = \begin{bmatrix} F_{B,m} & 0 & \cdots & 0 \\ F_{B,m-1} & F_{B,m} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ F_{B,2} & F_{B,3} & \cdots & F_{B,m} \end{bmatrix}\begin{bmatrix} F_{B,2}^{N-1} - F_{B,1}^{N-1} \\ F_{B,3}^{N-1} - F_{B,2}^{N-1} \\ \vdots \\ F_{B,m}^{N-1} - F_{B,m-1}^{N-1} \end{bmatrix}$$

- Minimize: Subject to:

$$\min\left(\sum (LHS - RHS)^2 + \kappa \cdot \max\left(\frac{dC_B}{dz}\right)\right)$$

$$0 = F_{B,1} > F_{B,2} > \cdots > F_{B,m} = 1$$

25

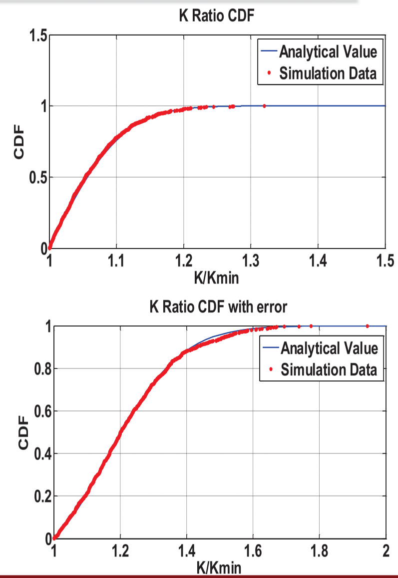
Effects of Error

Data → Remove Bias → Estimate Variation → ? Calculate Density

- Any estimation scheme is prone to error
- These errors affect the minimum ratio and hence its CDF

$$CDF\left(\frac{(B+dB)}{(B+dB)_{mk}} \middle| \frac{(B+dB)}{(B+dB)_{mk}} > 1\right)$$

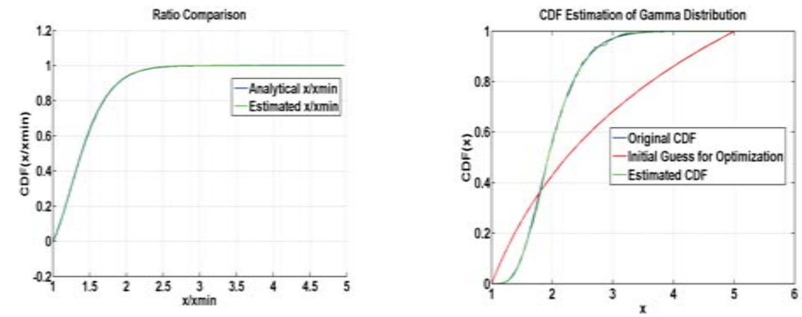
- Estimate (B + dB) using similar method
- Require statistics on the error of dB
  - › Estimate from previous filtering methods (non-linear least squares to estimate K)
- $dB \sim \mathcal{N}\left(0, \frac{\sigma_K}{\bar{\rho}}\right)$ $\qquad C_{B+dB}(x) = [C_B * P_{dB}](x)$



26

Solving for F

Data → Remove Bias → Estimate Variation → Calculate Density



- Test Case: Gamma Distribution
-

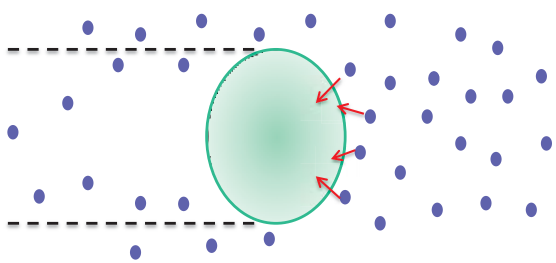
Problem: If the distribution shifted left or right and is scaled appropriately, get same observed result (unknown integration constant)!

How to determine the minimum, B_{min}?

27

Free Molecular Flow

Data → Remove Bias → Estimate Variation → ? Calculate Density



Mean free path:	λ
Characteristic length:	L
Number density:	N
Collision Area:	σ_A

- Knudsen number: $Kn = \frac{\lambda}{L}$ $\qquad \lambda \sim \frac{1}{N\sigma_A}$
- High Knudsen numbers: Free molecular flow (Kn >> 10)
  - › Basically collisionless, not a continuum (no bulk properties)
  - › Random thermal motions dominant: Maxwellian distribution

$$B = \frac{C_D A}{m}$$

min ↓

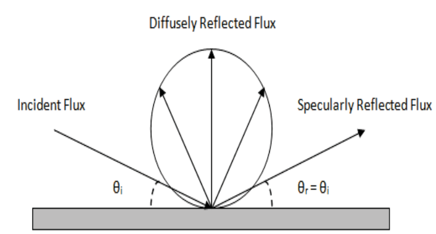
$$B_{min} = \frac{C_{D,min} A_{min}}{m}$$

28

Free Molecular Flow

Data → Remove Bias → Estimate Variation → ? Calculate Density

- Accommodation coefficient: $\alpha = \frac{E_i - E_r}{E_i - E_w}$



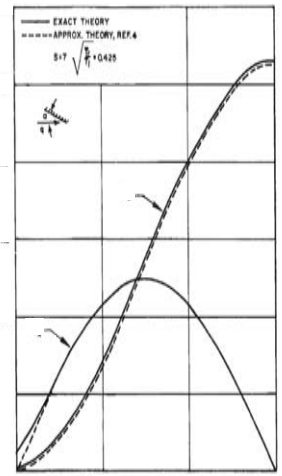
- Reflected particles classified as:
  - › Specular – perfect reflection about surface normal
  - › Diffuse – random
- Surfaces for satellites in LEO tend to become coated with adsorbed atomic oxygen; most reflections are diffuse (80-99%)

29 C_D on Flat Plate

Data → Remove Bias → Estimate Variation → ? → Calculate Density

$$C_D = \frac{A}{A_{ref}}\left[(2-\sigma_N)\cos\theta\left(\cos\theta(1+erf(\gamma))+\frac{1}{S\sqrt{\pi}}e^{-\gamma^2}\right)\right.$$
$$\left.+\frac{2-\sigma_N}{2S^2}(1+erf(\gamma))+\frac{\sigma_N}{2}\sqrt{\frac{T_r}{T_i}}\left(\frac{\sqrt{\pi}}{S}(1+erf(S))+\frac{1}{S^2}e^{-S^2}\right)\right]$$

$$\gamma = S\cos\theta \qquad T_r = T_i(1-\alpha)+\alpha T_w$$
$$S = \frac{U}{V_a} = \frac{U}{\sqrt{2R_{sp}T_a}}$$



30 Uncertainty in α

Data → Remove Bias → Estimate Variation → ? → Calculate Density

- Combine this with earlier results:

$$P(B,\alpha) = P(B|B_{min})P(B_{min}|\alpha)P(\alpha)$$

- B_{min} is a function of α:

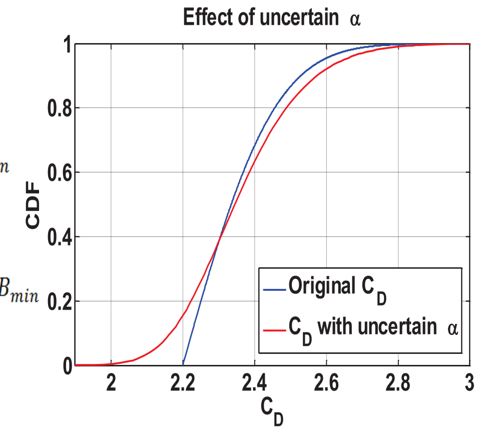
- Effect on m

$$C(B) = \int_{B_{min,\alpha=1}}^{B_{max}} C(B|B_{min})P(B_{min})\,dB_{min}$$

- Limits:

$$C(B_{mk}) = \int_{B_{min,\alpha=1}}^{B_{max}} C(B_{mk}|B_{min})P(B_{min})\,dB_{min}$$

$$\lim_{N\to\infty} P(B_{mk}) \to P_{min}$$



C_D ~ Half Normal

$\mathcal{N}^{\alpha}$ ~ (2.2, 0.1)

31 Calculating Density

Data → Remove Bias → Estimate Variation → Calculate Density (Recursion)

- Calculate density ρ:

Mean Estimate: $\rho_k = \frac{\bar{K}_k}{\bar{B}}$

- Minimum K
- Maximum B

Minimum Estimate: $\rho_k = \frac{K_{mk}}{\bar{B}_{min}}$

- Maximum K_{mk}
- Minimum B_{min}

- K contains estimation error
- B contains error associated with platform
- Nullify large estimation errors in K from affecting estimation of B
-

Have to choose which one to minimize!

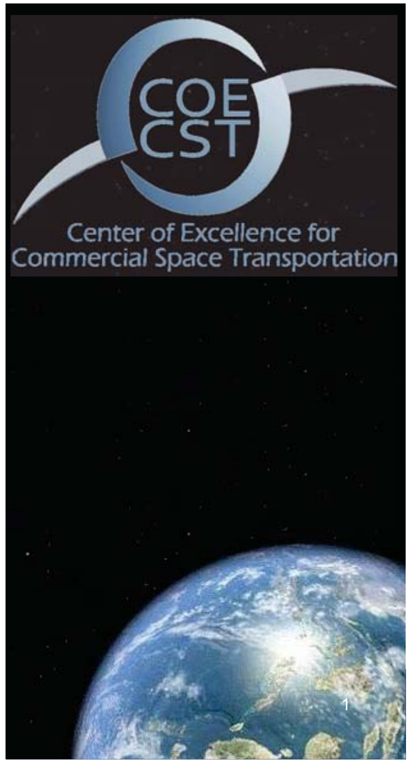
Separate estimation error from the random elements of the platform in question

COE CST Fifth Annual Technical Meeting

Task 187: Space Situational Awareness

PI: Dan Scheeres
Student: In-Kwan Park
University of Colorado

October 27-28, 2015
Washington, DC



Agenda

- Team Members
- Task Description
- Research Methodology
- Research Results
- Next Steps
- Conclusions and Future Work

Team Members

Direct Current / Past Support from the FAA COE
•Dan Scheeres, CU Professor, PI
•George Born, CU Professor, Co-I
•Bob Culp, CU Professor Emeritus, Co-I
•Brandon Jones, CU Assistant Research Professor
•Jay McMahon, CU Assistant Research Professor
•Kohei Fujimoto, CU PhD Student (graduated May 2013)
•In-Kwan Park, CU PhD Student (current support, graduating this Fall)
Related Research from Fellowship Students
•Aaron Rosengren, CU Graduate Student, NSF Fellow (graduated March 2014)
•Antonella Albuja, CU Graduate Student, NSF Fellow (graduated October 2015)
•Daniel Lubey, CU Graduate Student, NSTRF Fellow (graduated October 2015)
Government and Industry Partners
•AFRL Kirtland and Maui
•NASA Orbit Debris Program Office
•Analytical Graphics, Incorporated
•Orbital Sciences Corporation

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•Orbital Sciences Corporation

Task Description

- ***Space Situational Awareness***

  SSA = Cognizance of Resident Space Objects (RSO) and activities in orbital regions of interest, both now and in the short and long-range future.

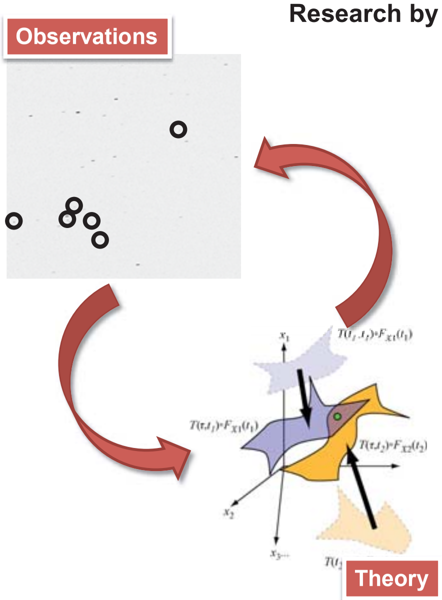
- **Objectives**: Improve SSA abilities in regions of interest to the FAA for space-based activities.
- **Current regions of focus**: LEO-*down* and GEO-*up*
- **Goals are to improve**: uncertainty modeling and propagation, precision long-term debris orbit and attitude propagation, non-gravitational model prediction and estimation, orbit estimation techniques.

Research Methodology and Results

- Directly funded FAA research on initial orbit determination, object correlation, uncertainty mapping and conjunction analysis
- Leverage other student support models to perform research of relevance to the overall goals of the FAA COE CST
  - Long-term orbit and physical dynamics of space debris
  - Current student support from NSF and NASA through fellowships
- Previous research output and results of relevance to our FAA CST COE research goals from combined team (since 2010)
  - Presented 34 papers at 20 conferences
  - Published 12+ papers in peer-reviewed journals
  - Submitted additional papers to journals
- Graduate students associated with these activities
  - 5 PhDs with some connection to FAA activities graduated in SSA
  - 1 Assistant Profs / 2 post-docs / 2 in Industry

Association of Optical Observations

Research by Kohei Fujimoto

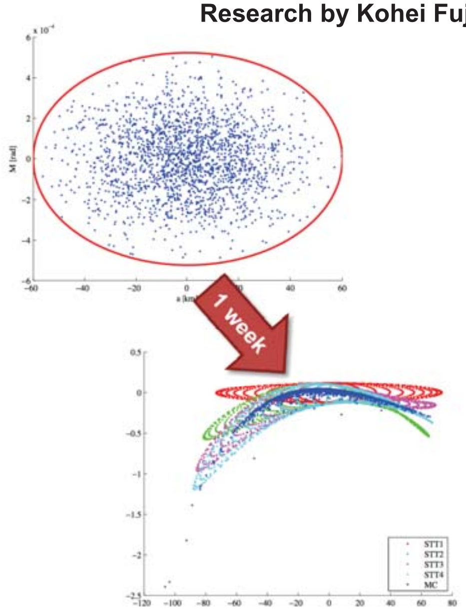


Credit: IHI Corp., Hamane, T. (GAO), Fujimoto, K.

- Direct Bayesian approach to observation association
  - Exploits sparseness of the estimation problem
  - Robust with little tuning
- Experimentation with real-world observations
  - Collaboration with IHI Corp., University of Bern
  - Developed techniques to take into account measurement error
- "Closing the loop" on the too-short-arc problem
  - Papers describing our research advances published in Journal ASR, JGCD

Analytic Propagation of Uncertainty

Research by Kohei Fujimoto & In-Kwan Park



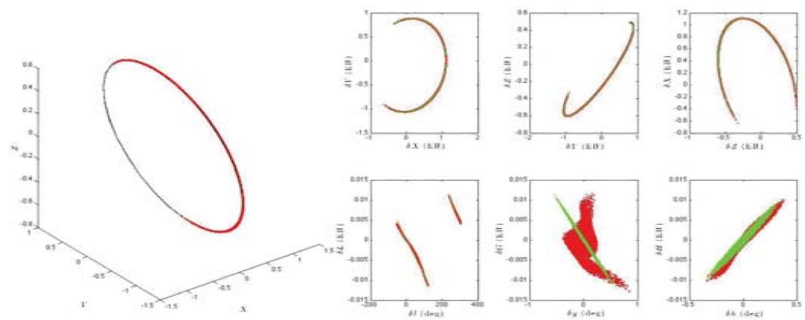
- Rapid non-linear uncertainty propagation
  - Special soln. to the Fokker-Planck eqn. for deterministic systems
  - State transition tensor description of the solution flow
- Added effects due to atm. drag
  - Classical results (King-Hele) applied to a modern problem
- Developed new approach to conjunction analysis
  - Mixes the use of analytical theories and GMMs
  - Papers published in JGCD

Necessary Accuracy for Uncertainty

- Research by In-Kwan Park: Focus on a fundamental question –

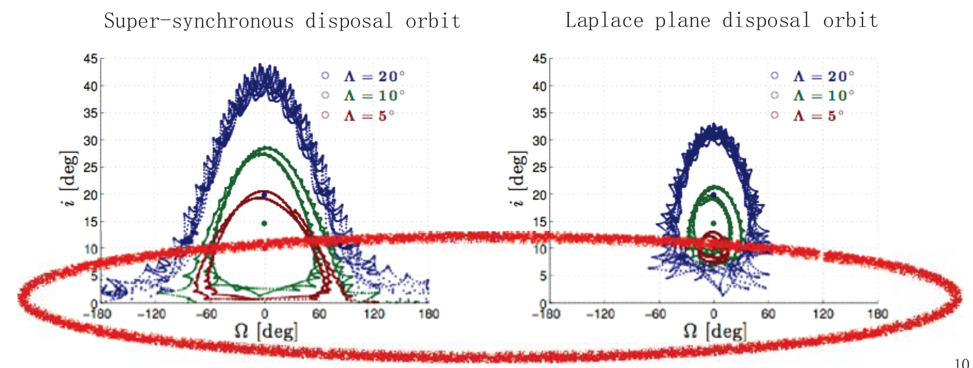
  "How much precision is needed in describing the dynamical motion of a spacecraft to ensure an accurate determination of propagated orbit uncertainty?"

  - Answer: Secular dynamics approximations can fully capture the first few moments of a statistical PDF distribution
  - Implications: Computationally fast theories can capture debris uncertainty, motivating rapid computation of conjunction analysis
  - Papers published in JGCD



Long-Term GEO Disposal Orbits

- Research by Aaron Rosengren:
  - Current GEO "disposal" orbits are boosted to higher altitudes, but stay in the same plane. Debris shed from these defunct satellites can – and will – cross into the GEO belt
  - Transferring satellites into the Laplace Plane for disposal will minimize future risk of orbit debris at GEO, maintaining this natural resource for future generations
  - Published in ASR



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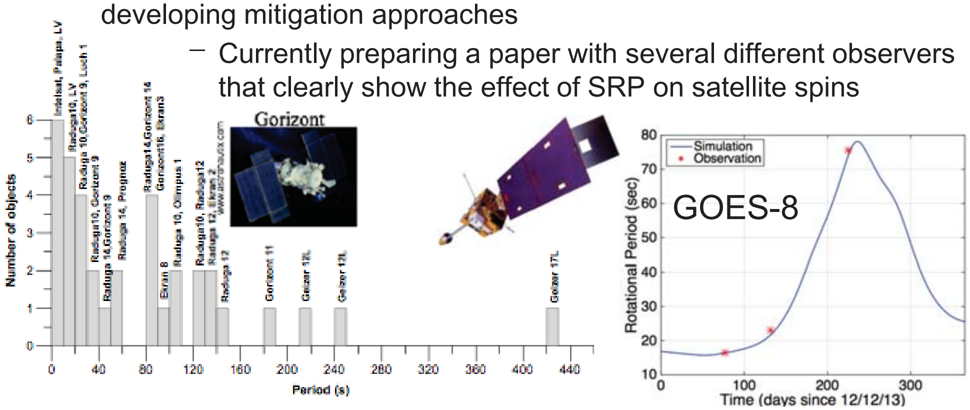
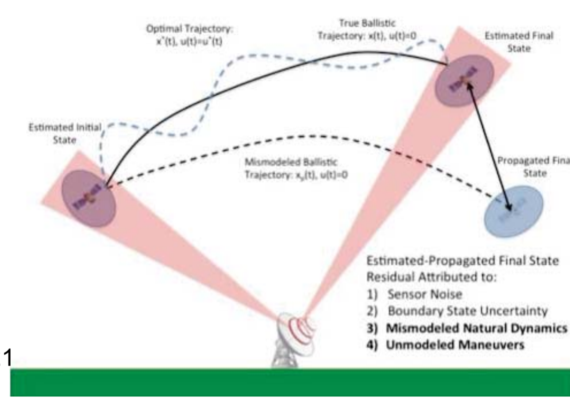
Evolution of Defunct Satellites

- Research by Antonella Albuja:
  - Observations of defunct GEO satellites shows that their rotation periods change over time, and that many of them rotate rapidly
  - Such evolutionary changes can occur due to environmental perturbations — especially due to solar radiation pressure torques
  - Understanding the physical evolution of defunct satellites is crucial for developing mitigation approaches
    - Currently preparing a paper with several different observers that clearly show the effect of SRP on satellite spins

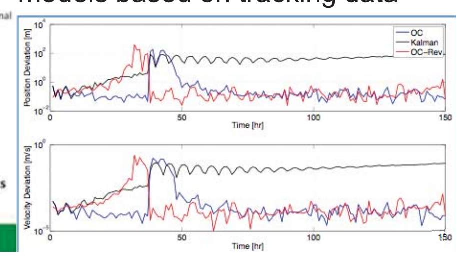


Orbit Debris Model Estimation

- Research by Daniel Lubey:
  - Space debris orbit estimation is limited by non-gravitational effects
  - These are unique for each body, and must be modeled and estimated accurately for generating precise long-term predictions



  - Current research is leveraging previous AFOSR-sponsored research on optimal control to develop automatic methods for estimating non-gravitational models based on tracking data



Current Status

- Current designated PhD student Park will defend in December, start post-doc in January
- Allotted funds through FY15 have been spent
- White paper proposal for continued support submitted March 2015
  - Proposal to combine previous work on conjunctions analysis into a computational tool for rapid and accurate "impact forecasting" for space vehicles traversing orbit regimes

Conclusions and Future Work

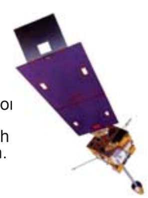
- Since 2011 using FAA support and leveraging AFOSR, NSF and NASA support
  - Have published extensively in SSA topics of interest to the COE
  - Have produced PhDs who hold SSA-related positions in industry, research and academia
- Spent allocated funds through May 2015
- Proposed future work to integrate past research into conjunction analysis forecasting tool

TASK 187. Space Situational Awareness

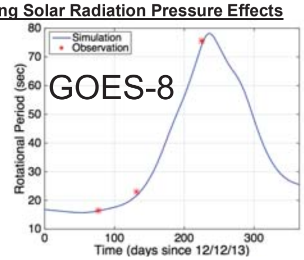
•**PROJECT AT-A-GLANCE**
•UNIVERSITY: University of Colorado at Boulder
•PRINCIPAL INVESTIGATOR: Dr. Dan Scheeres
•STUDENT RESEARCHER: Mr. In-Kwan Park (PhD)

RELEVANCE TO COMMERCIAL SPACE INDUSTRY
•Orbit debris remains a fundamental issue for all aspects of space utilization. Specific challenges remain in performing lo term forecasts for specific pieces of orbit debris. While the population of debris is relatively well understood — research advances continue to open new windows on this population.

STATEMENT OF WORK
•Effective space situational awareness faces the challenge of bringing together observations from disparate sensors and sources, developing computationally efficient dynamic propagation schemes for orbits and their uncertainty distributions, and formulating accurate estimation methods for the purpose of quantifying and qualifying space-based activities.
- •Maximize the information extracted from usual sources of SSA data (minimize uncertainty)
- •Identify how data should be collected to maximize information content (maximize efficiency)
- Recover and predict the space domain with more accuracy
- Timely estimation of the space-based environment to create actionable information.



Large Fluctuations of Spin Period in Defunct GOES-8 Satellite can be accurately fit by modeling Solar Radiation Pressure Effects



STATUS
- Graduated two FAA-funded PhD students: Kohei Fujimoto, May 2013 & In-Kwan Park Fall 2015
- Have a large combined student team focused on relevant SSA research topics of direct interest to the COE
- Presented over 34 distinct papers at 20 conferences
- Over 12 papers published with more in peer review

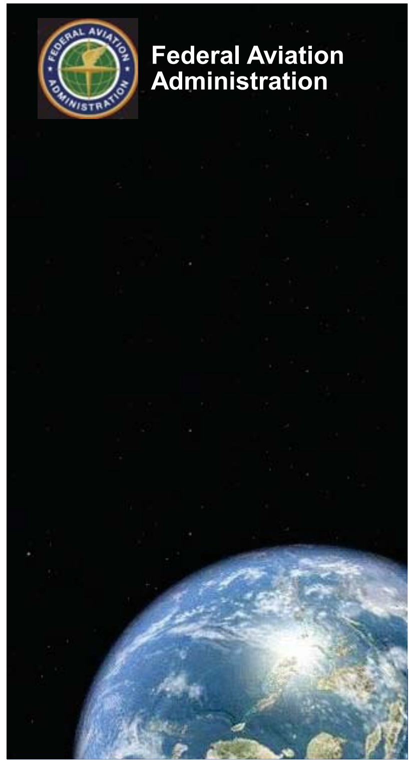
FUTURE WORK
- Next proposed stage of direct FAA funded research will focus on developing a rapid asset/debris conjunction analysis tool
- Non-directly funded research will focus on:
  - Long-term space debris dynamics (orbit and attitude)
  - Modeling and estimation of debris non-gravitational forces

COE CST 2015
ANNUAL
TECHNICAL MEETING #5:

Task 220: Update

PI: Patricia C. Hynes, Ph.D.
New Mexico State University

October 28, 2015



Overview

- Framework Review
- NTSB Report on SpaceshipTwo accident
- Recent mishaps at Spaceports
- Dissemination Efforts
- Next Steps-Conclusion

Context- Framework for Spaceport Operations

- FAA continuing mission is to provide the safest, most efficient aerospace system in the world. -www.faa.gov
- FAA-AST mission: ensure protection of the public, property, and the national security and foreign policy interests of the United States during commercial launch or reentry activities, and to encourage, facilitate, and promote U.S. commercial space transportation. -www.faa.gov
- Commercial Space Launch Act (CSLA)-originally enacted 1984 was amended in 2004 to provide a learning period restricting the ability of the FAA to enact safety regulations to allow the industry to build experience.

Body of Knowledge for Spaceport Operations & Best Practices

- An evolving collection of documents and information that fall within the Framework and support the development of space launch site interoperability. The database is constructed and maintained by the New Mexico State University Library. contentdm.nmsu.edu

Framework for Spaceport Operations

Sections relevant to mishaps/accidents at spaceports:

- 3.0-Emergency Response
- 5.0-Ground and Flight Safety
- 7.0-Mission Readiness

Virgin Galactic's SpaceShipTwo

NTSB Aerospace Accident Report
July 2015

- Scaled Composites SpaceShipTwo Accident.
  - Mojave Air and Space Port. Oct. 31, 2014

file://localhost/Users/Jim/Desktop/Day2-AM/AAR1502.pdf

NTSB- Spaceport Related Findings

1. Need for improved emergency response planning.
2. Need for complete commercial space flight database for mishap lessons learned.
3. Need for human factors guidance for design and operation of crewed vehicles.

Improved Emergency Response Planning

"Scaled Composites and local emergency response officials could improve their emergency readiness for future test flights by making better use of available helicopter assets." -NTSB Report, p. 68.

Database for Mishap Lessons Learned

"A database of lessons learned from commercial space mishap investigations would provide mutual benefits to public safety and industry promotion and would thus be consistent with the Federal Aviation Administration's mission and authority."

-NTSB Report, p. 68.

Human Factors Guidance

"[D]evelop and issue human factors guidance for operators to use throughout the design and operation of a crewed vehicle." -NTSB Report, p. 71.

Commercial launch mishaps at spaceports

- June 29, 2015-No Public Report

  SpaceX's Falcon 9- Cape Canaveral, FL.
- Oct. 28, 2014-No Public Report

  Orbital's Antares Rocket and Cygnus Spacecraft- MARS, Wallops, VA.
- Aug. 25, 2014-No Public Report

  Miltec/DoD-Pacific Spaceport Complex-Kodiak, AK (formerly Kodiak Launch Complex).

The Learning Period

- Legislation pending before Senate and House would extend the learning period-the regulatory moratorium.
- During the learning period, it is critical that our work continue.

Dissemination Efforts

- 32nd Annual International Test and Evaluation Symposium (ITEA)
  August, 2015, Arlington, Virginia-presentation by Hynes
- Range Commanders Council:
  - February, 2015 Edwards Air Force Base
- 65th International Astronautical Congress (IAC)
  September, 2014-Toronto, Canada-presentation by Herb Bachner
- American Association of Airport Executives (AAAE)
  February, 2015-Denver Colorado-presentation by Herb Bachner.

Next Steps-Conclusion

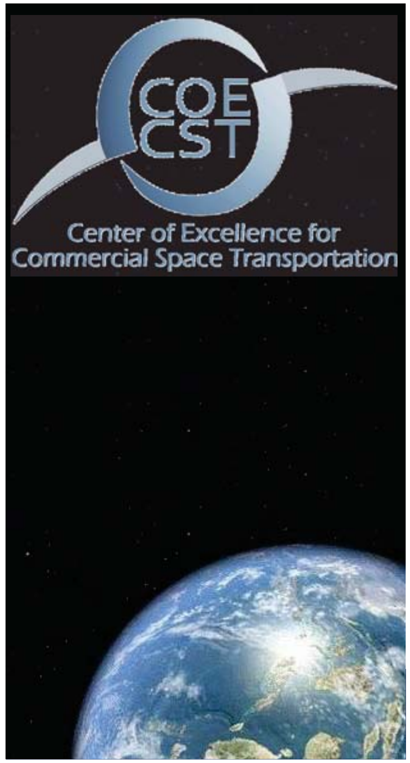
- Continue incorporating documents into the Body of Knowledge.
- Work in partnership with the identified industry group that will provide the NTSB recommended Data Base for Mishap Lessons Learned.
- Continue to be part of the solution.

COE CST Fifth Annual Technical Meeting

Task 244: Autonomous Rendezvous & Docking for Space Debris Mitigation

Bungo Shiotani
Norman Fitz-Coy (P.I.)

October 27-28, 2015
Arlington, VA



Agenda

- Team Members
- Task Description
- Schedule
- Goals
- Results
- Conclusions and Future Work

Team Members

- Principal Investigator
  - Norman Fitz-Coy
- Students
  - Bungo Shiotani (PhD student)
  - Kathryn Cason (accepted job with MEI)
  - Takashi Hiramatsu (PhD in 2012 – Keio Univ.)
- Organizations
  - Collaborator: NASA ODPO
  - Matching provided by: Space Florida

Task Description (Original)

- Active debris removal is required
  - Interests in small satellites (e.g., CubeSats) especially by new space entrant leads to:
    - More spacecraft → more failure (debris)
    - Debris likely to be non-cooperative
- Objective
  - Develop strategies to minimize interactions during removal of non-cooperative debris
  - Develop strategies for safe proximity operations / collision avoidance during removal

Task Description (Modified)

- Objectives
  - Identify/quantify the global growth trends of CubeSat-class satellite; assess the interests of US and international communities for CubeSat applications and investigate emerging CubeSat products (e.g., Planet Labs constellation of CubeSats).
  - Survey the assembly integration and testing practices of these CubeSat developers and utilize that information to investigate the mortality rates of CubeSats
  - Assess the space debris mitigation strategies utilized / implemented by these developers

Replace CubeSats with “Containerized” Satellites

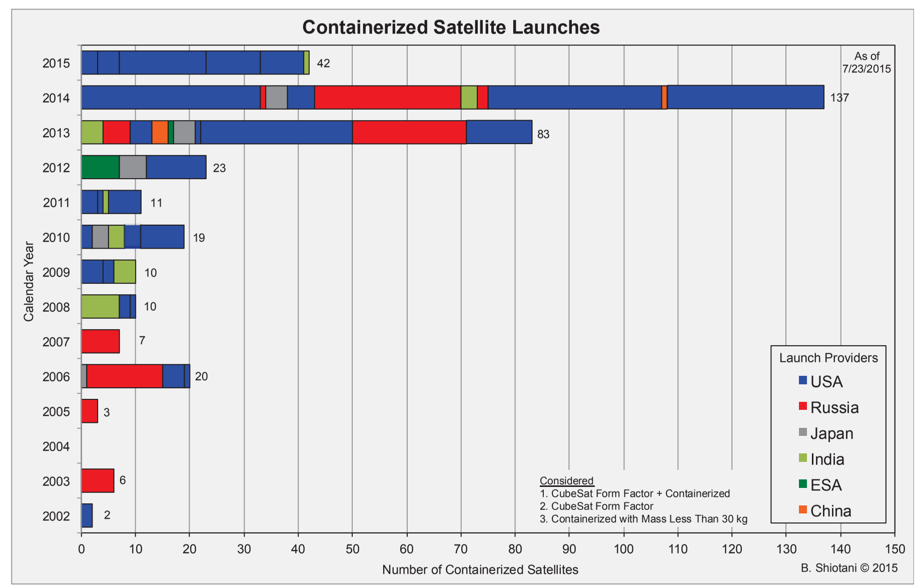
Schedule

- Start date: September 2014
- Develop survey strategy: October 2014
- Pilot test questionnaire: December 2014
  - Reviewed by NASA ODPO
- Disseminated questionnaire: January 2015
- Survey closed: May 2015
- Analyze survey results: June-Aug. 2015
- Finalize/publish results: September 2015

Goals

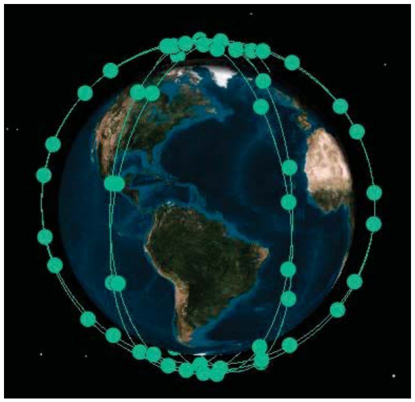
- Outcomes
  - Utilize the growth trends, mortality information, and mitigation strategies to access the impact of “containerized” satellites to LEO debris
  - Sensitize containerized satellite community of their potential impact on space debris
  - Work with NASA ODPO and IADC to develop protocols to reduce debris growth trend (e.g. modify 25-year rule)
- Relevance to FAA
  - Debris in LEO will re-enter the airspace and could interact with sub-orbital flights and/or air traffic
  - Collision with 5 mm sized debris could be consequential

Task Motivation

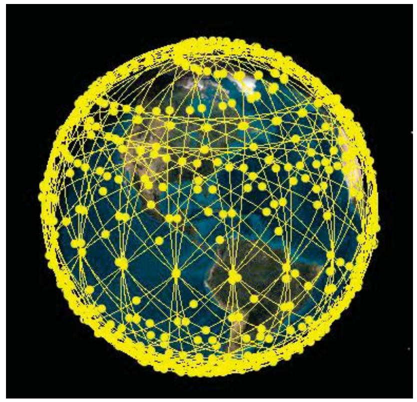


Task Motivation

- Debris growing due to increases launch rate of containerized satellites
- Large constellations (hundreds of satellites) are being “developed”

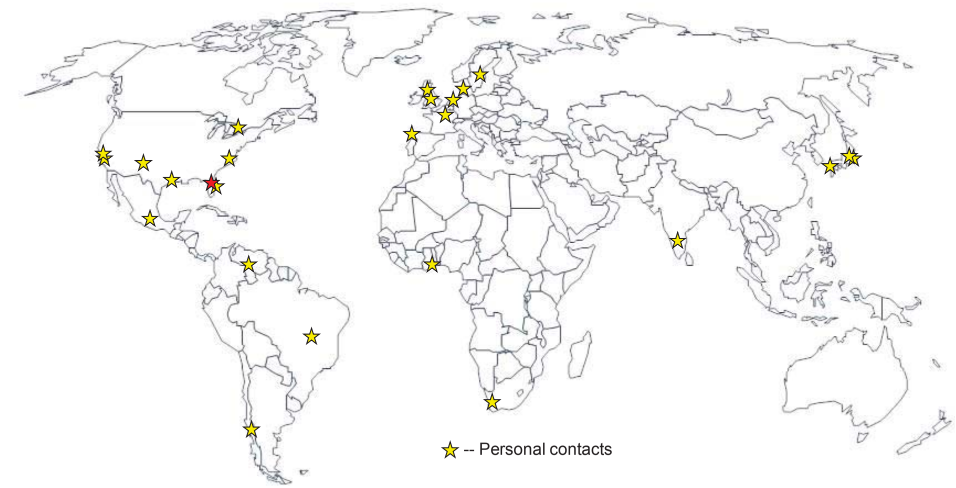


Constellation of traditional satellites (e.g., Iridium)



Constellation of containerized satellites (e.g., OneWeb, SpaceX, PlanetLabs)

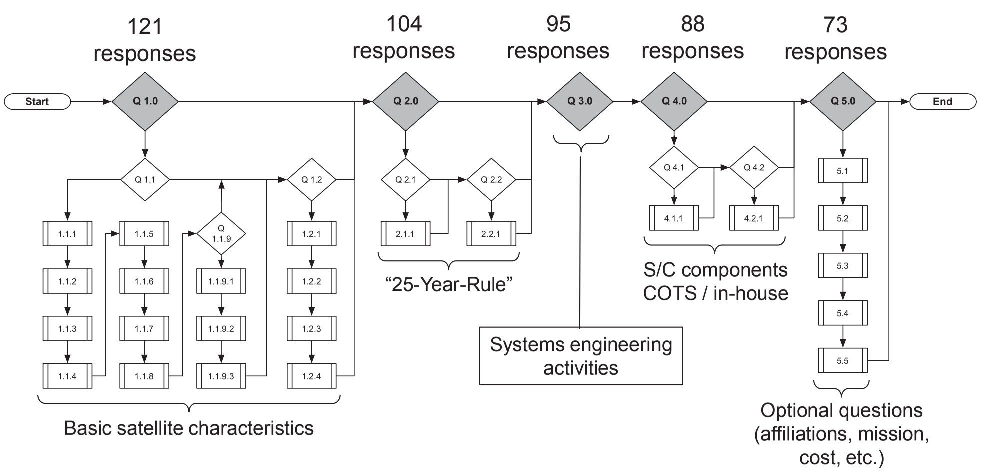
Containerized Satellite Survey



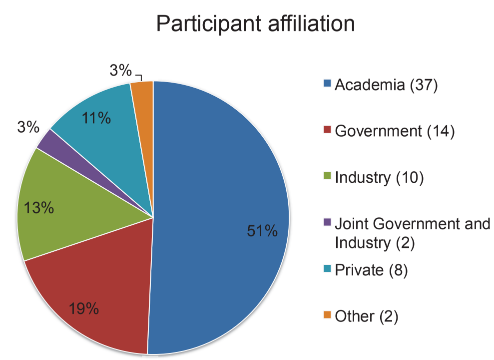
- Survey disseminated to small satellite community through mailing lists (e.g., CubeSat, AMSAT, and working groups of INCOSE and IAA) and personal contacts worldwide.

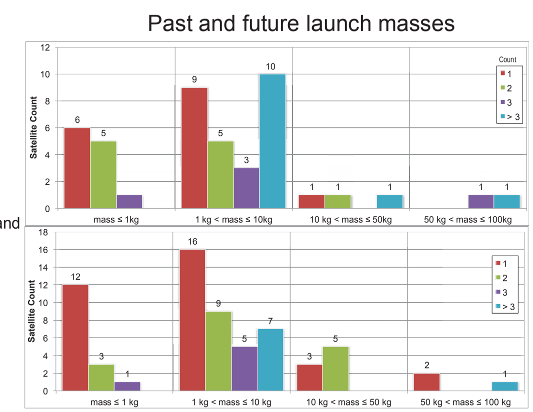
Survey Results

- 200 survey links opened



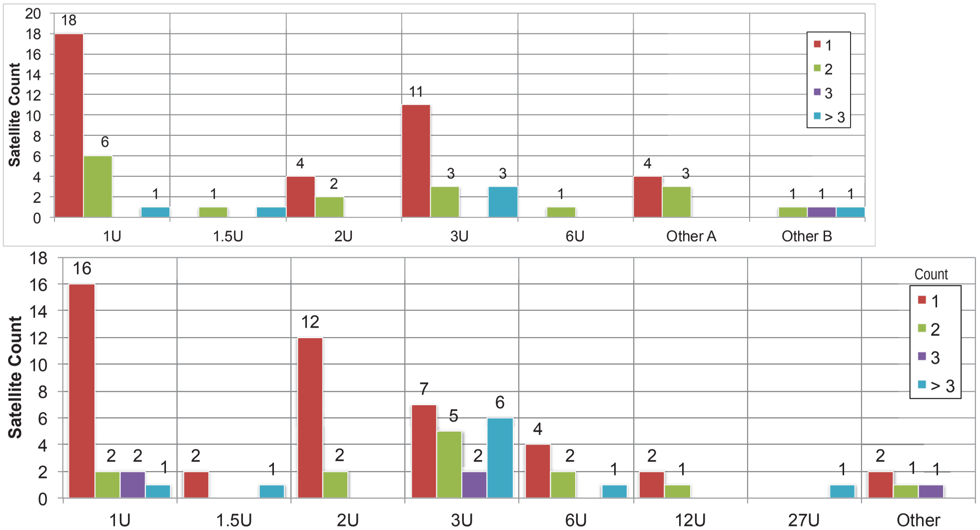
Survey Results





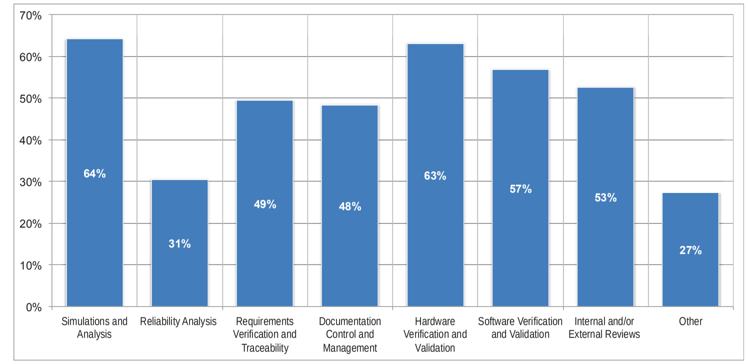
Survey Results

Past and future sizes



Survey Results

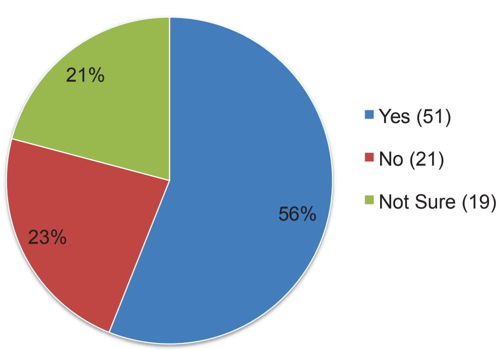
Systems Engineering Activities



Simulation & Analysis	Orbital, thermal, and structural	**Hardware V&V**	Environmental (thermal, vacuum, vibe)
Reliability Analysis	FTA	**Software V&V**	Hardware & software in-the-loop
Requirements	AES9100 QA, ICDs, QA plans	**Reviews**	Working groups, subject matter experts
Documentation	Versioning, server system, and software	**Other**	No SE activities

Survey Results

- 91 respondents familiar with the “25-Year-Rule”
  - 56% of these respondents have procedures in place to satisfy the “25-Year-Rule”



Selected Procedures
Orbital simulations and analyses
Reports and documents to governing administration
Active deorbit devices
Passive deorbit devices
By design (consider area-to-mass ratio)
Rely on launch providers to put us in low orbit
Purchase/request launch to low perigee altitudes

- Further details to be published in Journal of Small Satellites

Conclusions and Future Work

- Survey results show a healthy continuous growth of containerized satellites
- Small satellite community acknowledge the debris issue and either have procedures in place or are developing procedures to be in compliance with the “25-Year-Rule”
- Statuses vary depending on mission assurance (i.e., systems engineering) activities and affiliation
- The small satellite community is capable of becoming/being responsible users of space

Conclusions and Future Work

- Observations from the study
  - Lack of survey responses leads to inconclusive assessments (e.g., mortality rates)
  - Some participants thought the survey asked proprietary information and refused to answer
- Future work
  - Disseminate results (paper to be submitted)
  - Work with NASA Orbital Debris Program Office to develop protocols and continue assessment of debris
  - Work with INCOSE SSWG to develop a CubeSat reference model utilizing MBSE
  - Further assess mission assurance (i.e., systems engineering) activities

Acknowledgement

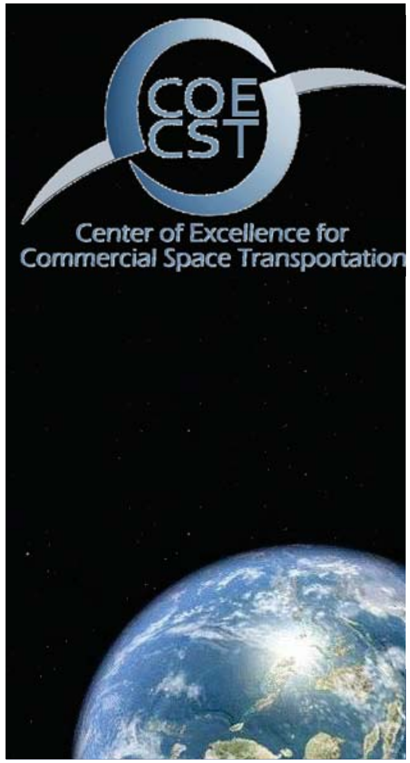
- We would like to express sincere gratitude to:
  - All participants that responded to the survey
  - NASA ODPO for their guidance

- Contact information
  - Bungo Shiotani bshiota@ufl.edu
  - Norman Fitz-Coy nfc@ufl.edu

Autonomous Spacecraft Rendezvous and Docking: Rapid Trajectory Generation

Griffin Francis
PI: Emmanuel Collins

October 27-28, 2015
Arlington, VA



Contribution Team

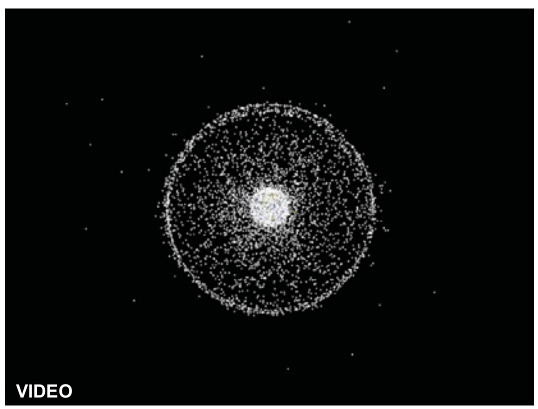
- Emmanuel Collins, PI
- Griffin Francis, PhD Student, Mechanical Engineering
- Aneesh Sharma, PhD Student, Computer Science
- Oscar Chuy, Scholar Scientist, Mechanical Engineering

FCAAP — Florida Center for Advanced Aero-Propulsion — Technologies for the Next Generation
CISCOR — Center for Intelligent Systems, Control, and Robotics

Motivation

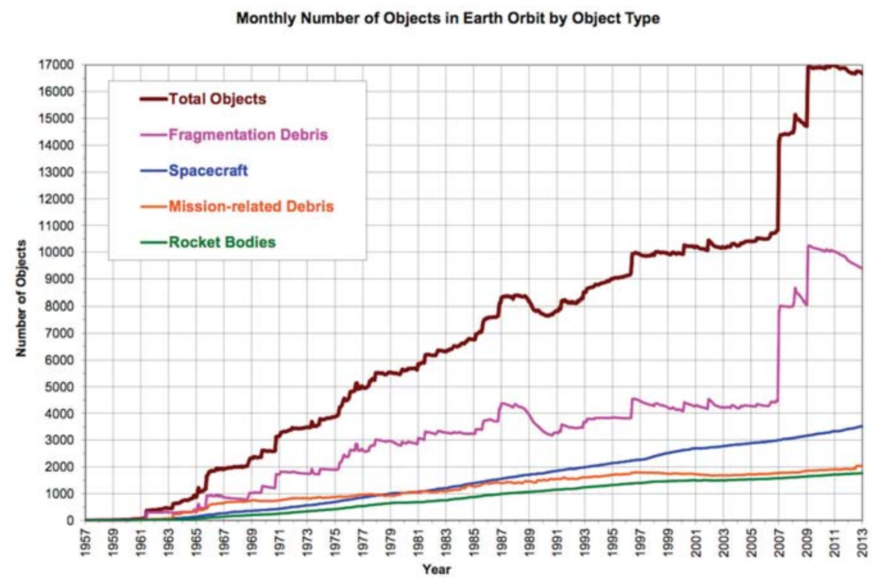
Purpose: As indicated by recent NASA study, there is an immediate need to develop orbital debris mitigation technology.

- A promising solution for direct debris removal is the development of a "Space Tow Truck."
- Requires automated guidance to approach targeted debris.



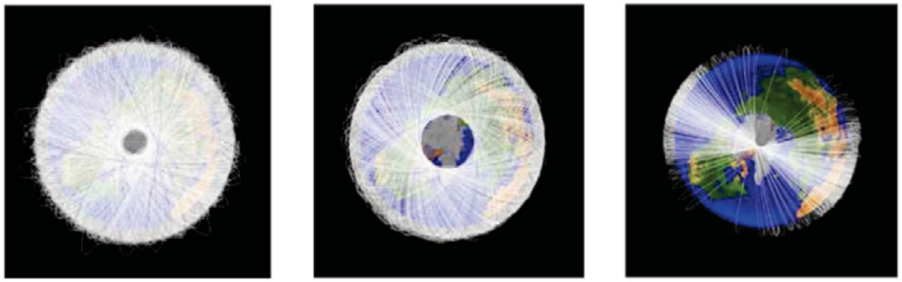
Debris in Motion: About 95% of these currently tracked objects in orbit are debris and not functional satellites. (NASA Orbital Debris Program Office)

Motivation



Task Description

Objective: Develop the technology for rapid (within a few seconds), onboard generation of dynamically feasible trajectories that enable a spacecraft to approach a target for docking.



Impact of Unmitigated Debris: The profiles of three major debris clouds resulting from the January 2007 destruction of the Chinese Fengyun-1C (left) spacecraft and the February 2009 collision between the Russian Cosmos 2251 (middle) and U.S. Iridium 33 (right) spacecraft. (NASA Orbital Debris Program Office)

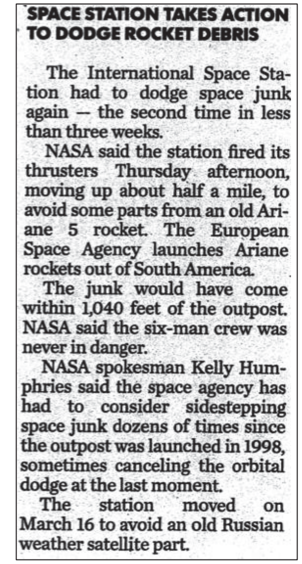
Research Goals

Commercial Application:

Ultimately, the debris problem represents a potentially necessary commercial endeavor.

- Analogous to traditional industry: Waste Management
  - Not "sexy," but certainly a sustainable commercial enterprise.
- Large scale efforts warrant the use of automated guidance to approach targeted debris.

Debris in the News (Right): Debris isn't just a future problem; as recently as six months ago, debris made headlines as the ISS maneuvered to avoid space junk. (USA Today, 04/14/2014)



SPACE STATION TAKES ACTION TO DODGE ROCKET DEBRIS

The International Space Station had to dodge space junk again — the second time in less than three weeks.

NASA said the station fired its thrusters Thursday afternoon, moving up about half a mile, to avoid some parts from an old Ariane 5 rocket. The European Space Agency launches Ariane rockets out of South America.

The junk would have come within 1,040 feet of the outpost. NASA said the six-man crew was never in danger.

NASA spokesman Kelly Humphries said the space agency has had to consider sidestepping space junk dozens of times since the outpost was launched in 1998, sometimes canceling the orbital dodge at the last moment.

The station moved on March 16 to avoid an old Russian weather satellite part.

Research Goals

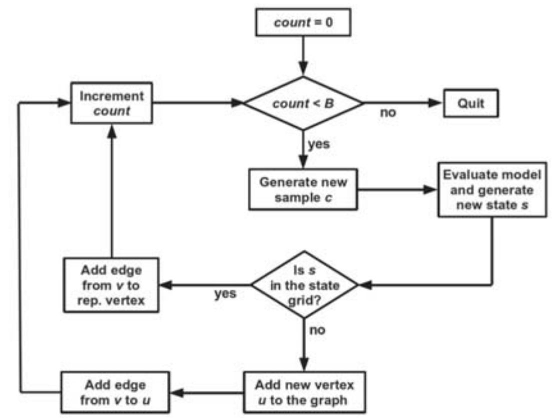
Technical Goals:

1. Develop spacecraft dynamic model for the planner to account for actuator characteristics, vehicle momentum, and power consumption.
2. Use the dynamic model to develop trajectories for effective rendezvous with targets.
3. Optimize trajectories based on relevant metrics such as distance, time, or energy.
4. Rapidly replan trajectories as new information becomes available.

Targeting Debris: Artistic conceptualization illustrating the challenge of navigating to pursue an object in an orbital environment that is densely occupied. (R. Harris/SPL)

Research Methodology

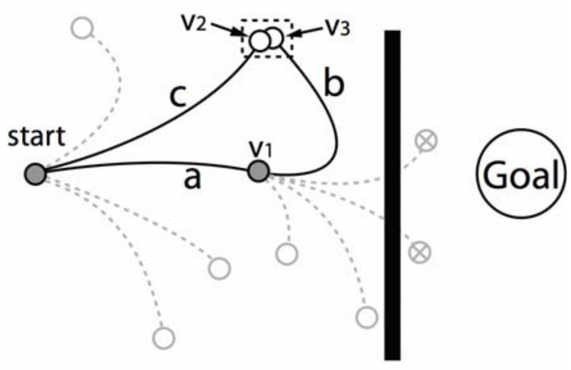
- The primary tool used is **Sampling-Based Model Predictive Optimization (SBMPO)**.
- SBMPO is a graph search method characterized by:
  - Graph that is based on sampling of model inputs;
  - Optimization via A*;
  - Incorporation of dynamic model in planning;
  - Ability to rapidly replan;
  - Generation of trajectories (time-dependent), not simply paths.



Fundamental Steps of SBMPO: (1) Select highest priority node in queue. (2) Sample input space. (3) Add new node to graph. (4) Evaluate new node cost. (5) Repeat 2-4 for defined number of successors. (6) Repeat 1-5 until stopping criteria is achieved.

Research Methodology

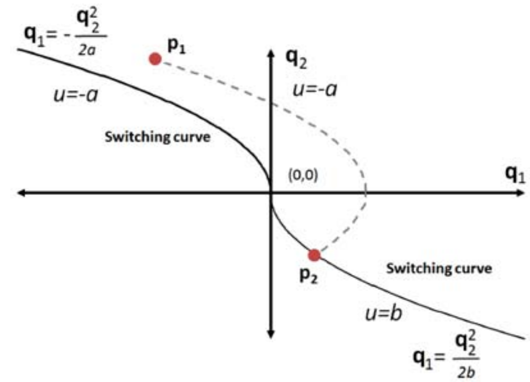
- A graph of the output space is generated through the expansion of nodes via the sampling of inputs to the system model.
  - Sampling via Halton, Hammersley, and other pseudorandom methods.
- The output space is discretized to avoid infinitesimal improvement of nearby nodes.
- Dynamically or spatial invalid nodes are immediately rejected from the graph.



Graph Generation: The process of node expansion, node rejection due to collision detection, and output space discretization via an imposed implicit grid encompassing nearby nodes V2 and V3.

Research Methodology

- The key to fast computations with SBMPO is the judicious selection of an optimistic heuristic.
  - Optimistic A* heuristic: a rigorous lower bound on the cost from the current node to the goal.
- For example, in a planning scenario requiring a specified velocity at the goal, a heuristic for minimum time optimization can be based upon the solution to the a "simple" time optimal control problem.



Derived from Pontryagin's Maximum Principle, this minimizing control curve corresponds to the solution of the time optimal control problem.

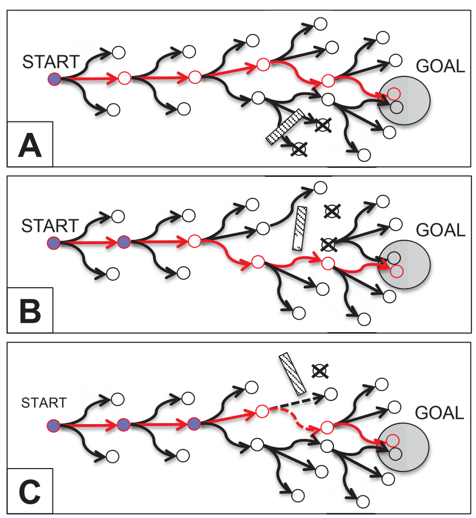
Research Methodology

Incremental Replanning:

(A) Algorithm forms initial graph and plans optimal trajectory.

(B) The graph is restored but the initial plan is violated due to obstacle movement. Invalid edges are removed and the trajectory is replanned.

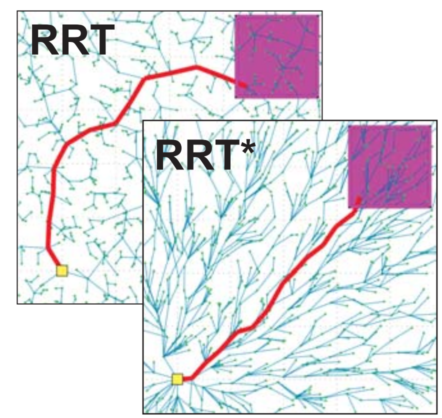
(C) The updated graph is restored but a more optimal trajectory is now achievable. Connectivity is restored and the trajectory is replanned.



Preliminaries

Introduction to Optimal Rapidly-Exploring Random Trees (RRT*)

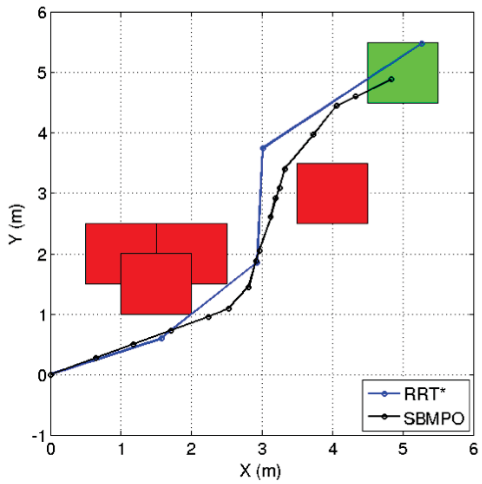
- Among the most popular motion planning methods, RRT* is an improvement of the RRT algorithm.
- Comparable to SBMPO, RRT* utilizes sampling, graph search, and cost-based optimization.
- However, RRT* does not employ prediction to speed up computations.



When compared with RRT (rear), it is clear that RRT* (front) produces a more optimal planning result. In fact, it has been proven that RRT* guarantees an asymptotically optimal solution. (*Sampling-Based Algorithms for Optimal Motion Planning*, Karaman and Frazzoli)

Preliminaries

Comparison of SBMPO with RRT* (Typical Result)



Simple Kinematic Model of a Mobile Robot for Path Planning:

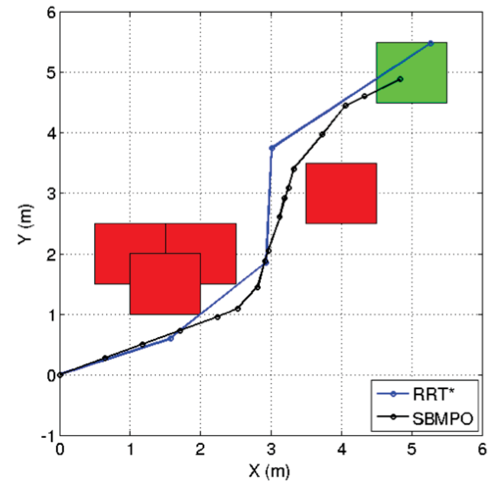
$$\begin{bmatrix} x_{k+1} \\ y_{k+1} \\ \theta_{k+1} \end{bmatrix} = \begin{bmatrix} x_k \\ y_k \\ \theta_k \end{bmatrix} + \begin{bmatrix} v_t \cos\theta_{k+1} \\ v_t \sin\theta_{k+1} \\ v_\theta \end{bmatrix} \Delta T,$$

x, y Vehicle position components
θ Vehicle heading
v_t Forward velocity
v_θ Rotational velocity

Here, the planners are attempting to compute minimum distance paths. Similar results are obtained when using other metrics, as well.

Preliminaries

Comparison of SBMPO with RRT* (Typical Result)



	SBMPO	RRT*
Distance (m)	7.39	8.28
Comp. Time (ms)	1.9	50.0

- Similar trajectories are determined, but SBMPO performs the calculation more than one order of magnitude faster.
- In complicated planning scenarios, this discrepancy in computation time prohibits the use of RRT* and similar approaches.
- As shown in this simple comparison, the use of a heuristic (in SBMPO) facilitates rapid computation.

Preliminaries

Development of an Appropriate Minimum Time Heuristic

Considering the equation describing the motion of a particle given by

$$r = v_i t + \frac{1}{2} a_i t^2,$$

where r is the distance to the goal, v_i is the current velocity, and a_i is the current acceleration. Based on this relationship, the predicted minimum time to reach the goal would be expressed by

$$t = \frac{-v_i \pm \sqrt{v_i^2 - 2a_i r}}{a_i}$$

➡ **Optimistic, but overly-conservative (i.e., naïve).**

Preliminaries

Development of an Appropriate Minimum Time Heuristic

Instead, assuming the controlled acceleration is bound by

$$-\underline{a} \leq a \leq \bar{a}$$

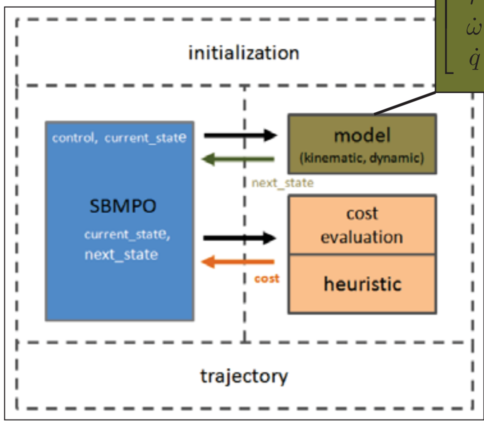
The solution of the minimum time control problem (i.e., Pontryagin's Maximum Principle) can be generalized to yield

$$t^2 - \frac{2v_i}{\underline{a}} t = \frac{v_i^2 + 2(\underline{a} + \bar{a})r}{\underline{a}\bar{a}}, \text{ if } r + \frac{v_i|v_i|}{2\bar{a}} < 0$$

$$t^2 + \frac{2v_i}{\bar{a}} t = \frac{v_i^2 - 2(\underline{a} + \bar{a})r}{\underline{a}\bar{a}}, \text{ if } r + \frac{v_i|v_i|}{2\underline{a}} > 0$$

Preliminaries

SBMPO Architecture and Six-DOF Relative Motion Model



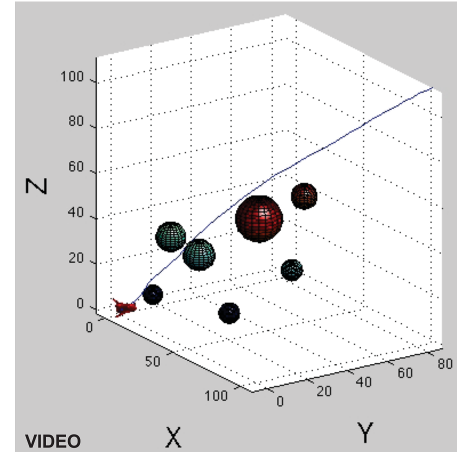
$$\begin{bmatrix} \dot{v} \\ \dot{r} \\ \dot{\omega} \\ \dot{q} \end{bmatrix} = \begin{bmatrix} \tilde{0} \\ \dot{v} \\ -J^{-1}\omega \times J\omega \\ \frac{1}{2}\Omega(\omega)q \end{bmatrix} + \begin{bmatrix} \frac{1}{m}\Theta^T(q)u(t) \\ \tilde{0} \\ J^{-1}\tau(t) \\ \tilde{0} \end{bmatrix}$$

r	Position vector, m
v	Velocity vector, m/s
ω	Angular velocity vector, deg/s
q	Rotation quaternion vector
Θ	Rotation matrix
Ω	Kinematic quaternion matrix
m	Mass, kg
J	Inertia matrix
u	Thrust control input vector
τ	Torque control input vector

Results

3D Trajectory Generation in Cluttered Space

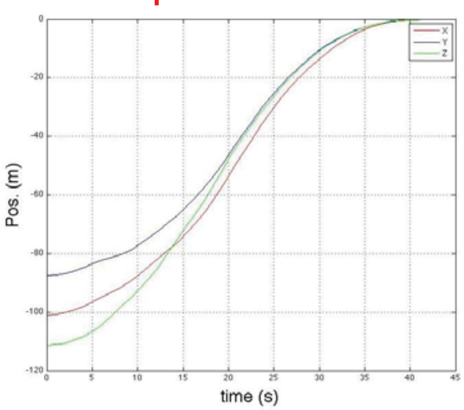
- Spacecraft is disoriented and trailing the target. Several nearby obstacles are detected.
- SBMPO sampled thrusters and rotation wheels aligned to the body axes (6 inputs).
- Maneuver time is optimized (similar result obtained minimizing distance).
- Zero relative velocity at the goal is enforced.
- Route to target is computed in less than one second.



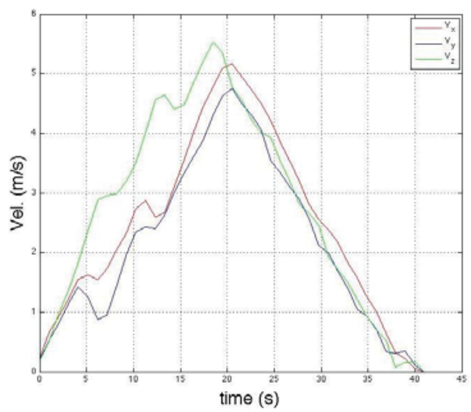
- Other approaches compute similar trajectories in 25+ seconds.

Results

3D Trajectory Generation in Cluttered Space



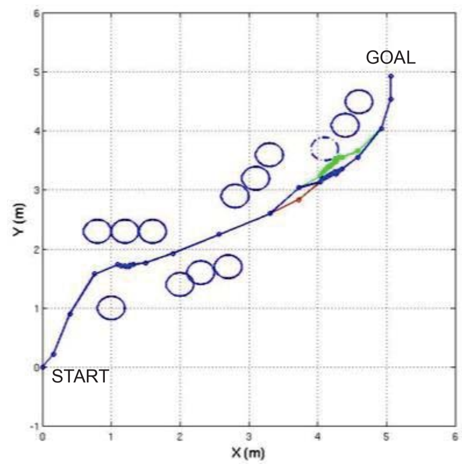
- Time is optimized (similar result obtained minimizing distance).



- Zero relative velocity at the goal is enforced.

Results

Efficient Replanning via Lifelong Planning A* (LPA*)



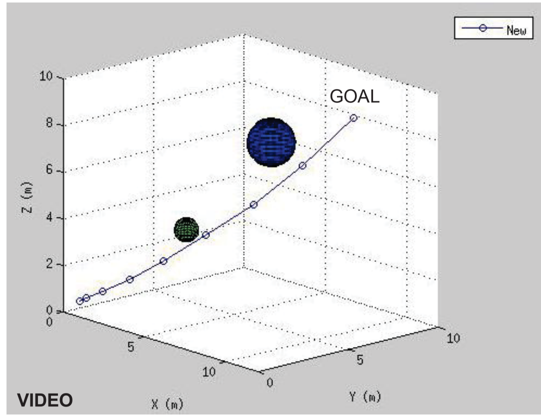
	Initial	Modified	
	SBMPO	w/ LPA*	SBMPO
Distance (m)	7.33	7.34	7.33
Comp. Time (ms)	887	13.6	653

A* algorithm as a substitute for traditional A*, the planner is able to utilize past trajectory data.
  - In terms of computation time, LPA* is much more effective when obstacle motion is likely.
- By enabling rapid replanning, LPA* essentially paves the way for an incremental version of SBMPO.
  - Crucial step for hardware implementation.

Results

3D Replanning in a Non-deterministic Environment

- Obstacle field changes as vehicle progresses to the goal.
- Route to target is replanned when changes in obstacle characteristics are detected.
- By using previous graph information and managing graph connectivity, minimal nodes are added.

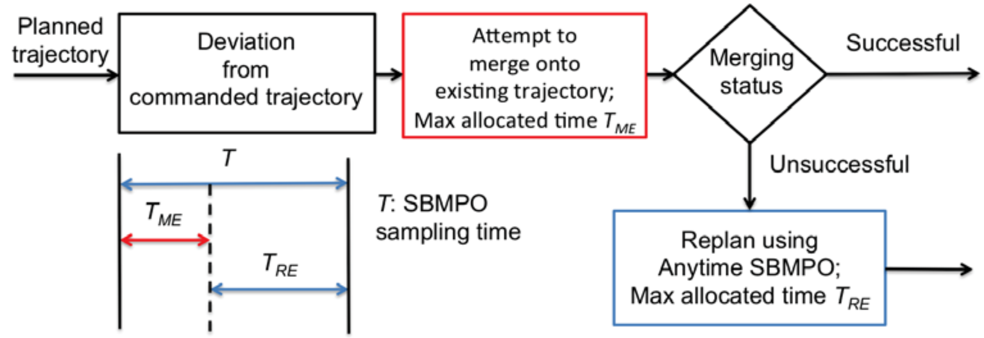


	Computation Time (ms)
w/ Replanning	44.1
w/o Replanning	531.3

Results

Trajectory Merging and Error Correction (via Anytime Planning)

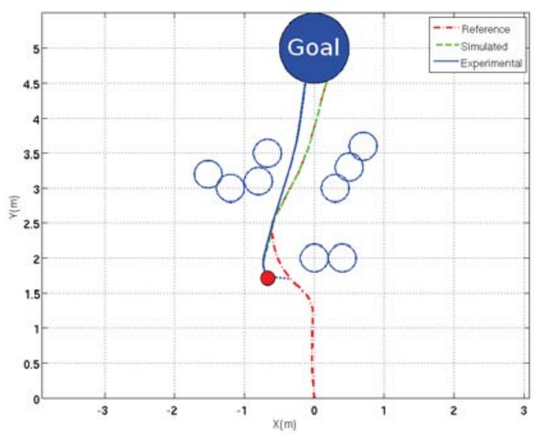
- Mitigate effects of trajectory drift via efficient course correction.
- Resample inputs in attempt to quickly merge back onto solution trajectory.



Results

Trajectory Merging and Error Correction (via Anytime Planning)

- When the vehicle is observed to have deviated from the original trajectory, this method computes a merging solution over a fixed time horizon.
  - The max. time for merging is computed such that replanning may occur within the SBMPO sampling time interval if merging fails.
- As a result, this approach is very effective when merging is more efficient than replanning.



Results

Publications

G. Francis, E. Collins, O. Chuy, and A. Sharma, "Sampling-Based Trajectory Generation for Autonomous Spacecraft Rendezvous and Docking," in *Proceedings of the AIAA Guidance, Navigation, and Control Conference*, Boston, MA, August 19-22, 2013.

A. Sharma, C. Ordonez, and E. Collins, "Robust Sampling-Based Trajectory Tracking for Autonomous Vehicles," 2014 IEEE International Conference on Systems, Man, and Cybernetics, San Diego, CA, Oct 5 – 8, 2014.

G. Francis, E. Collins, O. Chuy, and A. Sharma, "Rapid Trajectory Generation for Autonomous Spacecraft in Stochastic Environments" (in preparation), for submission to *Journal of Guidance, Control, and Dynamics*.

Conclusions and Future Work

Summary:

- Orbital debris poses an immediate and ongoing threat to our various space endeavors.
- The demonstrated research provides an efficient approach to navigation for autonomous space vehicles.
- This research paves the way for commercially-viable autonomous debris mitigation.

Upcoming:

- Synergize iterative and anytime planning paradigms to improve algorithm efficiency in dynamic environments.
- Extend trajectory merging approach to 3D scenarios.
- Implement additional planning constraints that may be encountered in a realistic application.

Task 329. Tracking and Monitoring Suborbital Commercial Space Vehicles

Dr. William H. Ryan

Research Faculty, 2.4-meter Telescope

(NM Tech/Magdalena Ridge Observatory)

Project Overview

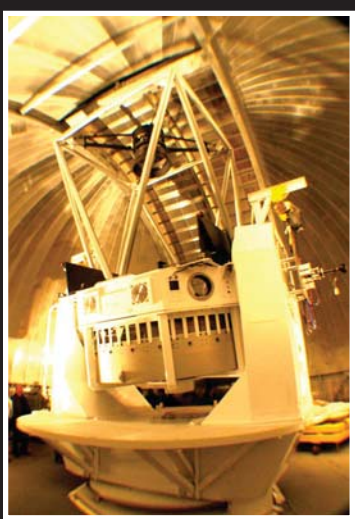
Ultimately: develop an asset ~100 km northwest of Spaceport America in New Mexico that can be utilized to **assess spacecraft health**, assist in **anomaly resolution**, and provide data for **mishap investigation** for Commercial Space Vehicle launches

Pilot Project: Develop the required tracking capabilities for this asset

The **Magdalena Ridge Observatory 2.4-meter telescope facility** (operated by the New Mexico Institute of Mining and Technology) will be used for this task. The observatory researchers have extensive experience tracking fast-moving natural and manmade objects in orbit, and this pilot project will allow for the extension and enhancement of that capability such that the launch of terrestrial objects can also be monitored.

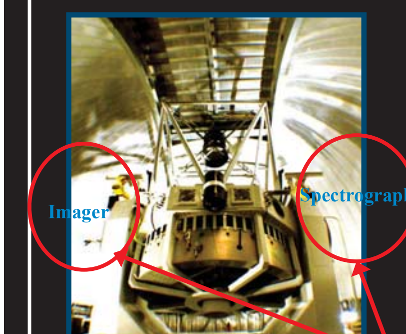
PI: Dr. Eileen Ryan — Director, MRO 2.4-meter Telescope
Co-I: Dr. William Ryan — Research Faculty, NM Tech R&ED
NM Tech Mech Eng Undergraduate

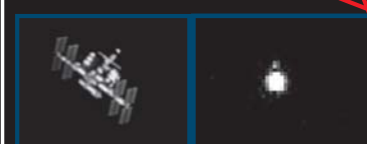
Magdalena Ridge Observatory 2.4m: Operational Sept 2008



- Near-Earth Objects: astrometric follow up and characterization
- DoD mission – SSA: sensor development and surveillance
- Supporting and enhancing NM education and outreach

Telescope Specifications

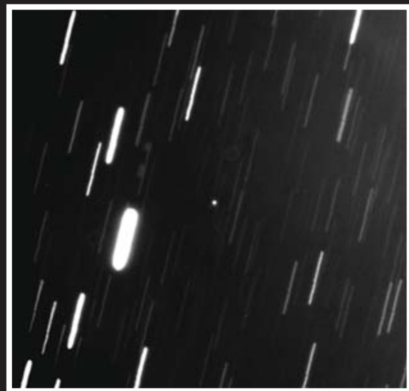




Images of the International Space Station (left) and resolved binary asteroid Kalliope/Linus (right) taken with the 2.4m telescope.

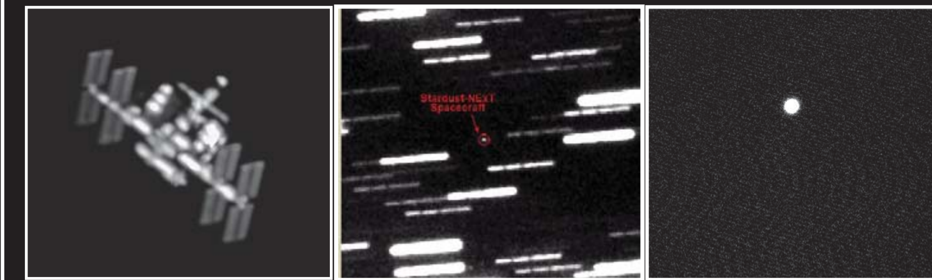
- Blind pointing is within 3 to 4 arcseconds
- Slewing and tracking rate is 10°/sec
- Acceleration is 3 degrees per sec^2
- Settling time is 5 sec after full sky slew
- Open loop tracking: at astronomical rates, 0.5 arcsec deviation over 5 minutes (over most gimbal angles)
- Ability to point 2 degrees below horizontal, retaining arcsec seeing at low elevations
- Can mount multiple instruments simultaneously

Near Earth Asteroid Tracking Precision



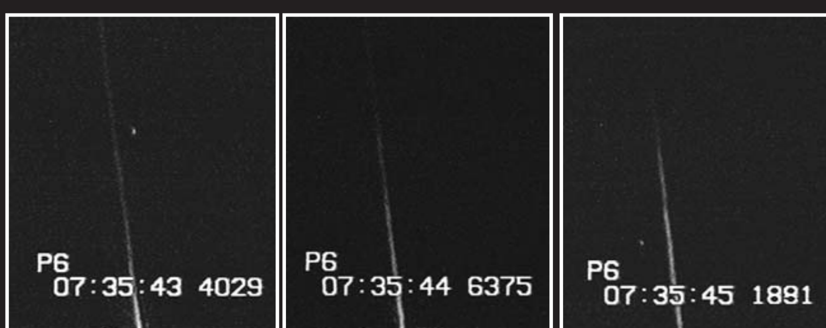
Tracking asteroid 2007 FK1 with the 2.4m Telescope on May 14, 2007.

Artificial Target Tracking



A single, resolved image (left) of the International Space Station (ISS) taken with the 2.4-meter telescope on December 14, 2010. An unresolved image (middle) of Stardust-NExT spacecraft during Earth gravity assist flyby taken on Jan 3, 2009, and a tracked image (right) taken with the 2.4-meter telescope of newly generated space debris: the tool-bag lost by a shuttle astronaut while servicing the ISS on November 19, 2008.

Upper Atmospheric Research: Tracking a NASA Sub-Orbital Rocket



GPS open-loop tracked time sequence covering a 3 second period during launch for a NASA Black Brandt rocket imaged by the MRO 2.4-meter telescope in 2014. The sub-orbital rocket was launched at White Sands Missile Range and the second-stage burn is visible in the center of the image sequence. Other artifacts in the images are background stars.

Pilot Project

Current tracking capability based on offsets being performed to a predefined telescope track. Terrestrial target motions are governed by less predictable variables, hence relying on a predetermined track is less desirable.

- Develop software to perform fully autonomous, closed-loop tracking using both acquisition telescope (AT) and 2.4-meter imager data (NM Tech Mech. Eng. Senior)
- Analyze test tracking data, identify limitations, then improve (8 half-nights of observing time)

Test Targets

A stratospheric balloon prepares for take off at Fort Sumner, N.M.

NASA launches a series of very large stratospheric balloons from Fort Sumner, NM each year. Fort Sumner is approximately 275 kilometers due east-northeast of the MRO facility and the stratospheric balloons would provide good test targets for the new tracking.

- 100 km/hr @275 km ~ ½ deg/min
- ½ deg(AT FOV)@275 km ~ 2.4 km
- 4.5 arc-min(2.4m FOV)@275 km ~ 400 meters
- candle@275 km V~16

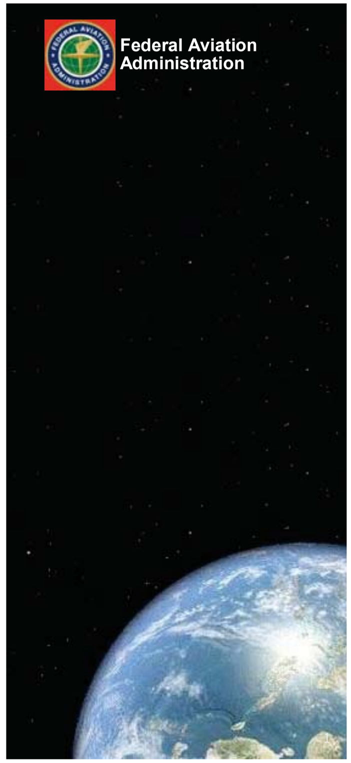
Milestones in 2016

- Software algorithms for autonomous closed-loop tracking of fast-moving terrestrial targets.
- Collected observations of suborbital balloon launches or other test targets (over an 8-half night time period).
- Data reduction and analysis with associated performance assessment. New strategies for tracking will be implemented if the first trial efforts need significant improvement.
- Dissemination of results & required outcome reporting.

Optimal Aircraft Rerouting During Commercial Space Launches

Rachael Tompa
Mykel Kochenderfer
Stanford University

Oct 28, 2015



Motivation

Problem:

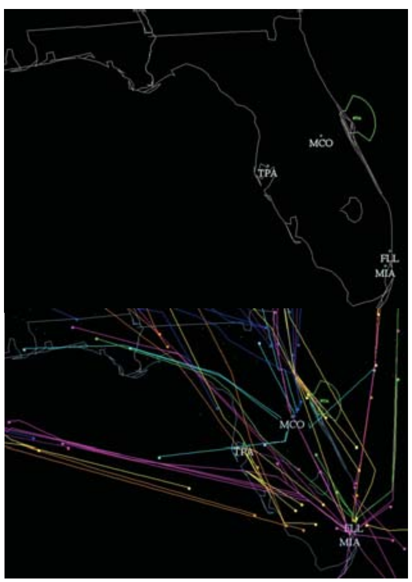
- Launch vehicle anomaly can lead to 10,000+ pieces of debris
- Projected increase in commercial space launches

Current process: FAA shuts down large column of airspace

- Airspace shut for hours causing many aircraft reroutes

Research area: FAA is investigating methods to reduce airspace disruptions while maintaining airspace safety

Motivation Continued



Dynamic restrictions would:

- Allow safety zones to change throughout launch trajectory and launch vehicle health
- Account for uncertainties
- Adapt to any anomalies
- Promote efficiency
- Ensure safety

Proposed solution:

Model problem as a Markov Decision Process and solve for optimal policy

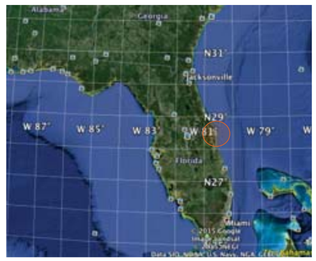
Outline

- ➢Commercial Space Launch Scenario
- ➢Problem Formulation
- ➢Results
- ➢Conclusions

Scenario

Launch Environment
- Cape Canaveral
- October

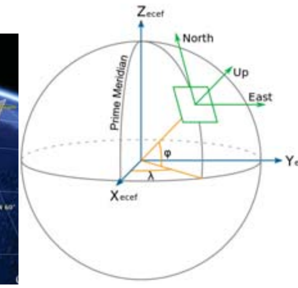
Aircraft: Boeing 777 – 200
- Cruise Speed at 35,000 ft (10.7 km): 0.84 Mach
- Turn Rate: standard rate (3° per second) and half standard rate (1.5° per second)



Launch Vehicle

Vehicle: Two-stage-to-orbit rocket

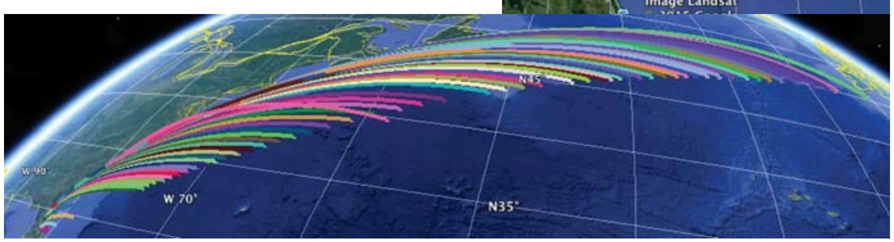
Trajectory:
- Derived longitude latitude altitude position
- Modeled as a 2D trajectory using east and north coordinates of the east north up reference frame



Debris Model

Look at 11 types of debris
- Ballistic coefficient, size, weight

Update trajectory at every time step
- Launch vehicle state vector as the initial state
- Trajectory found with RSAT



RSAT Weather Inputs

Model: Global Forecast System

Location: Kennedy Space Center

Range: 1 to 25 km

Inputs at each Height:
- Latitude and longitude position of measurement
- Mean density
- Density standard deviation
- Wind velocity in up, west, and south directions
- Wind velocity standard deviations

For initial implementation, all inputs are the average of a month's worth of data

Safety Thresholds

Where

Location debris trajectory intersects 35,000 feet

Ellipse around location

- Minor axis = 500 feet
- Major axis = 1000 feet in direction of launch vehicle at time of anomaly

When

Time debris trajectory intersects 35,000 feet ± 20 sec

Anomaly is modeled for that time step ± 10 sec

Outline

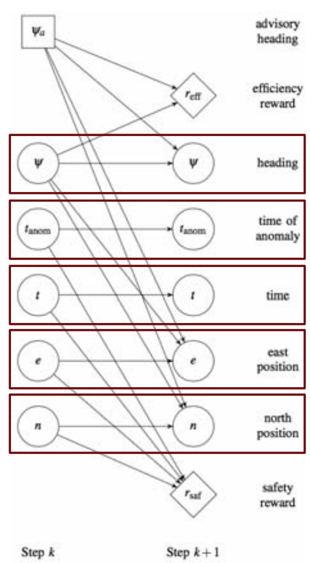
- ➢Commercial Space Launch Scenario
- ➢Problem Formulation
- ➢Results
- ➢Conclusions

Markov Decision Process Overview

S is the **state space**: a set that contains all possible states

A state s ∈ S captures:

- Aircraft position
- Aircraft heading
- Time of anomaly
- Time since launch

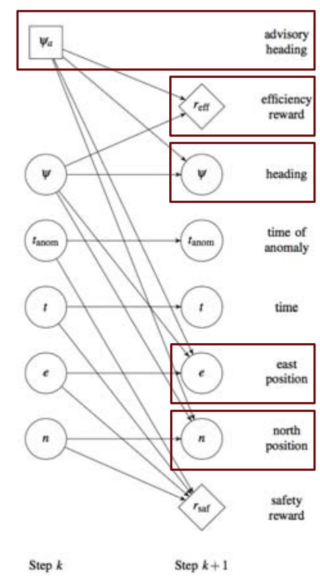


Markov Decision Process Overview

A is the **action space**: a set that contains all possible actions

An action a ∈ A corresponds to:

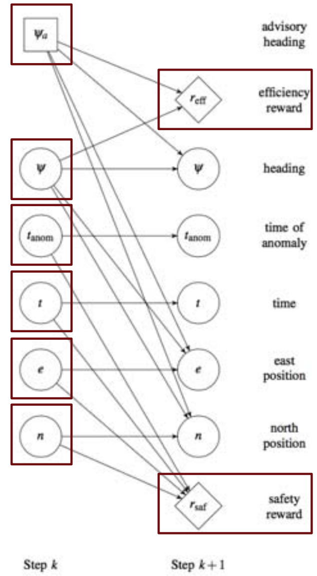
- heading change advisory



Markov Decision Process Overview

R is the **reward model**:

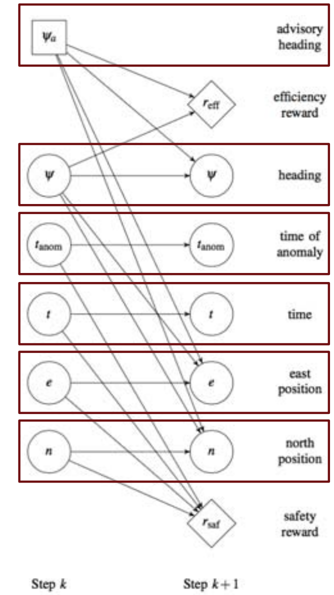
- Current state, s
- Action, a
- Immediate reward: R(s, a)
- Reward penalizes disruption and violations of safety thresholds



Markov Decision Process Overview

T is the **transition model**

- Current state, s
- Action, a
- New state, s′
- Probability of transitioning to s′: T(s′ | s, a)
- Captures uncertainty in the launch vehicle and aircraft trajectories



Aircraft State Space

Variable	Discretization	Units
e	$-25{,}000, -23{,}000, \ldots, 51{,}000$	meters
n	$-45{,}000, -43{,}000, \ldots, 65{,}000$	meters
ψ	$0, 15, \ldots, 360$	degrees
t_{anom}	NIL, $0, 10, \ldots, 110$	seconds
t	$0, 10, \ldots, 810$	seconds

Grid: State space modeled as a 5 dimensional grid with all possible combinations of the components

- 58,203,600 possible states

Action Space

Possible Actions

- 15° heading changes (for 10 second intervals) from 0° to 360°
- An additional aircraft action, NIL

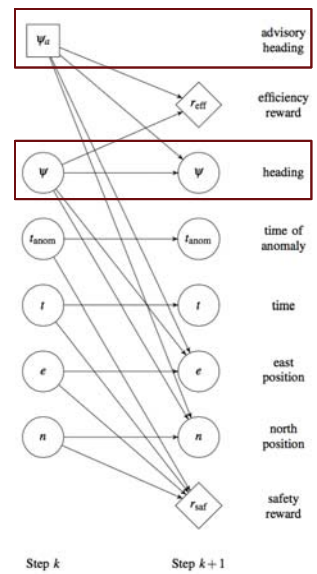
NIL (No Advisory)

- If there is no advisory, the aircraft follows a normal distribution
- This representation accounts for future aircraft trajectory uncertainty

Transition Model

Heading Update

- If NIL, there is a normal distribution of possible headings
- If advised heading is current heading, pilot always responds
- If advised heading is new heading, pilot responds 50% of the time (average response delay = 20 sec)



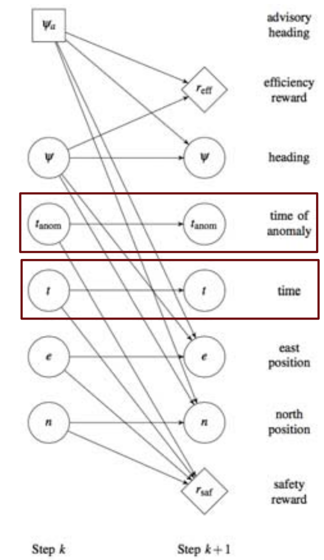
Transition Model

Time of Anomaly Update

- If an anomaly has already occurred, t_{anom} does not change
- If an anomaly has not occurred, 5.2% of the time, an anomaly occurs at the next time step
- The anomaly rate is equivalent to 50% over the duration of the first stage

Time Update

- Time increments by 10 sec



Transition Model

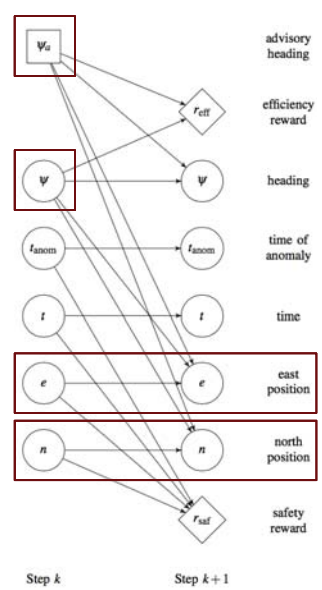
Position Updates

$$\begin{bmatrix} e \\ n \end{bmatrix} \leftarrow \begin{bmatrix} e + v\sin(\psi) \\ n + v\cos(\psi) \end{bmatrix}$$

- v = 0.84 Mach

Comments

- Values are interpolated if not exactly on a grid node
- MDP terminates at 810 sec



Reward Model

Reward = $\lambda\, r_{eff} + r_{saf}$

Efficiency	
ψ = NIL	0
No Change	−0.01
ψ Change $\leq 30°$	−1
ψ Change $> 30°$	$-\infty$
Safety	
$\leq$ Threshold from Launch Vehicle	−1
$>$ Threshold from Launch Vehicle	0
$\leq$ Threshold from Debris	−1
$>$ Threshold from Debris	0

Solution

Returns:

- Policy: action for every possible state
- Optimal policy maximizes immediate rewards(utility):

Method: E $$U^*(s) = \max_{a \in A} \left[R(s,a) + \sum_{s' \in S} T(s' \mid s,a) U^*(s') \right]$$

- Cycles over all of the possible states and actions
  - Backward induction allows a single sweep through all of the states

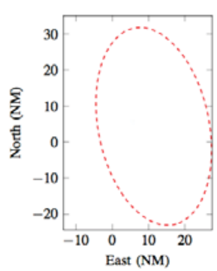
Computing an optimal policy required ten minutes on 20 Intel Xeon E5-2650 cores running at 2.4 GHz

Outline

- ➢Commercial Space Launch Scenario
- ➢Problem Formulation
- ➢Results
- ➢Conclusions

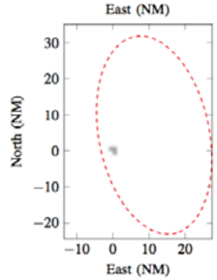
Utility Results

Aircraft headed 225°, Anomaly at 80 s after launch



0 s after launch:

- No anomaly knowledge
- Knowledge on debris trajectories
- Pilot response rate
- Launch vehicle traverses at 50 sec

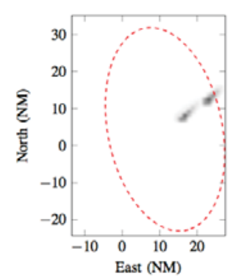


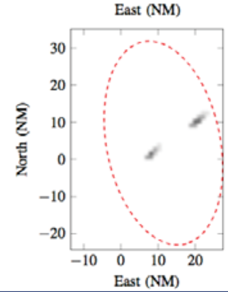
50 s after launch:

- Region with a negative utility where Launch vehicle traverses

Utility Results

Aircraft headed 225°, Anomaly at 80 s after launch



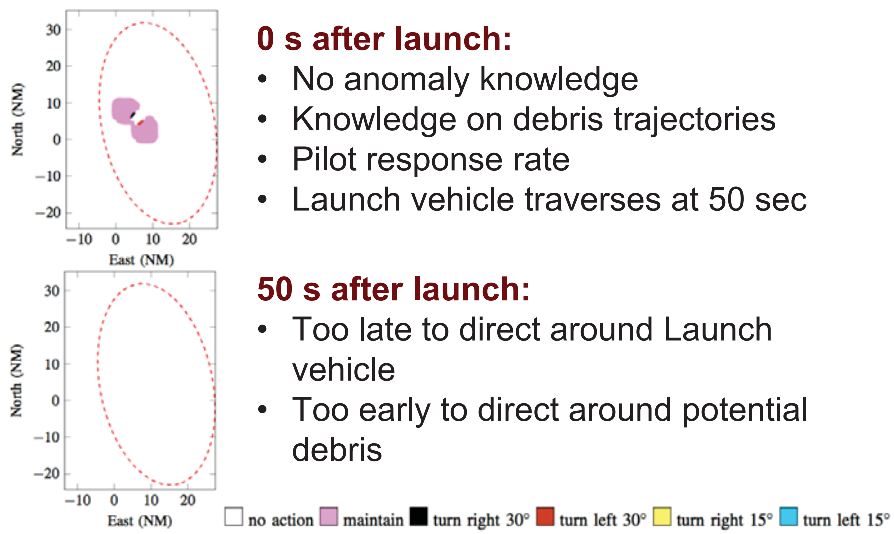


250 s after launch and 400 s after launch:

- Positions of the debris known
- Positions of debris or future debris have large negative utilities
- Negative utilities cover direction of the aircraft leading to those locations

Policy Results

Aircraft headed 225°, Anomaly at 80 s after launch

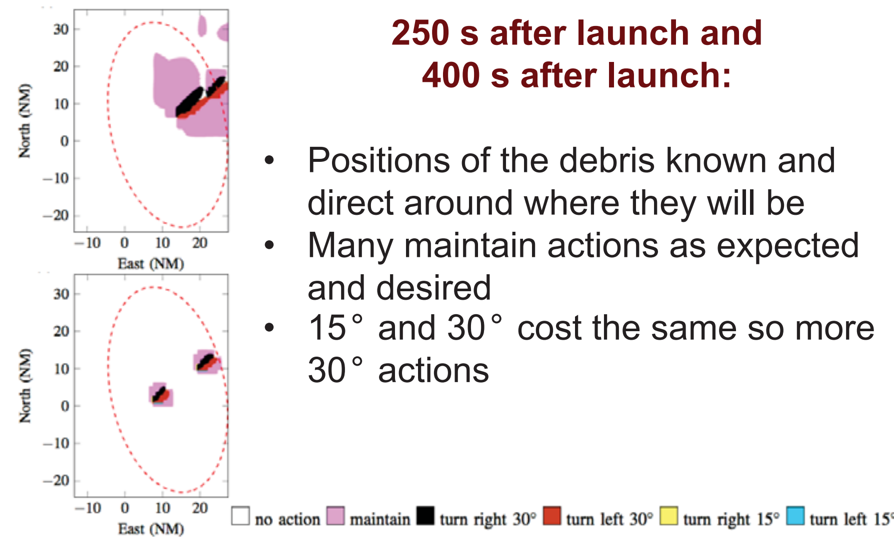


0 s after launch:
- No anomaly knowledge
- Knowledge on debris trajectories
- Pilot response rate
- Launch vehicle traverses at 50 sec

50 s after launch:
- Too late to direct around Launch vehicle
- Too early to direct around potential debris

Policy Results

Aircraft headed 225°, Anomaly at 80 s after launch

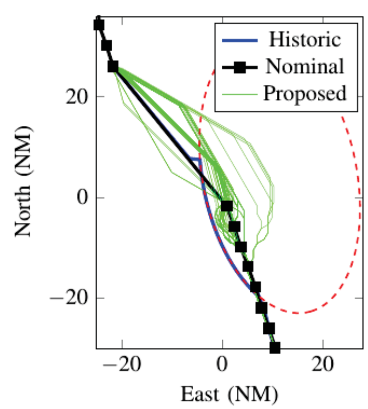


250 s after launch and 400 s after launch:

- Positions of the debris known and direct around where they will be
- Many maintain actions as expected and desired
- 15° and 30° cost the same so more 30° actions

Scenario Simulation Results

- Real Flights – Cape Canaveral
- Simplified temporary flight restriction representation
- 100 different start times
- Varying times of anomaly
- Results weighted based on likelihood

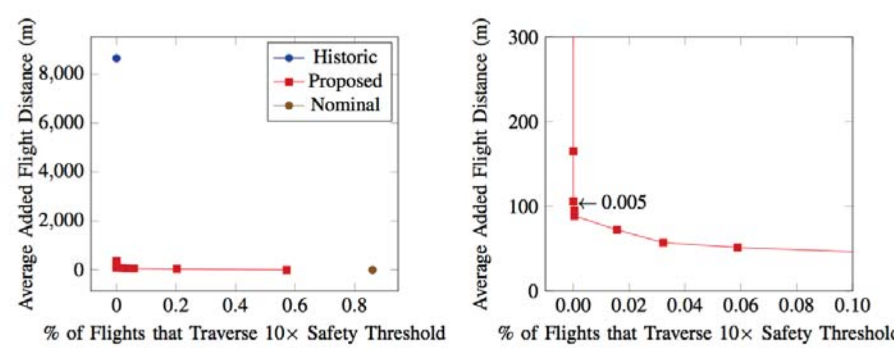


	Nominal	Historic	Proposed
% Rerouted	0.00	100.00	2.90
Average Added Distance (m)	0.00	8654.30	106.00
% Traverse 10× Safety Region	0.86	0.00	0.00

Efficiency Trade-Off Analysis

Reward = $\lambda\, r_{eff} + r_{saf}$

Investigation on the weighting of efficiency vs. safety



Conclusions

- Modeled commercial space launch and interactions with aircraft as MDP
- Dynamic safety regions much smaller than historic static regions
- Compared to historic safety regions, proposed safety regions result in fewer rerouted flights, smaller flight deviations during reroutes, and no degradation of safety
- Number of aircraft rerouted with proposed system is approximately 3% of the historically rerouted flights

Future Work

- Investigate additional metrics with the use of FACET
- Continue efficiency trade-off analysis
- Model additional debris trajectories
- Explore necessity of real time weather information

Thank you, Questions?

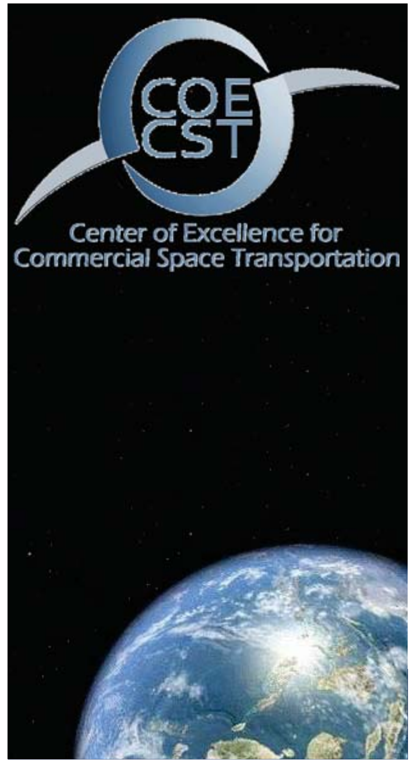
SISL
Stanford Intelligent
Systems Laboratory

COE CST Fifth Annual Technical Meeting

Task 228: Magneto-Elastic Sensing for Structural Health Monitoring (SHM)
Task 323: SHM Framework

Andrei Zagrai and Warren Ostergren

October 27-28, 2015
Arlington, VA



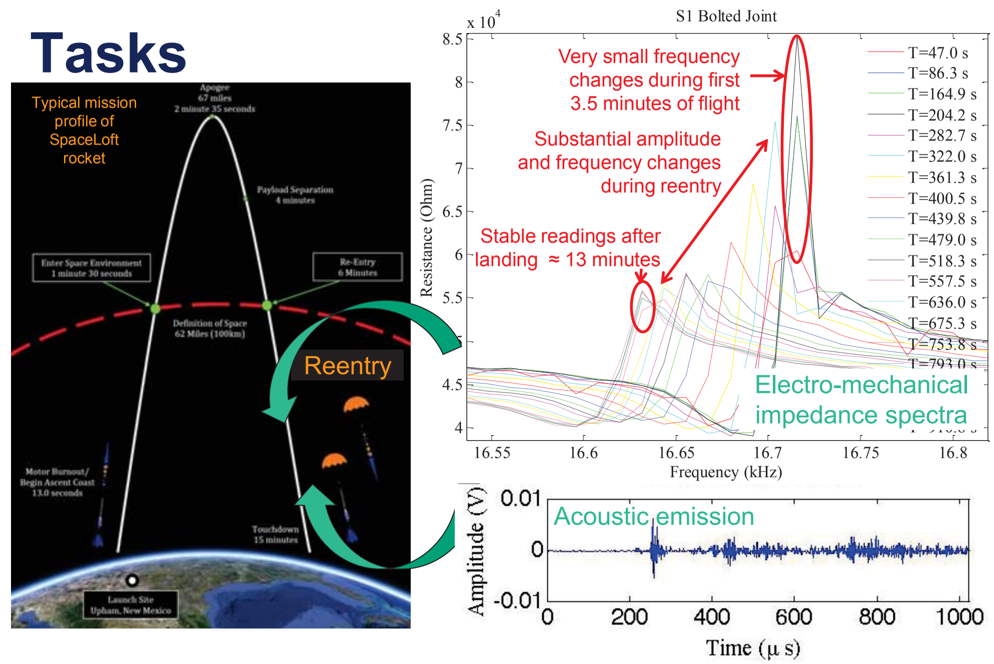
Team Members

- Andrei Zagrai & Warren Ostergren (PIs)
- Blaine Trujillo (GR ME)
- Mary Anderson (GR ME) - also supported by NMSGC
- 2 Undergraduate student design teams working on space payload
- Valerie Jenkins (lead), Daniel Archuleta, Daniel Wimberly, Dylan Purcell, Carl Peart, Tyler Marquis, Aaron Zucherman

Task Description

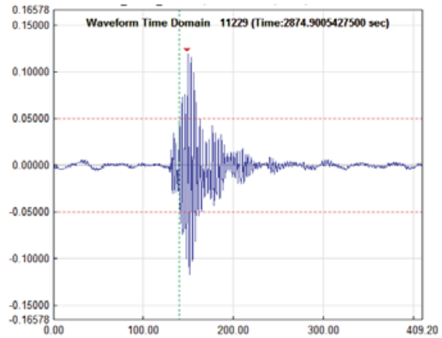
- The GOAL of the task is to make commercial spaceflight safer and less expensive
- OBJECTIVES of the task include:
  - Explore various Structural Health Monitoring (SHM) as safety enhancers and cost reducers for commercial space vehicles and demonstrate their utility during space flights.
  - Investigate acoustic emission due to thermal fatigue and thermal dependence of electro-mechanical impedance method.

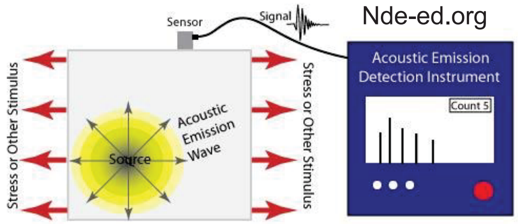
Tasks



Acoustic Emission Principles

- Acoustic emission (AE) is passive sensing technology that allows for monitoring acoustic activity in structural material
- AE acquisition hardware includes state-of-the-art Mistras Micro-II Digital AE System and a variety of conventional (Micro-80) or new (PWAS) acoustic

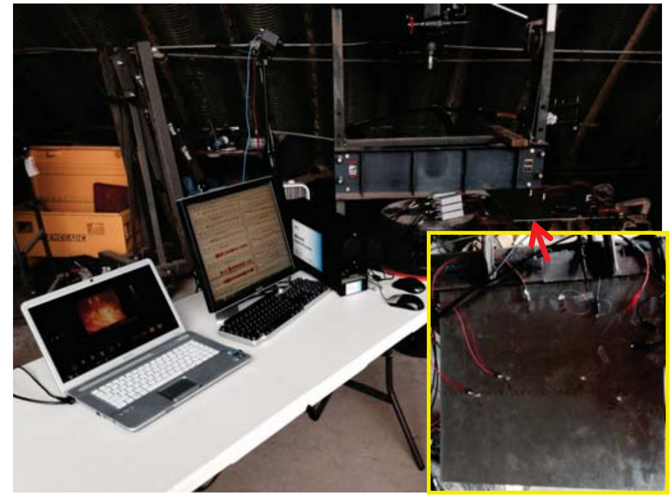




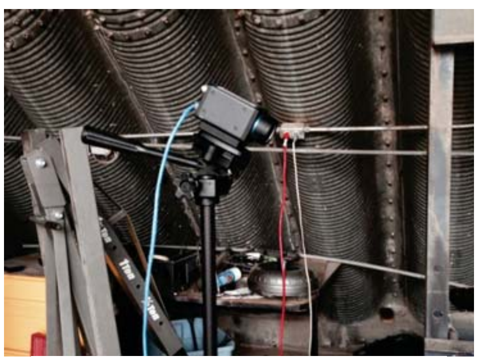
Nde-ed.org

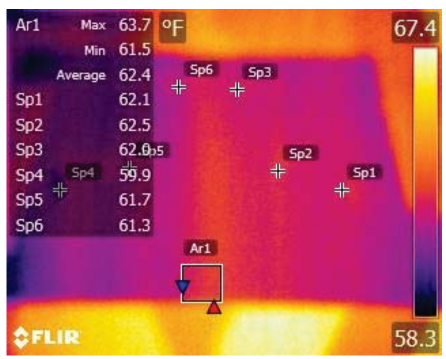
Thermal Fatigue Experimental Setup

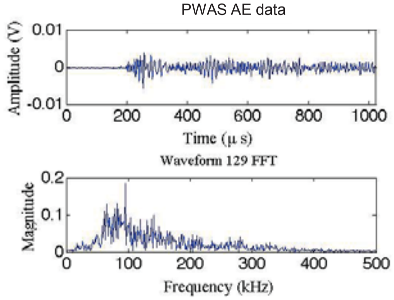
- Observe AE during thermal fatigue of 6061-T6 aluminum
- PWAS and Micro-80 sensors
- Infrared (IR) data
  - FLIR Ax5 series camera
- Heat Application
  - Butane torch

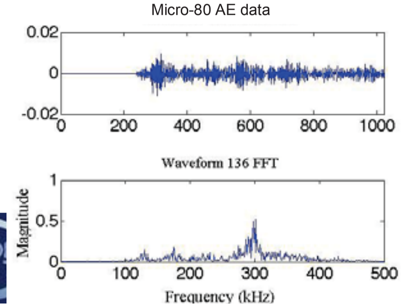


AE and Thermal Results

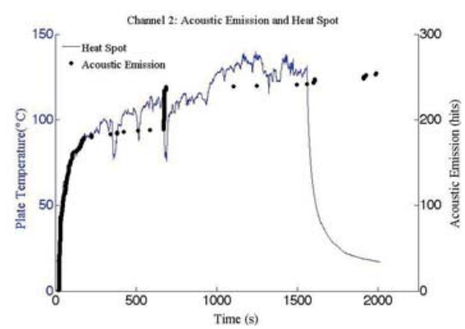




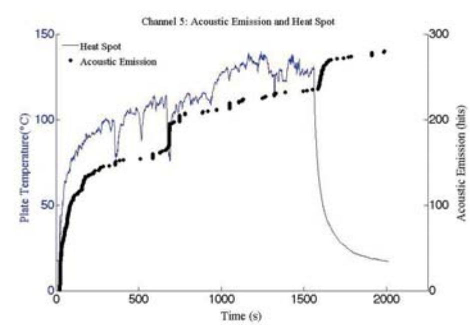




Test 1 Clamped-Clamped Plate

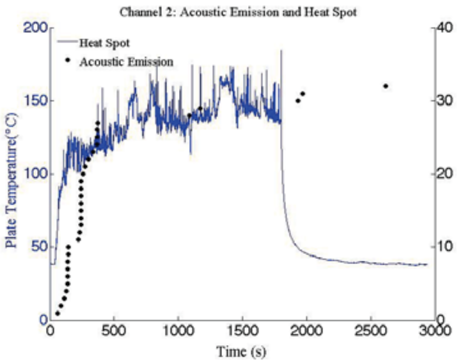


PWAS AE data

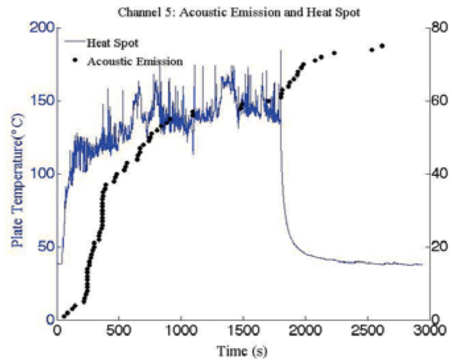


Micro-80 AE data

Test 2 Clamped-Free Plate

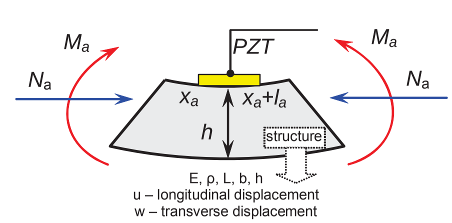


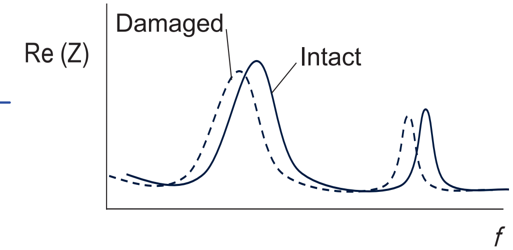
PWAS AE data



Micro-80 AE data

Electro-Mechanical Impedance



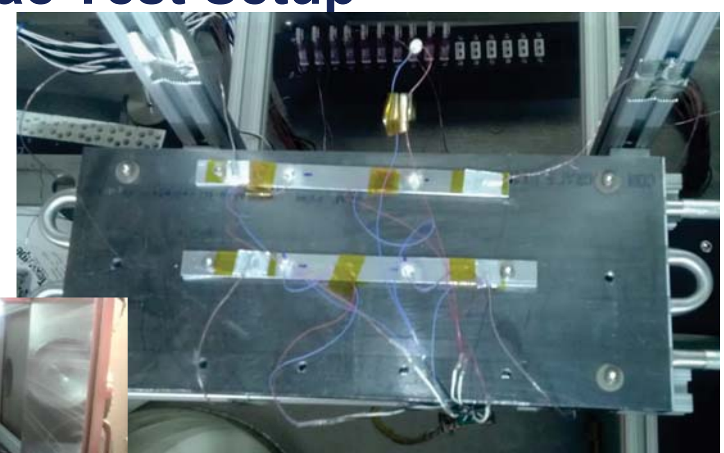


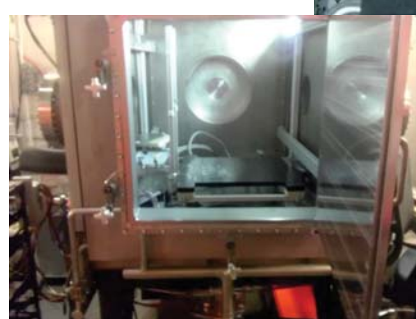
- Mechanical coupling between sensor and host structure (**Rigid Adhesive**)
- Internal coupling between piezoelectric electrical and mechanical properties (**Piezoelectric Effect**)
- Mechanical properties of host structure reflected in piezoelectric electrical properties (**Electromechanical Impedance**)
- Allows measurement of structure dynamics as an electrical quantity
- Enables high-frequency structural response characterization and SHM

Space Environment Emulation

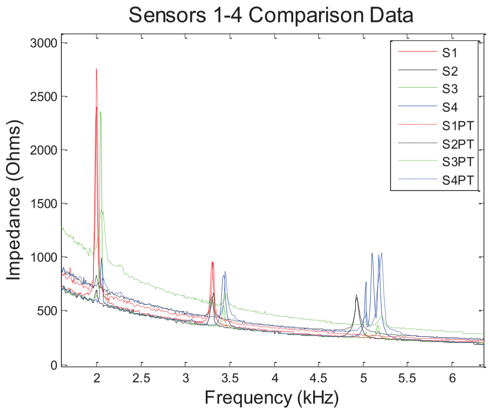
- How does the harsh environment of space affect a known method of structural health monitoring?
- Emulate space environment
  - Vacuum
  - Extreme temperatures
- Vacuum Thermal Chamber at AFRL
  - Chamber Pressure 2 x 10-6 Torr
  - FTS RC2111 Recirculating Chiller
  - Range -80ºC to +75ºC
- HP 4192A Impedance Analyzer (5 kHz to 13 MHz)

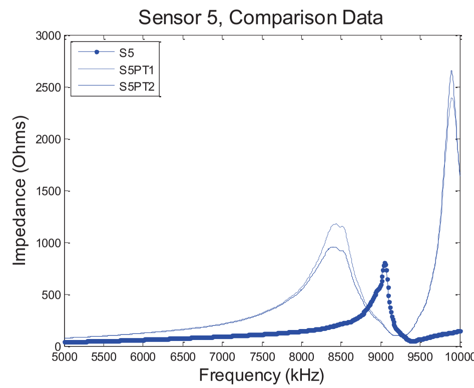
ThermalVac Test Setup





Baseline Data

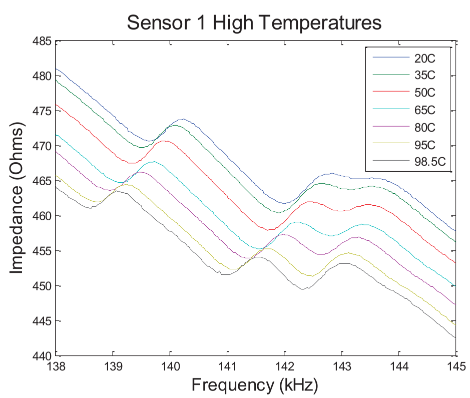


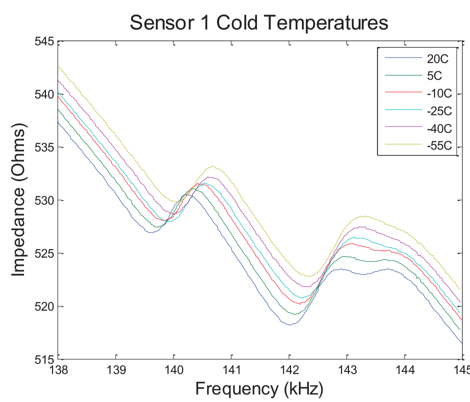


Thermal Vac Test

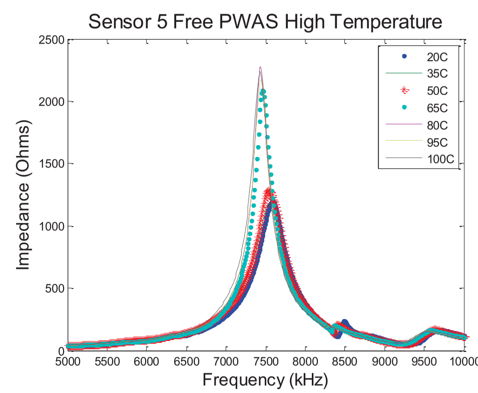
Temperature Increments for Thermal Experiment	
20 °C	20 °C
35 °C	5 °C
50 °C	-10 °C
65 °C	-25 °C
80 °C	-40 °C
95 °C	-55 °C
Maximum (TBD)	Minimum (TBD)
80 °C	-40 °C
50 °C	-10 °C
20 °C	20 °C

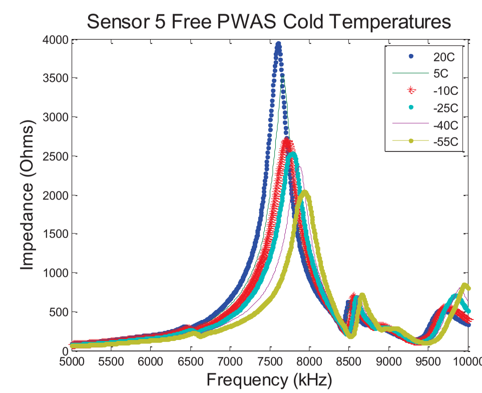
Thermal Vac Test





Thermal Vac Test

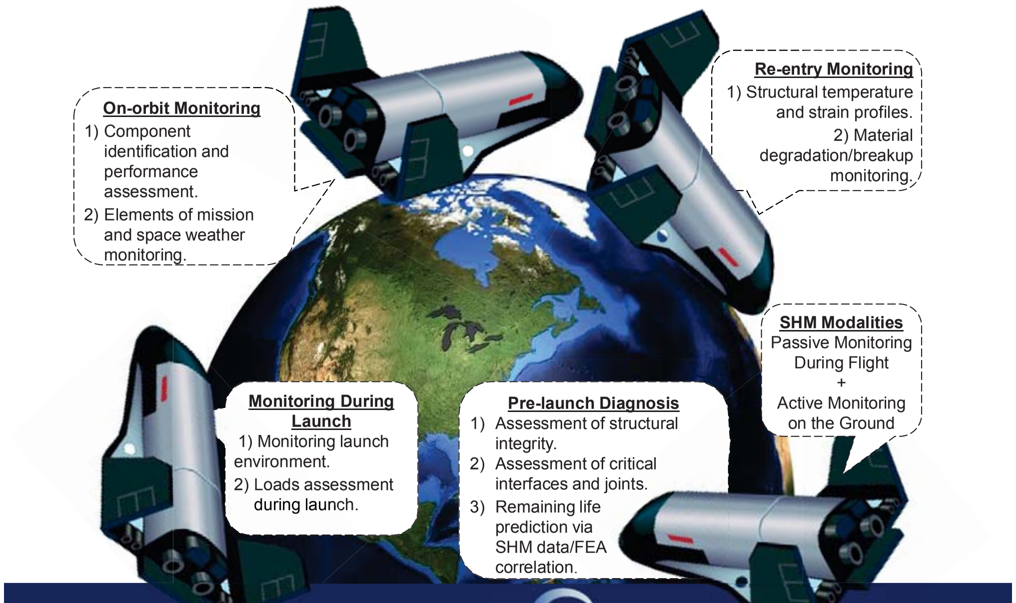




Conclusions and Future Work

- Exposure to cold causes impedance signature to move to higher frequencies, which is consistent with previous investigation in atmosphere. Anomaly at 65ºC has been observed and is currently under investigation
- Correlation between surface temperature and acoustic emission activity during thermal fatigue of Al 6061-T6 has been observed, which opens an opportunity for system disintegration monitoring during reentry.
- Task 323 Structural Health Monitoring Framework

SHM Framework



Task 323 SHM Framework

- Previous work demonstrated utility of SHM and its operation in suborbital flight environment.
- Task 323 focuses on SHM architecture and guidelines for integrating SHM with spaceflight recorder (aka "black box").
- Year 1: Investigate current approaches on sensor information integration in space vehicle. Identify criticality levels of information collected and its use in decision-making.
- Year 1: Prepare hardware for evaluation of space effects on structural condition and sensor system.

Publications/Presentations

- Zagrai, A.N., Demidovich, N., Cooper, B., Schlavin, J., White, C., Kessler S., MacGillivray, J., Chesebrough, S., Magnusion, L., Puckett, L., Tena, K., Gutierrez, J., Trujillo, B., Gonzales, T., (2015) "Structural Health Monitoring during Suborbital Space Flight," paper at 66th International Astronautical Congress, 14 October 2015, Jerusalem, Israel.
- Anderson, M., Zagrai, A., Doyle, D., Hengeveld, D., and R. Wilson,M.R. (2015) "Consideration of thermal effects in electro-mechanical impedance measurement for space structures", paper International Workshop on Structural Health Monitoring (IWSHM) at Stanford University, 3 September 2015, CA, USA
- Zagrai, A.N., Demidovich, N., Cooper, B., Schlavin, J., White, C., Kessler S., MacGillivray, J., Chesebrough, S., Magnusion, L., Puckett, L., Tena, K., Gutierrez, J., Trujillo, B., Gonzales, T., (2015) "Structural Condition Assessment during Suborbital Space Flight," presentation at Commercial and Government Responsive Access to Space Technology Exchange (CRASTE), 23 June 2015, Chantilly, VA, USA.
- Zagrai, A, Cooper, B., Schlavin, J., Clemens, R., White, C., Kessler, S., (2014) "Assessing structural condition during suborbital space flight," Technical presentation at ASME Conference on Smart Materials, Adaptive Structures and Intelligent Systems, September 9, 2014, Newport, RI, presentation: SMASIS2014-7726.

Acknowledgements

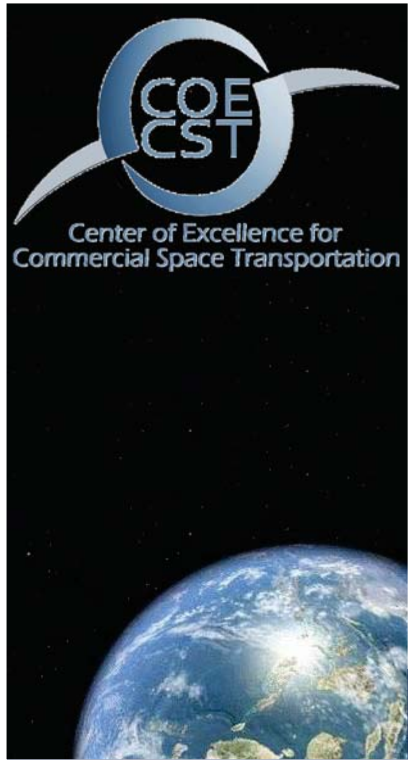
- Federal Aviation Administration (FAA) through Center of Excellence for Commercial Space Transportation, AFRL Space Vehicles Directorate, and NMT Department of Mechanical Engineering for assistance and support
- New Mexico Space Grant Consortium and Patricia C. Hynes
- AFRL: Derek Doyle, Derek Hengeveld, and Michael R. Wilson
- NMT: Graduate Student Association, Ian Lopez-Pulliam, William Valiant.

COE CST Fifth Annual Technical Meeting

TASK 241. High Temperature, Optical Sapphire Pressure Sensors for Hypersonic Vehicles

PI: William Oates
PhD Students: <u>Justin Collins</u>, Harman Singh Bal, Peter Woerner

October 27-28, 2015
Arlington, VA



Overview

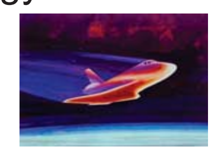
- Team Members
  - William Oates, Justin Collins, Harman Singh Bal, Peter Woerner (FSU)
  - Collaborators: Mark Sheplak & David Mills (UF)
- Motivation
- <u>High temperature experiments</u>
- Theory and modeling of laser machined sapphire
- Conclusions and future work
- Schedule

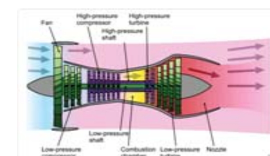
Team Members

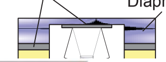
- Team Members
- PI: William Oates, PhD student: Justin Collins (FSU)
- Collaborators: Prof. Mark Sheplak & Post doc: Dr. David Mills (UF)
- Acknowledgements
  - FAA COE-CST
  - Space Florida Matching Funds

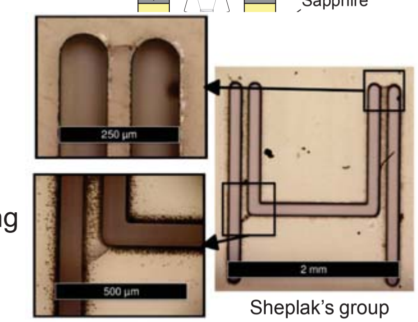
Motivation and Overview

- Lack of sensor technology in >1000°C environments
  - Hypersonic vehicles
  - Gas turbines
- Pressure sensor technologies
  - Capacitive, piezoresistive, optical
  - Optical: no EMI, high temperature capability, simple fabrication; <u>packaging/manufacturing challenges</u>
- Sapphire optical sensing
  - Laser ablation and spark plasma sintering
  - Impact on structural integrity?





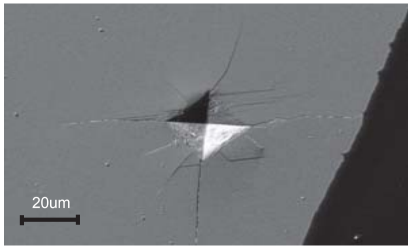


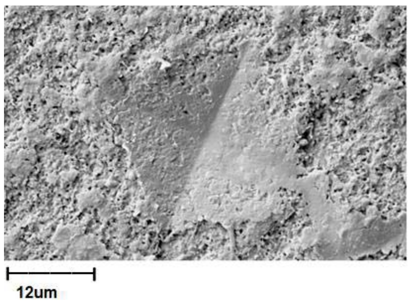


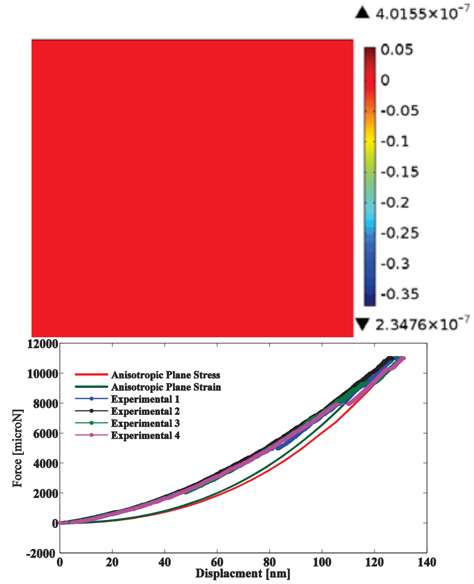
Sheplak's group

http://www.nasa.gov/centers/ames/research/2007/faq-shuttlereentry.html
http://en.wikipedia.org/wiki/File:Turbofan_operation.png

Nanomechanics of Sapphire

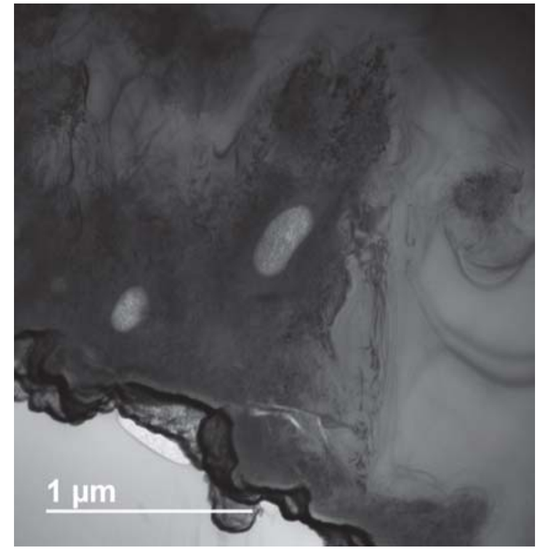






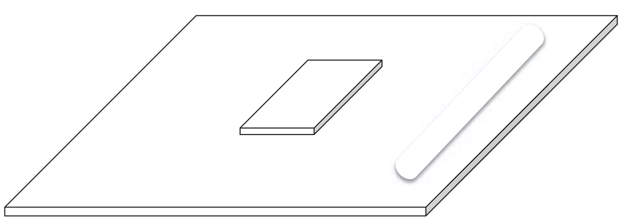
Nanoscale Laser Damage

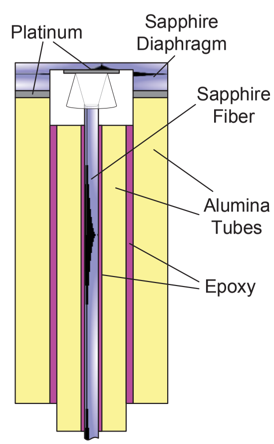
- Laser machining (UF—Sheplak's group)
  - 10 picosecond pulsed laser
  - Varying fluence and frequency rates
- Transmission electron microscopy (TEM)
  - National High Magnetic Field Laboratory
  - Presence of laser induced dislocations

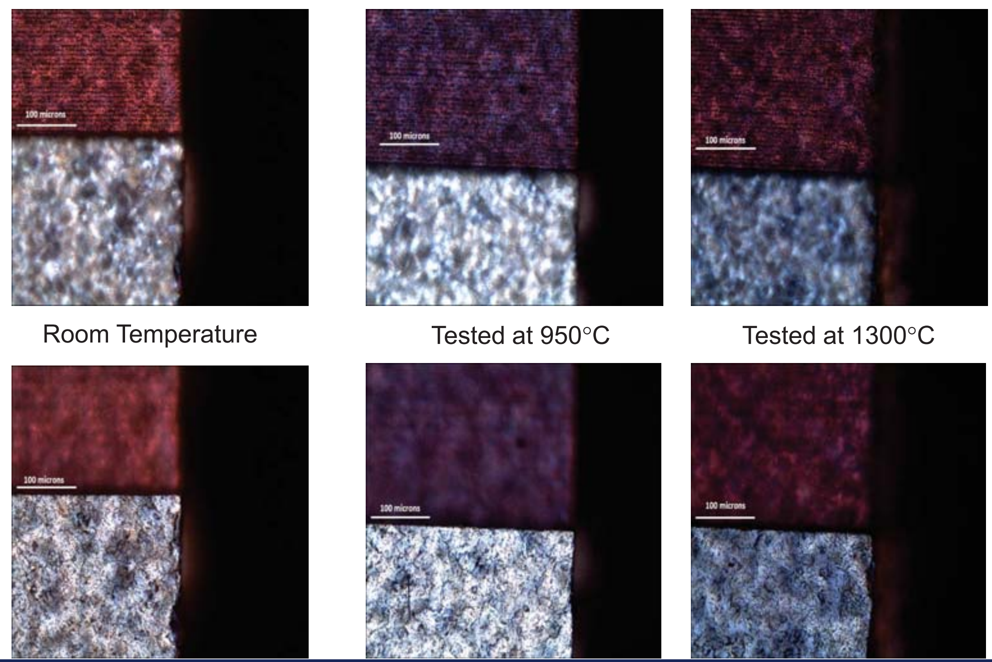


Strength Characterization

- Sensor reliability
  - Target: measure pressure up to 1000 psi @ 750-1600°C
- Thermomechanical flexural testing
  - 4-point bending
  - Laser machined sapphire (16×6×0.1mm³)
    - Milled center region—20 μm depth





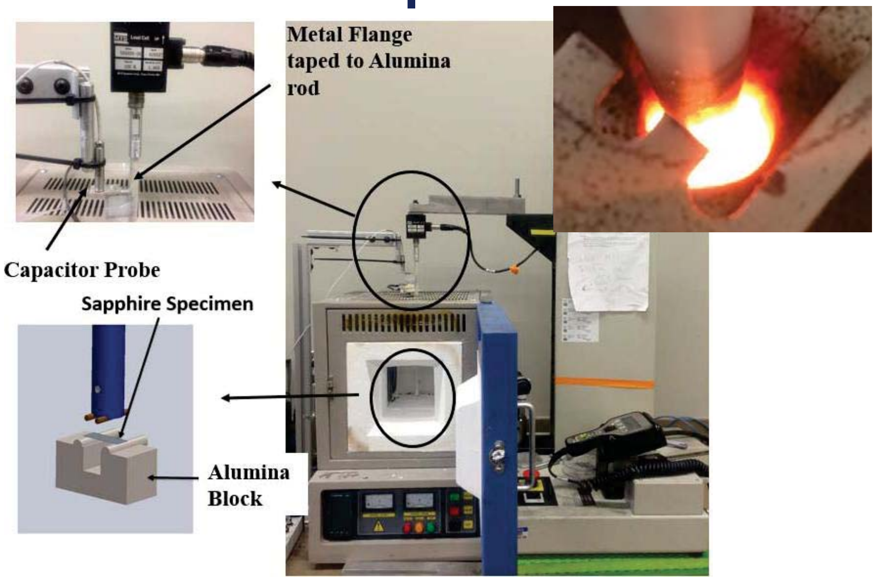


Room Temperature

Tested at 950°C

Tested at 1300°C

Experimental Set-up



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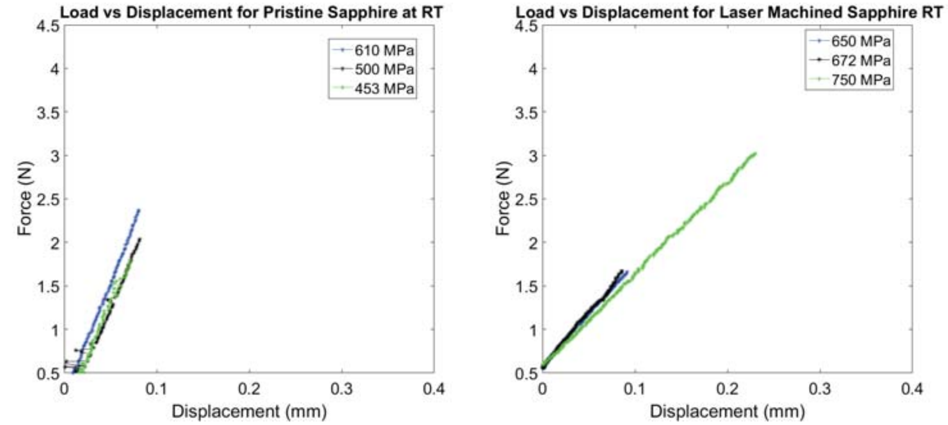
Experimental Results



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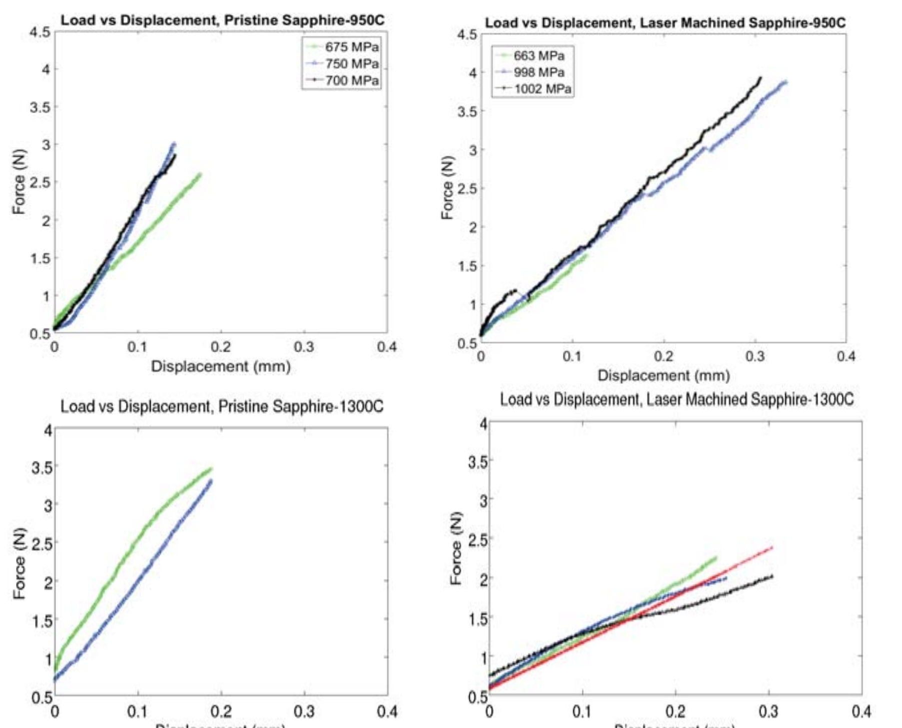
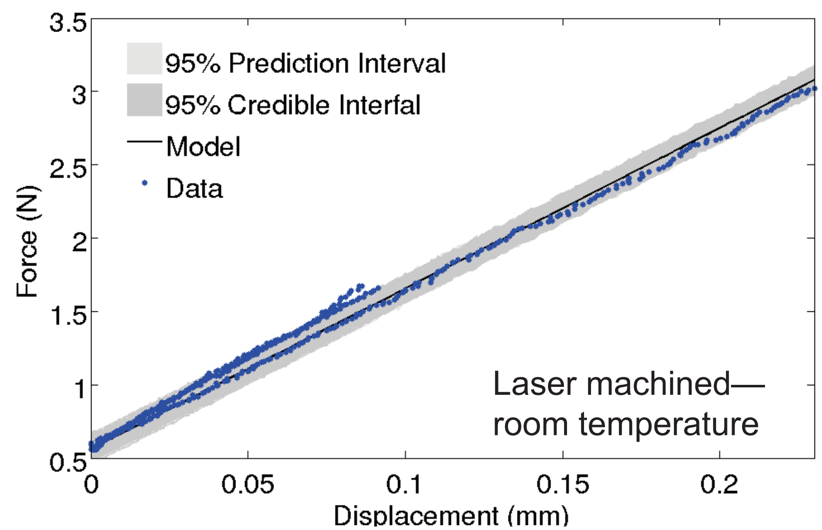


COE C... Octobe...

Bayesian Uncertainty Analysis



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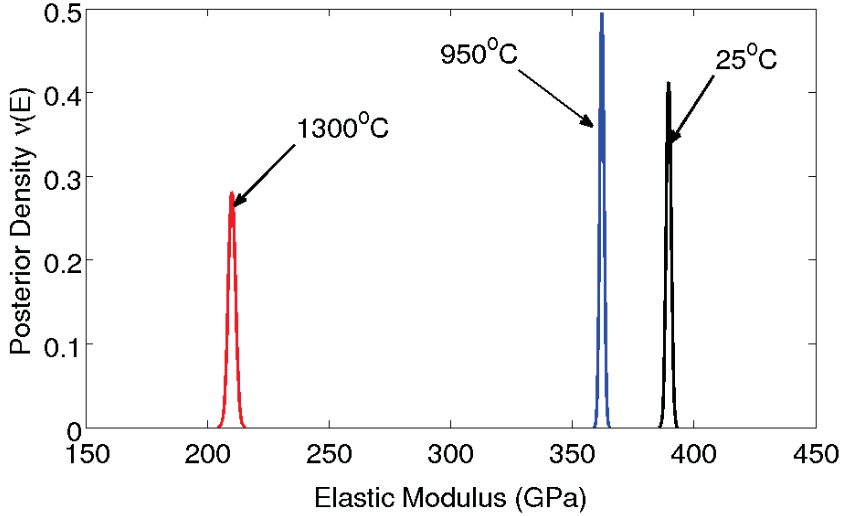
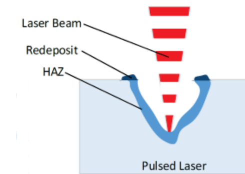
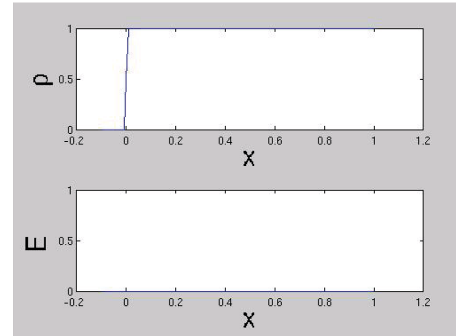
Uncertainty of Elastic Modulus

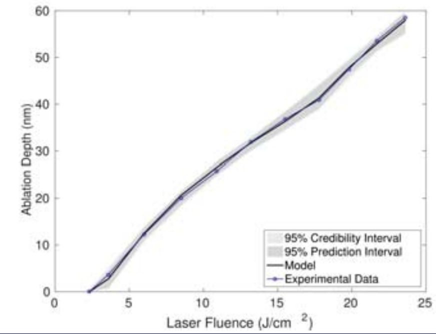


Overview of Laser Ablation

- Multiphysics model developed
- Validated using Bayesian statistics in light of data from the University of Florida
- Model couples electromagnetics of light with electronic structure evolution







Conclusions and Future Work

- Mechanical properties of laser machined sapphire quantified
  - Theory and experimental fracture analysis (prior research)
  - Laser and nanomechanical dislocation measurement and modeling (prior research)
  - Experimental high temperature strength characterization (current efforts)
  - Light-matter interactions and thermomechanical reliability predictions (current efforts)
- Next Steps
  - Dissemination of results
  - Rigorously understand laser machined surface properties
  - System integration and hot jet testing

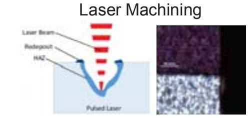
TASK 241. High Temperature, Optical Sapphire Pressure Sensors for Hypersonic Vehicles

PROJECT AT-A-GLANCE
- UNIVERSITY: Florida State University
- PRINCIPAL INVESTIGATOR: William S. Oates
- STUDENT: Justin Collins

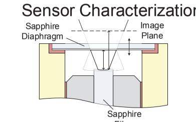
RELEVANCE TO COMMERCIAL SPACE INDUSTRY
- Development of high temperature sapphire based pressure transducers for structural health monitoring.

STATEMENT OF WORK
- Implement sapphire based pressure transducer that can operate in high temperature environments (~1000°C to 1200°C)
- Sapphire cannot be manufactured using conventional silicon based chemical etching
- Sapphire based transducer requires a strong understanding of mechanical property changes due to laser micromachining
  - Combined studies of single crystal dislocation mechanics and experimental testing focused on improved sensor reliability and manufacturing methods

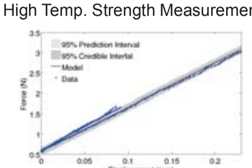
Laser Machining



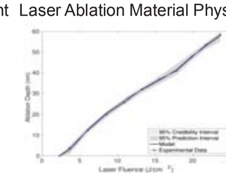
Sensor Characterization



High Temp. Strength Measurement



Laser Ablation Material Physics



STATUS
- High temperature thermo-mechanical set-up designed and validated
- Modulus and strength of sapphire and alumina characterized from room temperature to 1300°C
- Material physics of laser ablation analyzed over broad range of laser fluence conductions
- Uncertainty in modulus and laser ablation quantified using advanced Bayesian statistics algorithms

FUTURE WORK
- Rigorous assessment of damage evolution during loading and unloading of laser machined sapphire specimens
- Pressure transducer characterization with Univ. of Florida

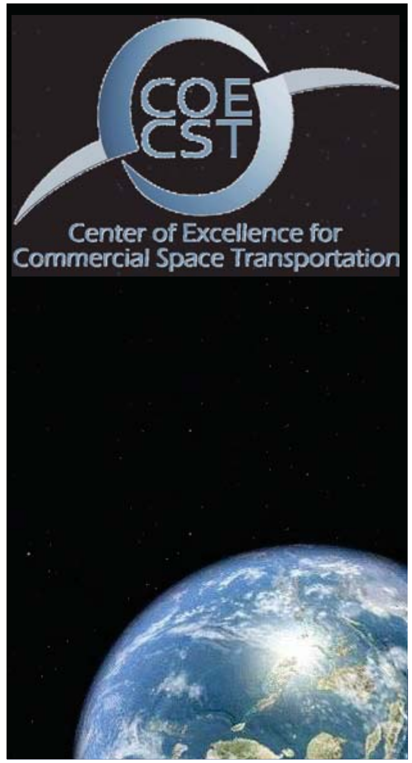
COE CST Fifth Annual Technical Meeting:

Ultrahigh Temperature Composites for Thermal Protection Systems (TPS)

Chris Harris, Jay Kapat, Jan Gou

Department of Mechanical and Aerospace Engineering
University of Central Florida

October 26-28, 2015
Arlington, VA



Agenda

- Team Members
- Task Description
- Goals
- Research Methodology
- Results
- Conclusions and Future Work

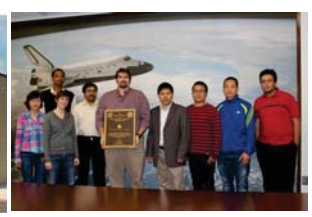
Team Members

Principle Investigators

- **Jan Gou -** Composite materials and structures, advanced composites manufacturing: PMCs, CMCs and C/C composites
- **Jay Kapat -** Heat transfer, film cooling, aerodynamics testing

Graduate Student

- **Chris Harris**: High temperature composites design, fabrication and testing, CMC/PMC hybrid composites development for thermal protection systems



Task Description

Develop **ultrahigh temperature**, **light weight** and **cost effective** polymer derived ceramics composites (PDCC) for thermal protection systems.

STATEMENT OF WORK

- Design and fabrication of polymer derived ceramics (PDC) based ceramic matrix composites.
- Ground testing of PDCC thermal protection systems with Oxyacetylene Exposure Test, Shock Tube Test and Hot Jet Facilities.
- Multi-scale modeling of PDCC thermal protection systems.

Current Approach

- PICA: Phenolic Impregnated Carbon Ablator
- SICA: Silicone Impregnated Carbon Ablator
- Carbon/Carbon Composites

Problems

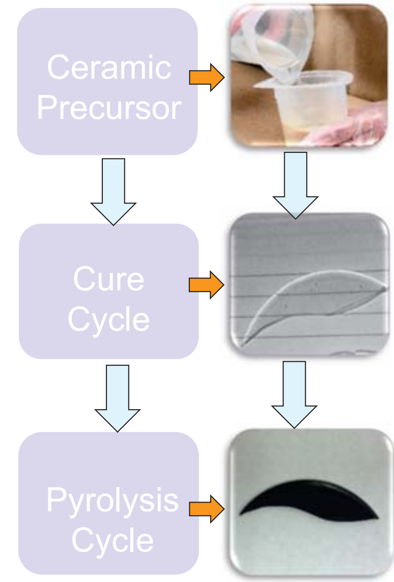
- The resulting chars are structurally weak and susceptible to mechanical erosion, severely reducing the lifetime of the TPS. Reducing spallation or erosion of the char can enable use of less ablative materials thereby reducing the total weight of TPS.
- The evaluation of ablation performance needs to consider the structural integrity of TPS structures
- Recession monitoring is most important measurement to the aerothermal analysis of the TPS structure. This measurement provides critical information about how the TPS mass and shape changes during the fight.

Polymer Derived Ceramics Matrix

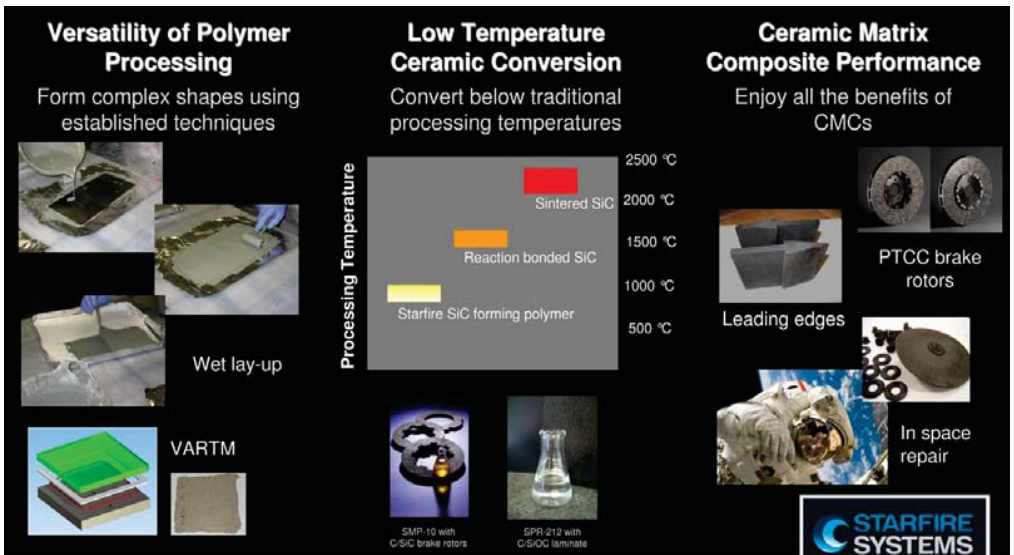
Property	Starfire System Polysiloxane(PSO)	Starfire System Polycarbosilane (PCS)
Denotation	SPR-688/SPR-212	SMP-10
Operating temperature	1,100 °C	1,800 °C
Density	1.11 g/cm^3	0.998 g/cm^3
Catalyst	Platinum CAT-776	Dicumyl Peroxide

High performance:

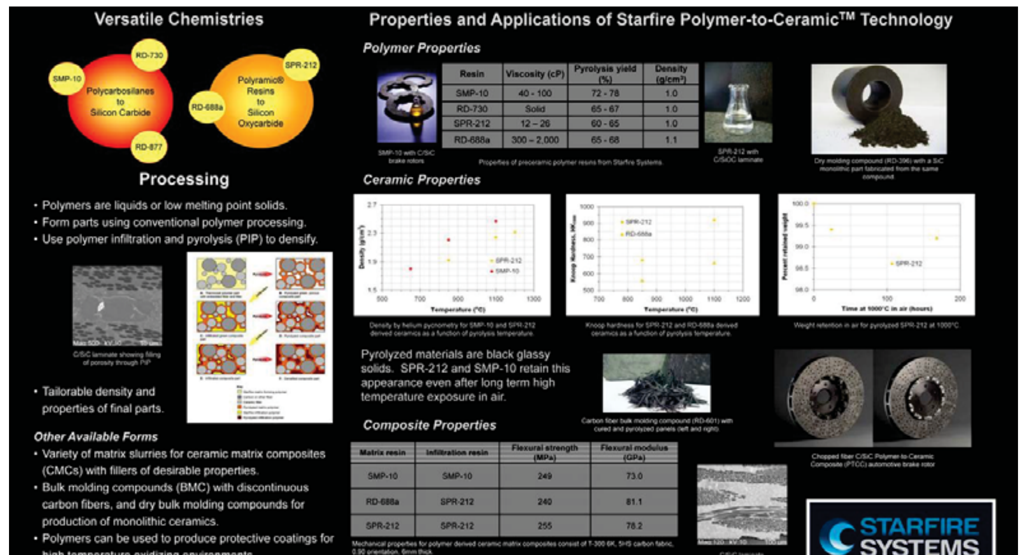
- Low cost
- Near net shape manufacturing
- Outstanding thermo-chemical stability



Polymer to Ceramic Technology



Polymer to Ceramic Technology



High Temperature Ceramic Fibers

Trade-Name	Manufacturer	Use Temperature	Cost ($/Kg)	Filament Diameter (μm)	Density(g/cc)	Tensile Strength (MPa)	Tensile Modulus (GPa)	Composition	Thermal Expansion (Ppm/°C)
T300	Toray	300~350 °C	68	7	1.74	3100	230	C	-0.7
Nextel 720	3M	1204 °C	660	10~12	3.4	2930	260	Al_2O_3/SiO_2	6
SCS-Utra	Specialty Material	1371 °C	~9000	142	3.08	3900	380	SiC	4.1
SiC-1900X	MATECH	~ 1482 °C	-	10~12	3.14	2500	367	β-SiC	-
Nicalon NL-200	Nippon Carbon	1100 °C	~2000	14	2.55	3000	220	SiC	3.1-3.2
Hi-Nicalon	Nippon Carbon	1230 °C	8000	14	2.74	2800	270	SiC	3.3-3.5
Hi-Nicalon Type S	Nippon Carbon	1450°C	13000	12	3.1	2600	420	SiC	3.5
Sylramic	COI Ceramics	1420 °C	10000	10	3.55	3200	380	SiC	5.4
Tyranno SA 1-3	Ube Industries	1700 °C	5000	10	3.02	2800	375	SiC	-

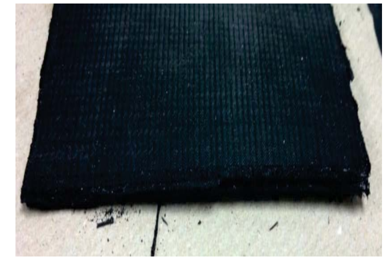
High Temperature Ceramic Fibers

BMC's

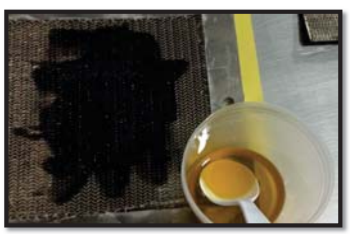
Use of numerous short and randomly oriented fibers to reinforce the ceramic matrix. This method ensures a higher volume of PDC matrix within the composite, prioritizing the ceramic matrix characteristics.

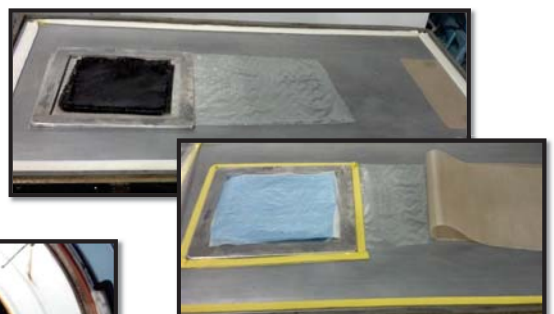
Continuous Fiber

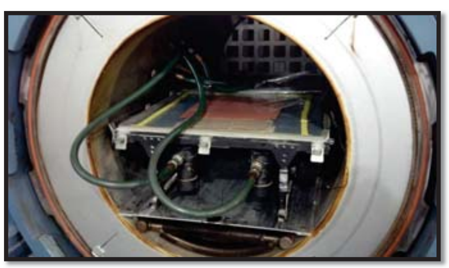
Use of continuous fiber fabric to reinforce the ceramic matrix. This method retains a higher mechanical tolerance within the composite, prioritizing the fiber characteristics while incorporating PDC properties to better transfer loads.



Panel Fabrication







Panel Fabrication

Cure Cycles for Each Resin
(20 psi, 28 inHg):

	Polysiloxane	Polycarbosilane
Ramp Up	3°C/min	3°C/min
Hold Temp	100°C	170°C
Hold Time	90 min	90 min
Ramp Down	3°C/min	3°C/min

Pyrolysis

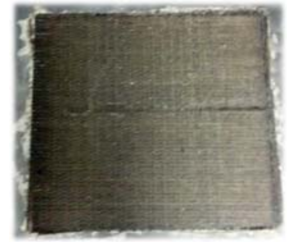
- Pyrolysis removes the polymers chains, leaving the ceramic backbone
- Below 1000°C, ceramic is amorphous

Pyrolysis of Polysiloxane Panels

- Pyrolysis Cycle:

Ramp Up	1°C/min
Hold Temp	650°C
Ramp Up	2°C/min
Hold Temp	850°C
Hold Time	90 minutes
Ramp Down	5°C/min

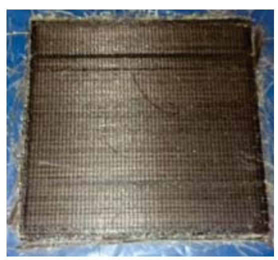
- Panel Shrinkage: ~8%



LBF107 After Pyrolysis

Pyrolysis of Polycarbosilane Panels

- Same pyrolysis cycle initially used
  - Caused panels to be warped
- Probable cause: Differences in thermal expansion caused stress between the fibers and the matrix during ramp up and ramp down
  - Slower pyrolysis cycle
  - Change the panel layup



LBF204 After Pyrolysis

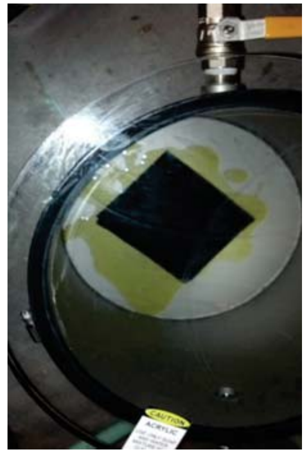
Variation in Pyrolysis Cycles

- Various pyrolysis cycles attempted
  - More holds during ramp up
  - Slower ramp down
- Slightly reduced the amount of warping

LBF203	LBF204	LBF206	LBF207	LBF208
1°C/min	1°C/min	1°C/min	1°C/min	1°C/min
650°C	200°C	200°C	260°C	650°C
No Hold	60 min	60 min	180 min	No Hold
2°C/min	1°C/min	1°C/min	1°C/min	2°C/min
850°C	400°C	300°C	300°C	850°C
90 min	60 min	60 min	60 min	90 min
-5°C/min	1°C/min	1°C/min	1°C/min	-1°C/min
	600°C	500°C	500°C	
	60 min	60 min	60 min	
	1°C/min	1°C/min	1°C/min	
	700°C	600°C	600°C	
	60 min	60 min	60 min	
	1°C/min	1°C/min	1°C/min	
	850°C	700°C	700°C	
	60 min	60 min	60 min	
	-0.75°C/min	1°C/min	1°C/min	
	350°C	850°C	850°C	
	-1°C/min	60 min	60 min	
	100°C	-0.75°C/min	-0.75°C/min	
		100°C	100°C	

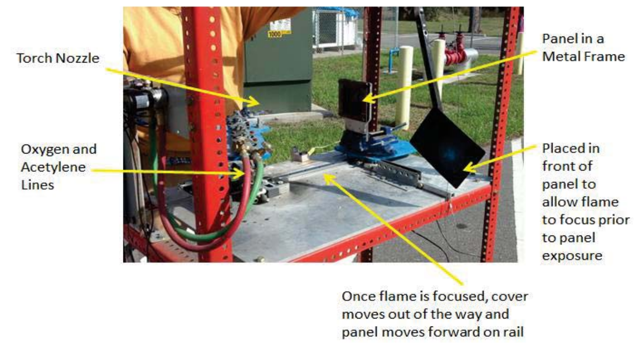
Re-infiltration and Pyrolysis

- In order to increase the ceramic content, panels were put in a vacuum chamber with resin and held under vacuum for 90 minutes
- Panels were then pyrolyzed again
- The second set of polycarbosilane panels underwent re-infiltration and pyrolysis cycles.

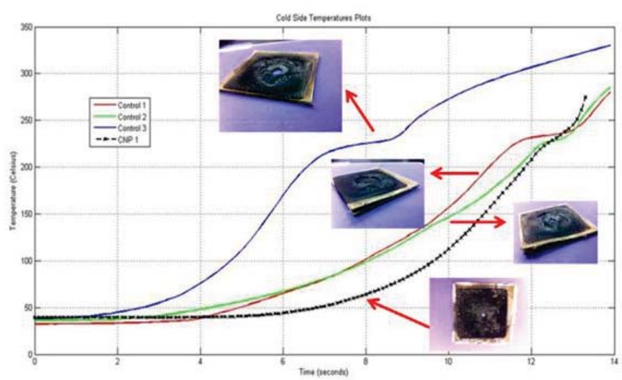


Oxyacetylene Torch Testing

- Oxyacetylene Torch Testing
  - Referencing ASTM E285
  - Heat flux of 835 W/cm^2



Results



Composites Thermal Protection Systems (TPS)

Conclusions

- Ceramic fiber reinforced PDCC composites panels have been fabricated.
- Pyrolysis has been performed to obtain a ceramic matrix in the PDCC composites.
- Re-infiltrated panels have showed better performance in the torch testing.

Future Work

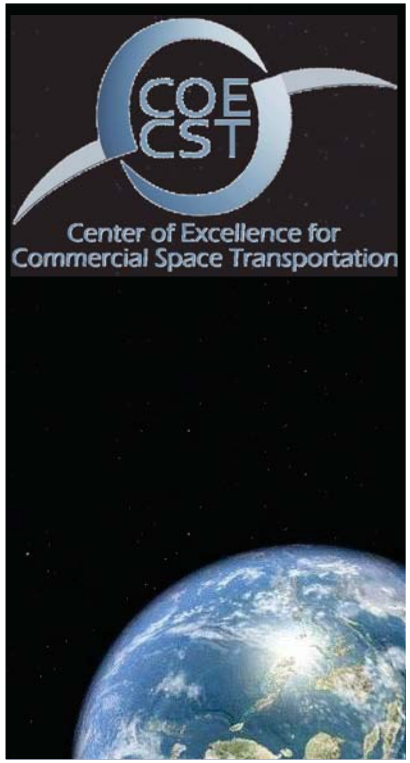
- Resin transfer molding (RTM) process with ceramic fiber preform will used to fabricate composite panels.
- Hybrid CMC/PMC composites with PDC resin and phenolic resin will be developed for high ablative performance. PDCC composites serve as skeleton and phenolic resin serves solid coolant.
- Ground testing of PDCC composites will be conducted with Oxyacetylene Exposure Test, Shock Tube Test and Hot Jet Facilities.

COE CST Fifth Annual Technical Meeting

Task 293. Reduced Order Non-Liner Structural Model

Donghyeon Ryu, Ph.D.

October 27-28, 2015
Arlington, VA



Agenda

- Team Members
- Task Description
- Schedule
- Goals
- Results
- Conclusions and Future Work

Team Members



- Principal Investigators:
  - Donghyeon Ryu, Ph.D., Assistant Professor of Mechanical Engineering, NMT
  - Keith Miller, Ph.D., Adjunct Professor of Mechanical Engineering, NMT
- Student:
  - Mr. Kevin Vedera, BS MENG (May 2016)
- FAA Technical Monitor:
  - Mr. Nickolas Demidovich
- Lead Organization: New Mexico Tech
  - Research Partner: Sandia National Laboratories
  - Industry Partners: United Launch Alliance, Ball Aerospace

Task Description

- Research Motivation:
  - Finite element analysis of whole structures requires a computational model with large degree of freedoms (DOF), which increases computational costs.
- Methodology:
  - Substructuring: a part of structure (or substructure A) is modeled with reduced DOFs and model of rest part (or substructure B) is experimentally derived to enhance accuracy.

Schedule

- Spring and Summer 2015
  - Testing substuctures of the beam specimen to extract modal parameters of the substructures
  - Validation of testing methodology and MATLAB modal parameter extraction code by comparing the experimental and COMSOL FEA models
- Fall 2015
  - Development of MATLAB substructuring using the updated Craig-Bampton method

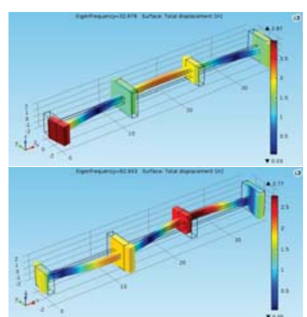
Goals

- Goals of Specific Task
  - Development of substructuring MATLAB code to combine experimentally derived modal substructure components to reduced-order finite element models of substructures
- Relevance to Commercial Space Industry
  - This methodology will aid in determining the performance and safety margins of commercial space vehicles

Results: Validation of GMAP Code

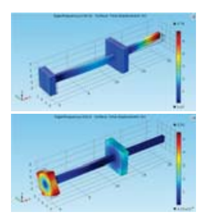
- Global Modal Analysis Package (GMAP) algorithm was used in MATLAB modal analysis code
  - GMAP code was validated for testing the whole beam

Whole Beam Natural Frequency [Hz]		
Mode	Experimental	Truth model
1	34.0	33.0
2	65.8	65.5
3	93.8	92.9
4	146.6	149.9
5	185.4	183.5



Results: Testing Substructure

- Modal Analysis of Substructures:
  - Reduced-order COMSOL beam model analysis of substructure A: missing one mode and limited accuracy
  - Experimental modal analysis of substructure B: matching with truth computational model



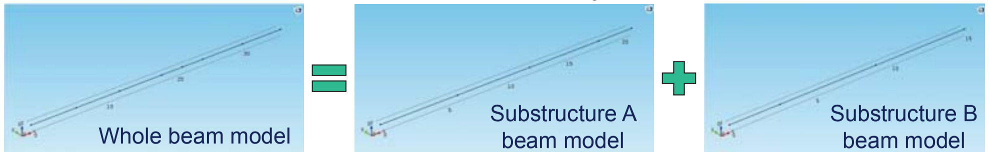
Beam model of substructure A

Experimental modal analysis of substructure B

	Natural Frequency [Hz]	
Mode	Substructure A (Reduced Order)	Substructure B (Experimental)
1	132	239
2	265	323
3	333	582
4	681	851
5	N/A	1198

Results: Substructuring

- Validation of Updated Craig-Bampton Method:
  - Combining mass and stiffness matrices of substructure A and B beam model COMSOL analysis



Whole Beam Natural Frequency [Hz]				
Mode	Experimental	Truth model	Beam model	Substructuring
1	34.0	33.0	36.0	251.3
2	65.8	65.5	161.9	441.3
3	93.8	92.9	244.3	476.2
4	146.6	149.9	271.9	538.8
5	185.4	183.5	491.7	561.4

Conclusions and Future Work

- Summary:
  - Experimental method was improved to yield reliable modal analysis using GMAP MATLAB code.
  - Modal parameters of substructures were acquired using COMSOL beam model and experimentation.
  - The developed MATLAB substructuring code was tested with COMSOL beam model substructures.
- Next Step:
  - Improvement of accuracy of the MATALB substructuring code to substructure reduced-order computational model and experimentally derived model

TASK 293. Reduced Order Non-Linear Structural Model

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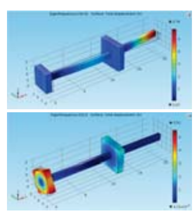
PROJECT AT-A-GLANCE
- UNIVERSITY: New Mexico Tech
- PRINCIPAL INVESTIGATORs: Dr. Donghyeon Ryu and Dr. Keith Miller
- STUDENT: Mr. Kevin Vedera
- FAA TECHANICAL MONITOR: Mr. Nickols Demidovich

RELEVANCE TO COMMERCIAL SPACE INDUSTRY
- The structural integrity of commercial launch platforms must be assessed for each mission, i.e. safety certification or recertification. A significant amount of structural response data must be collected in order to state confidence bounds on the computed safety margins. Experimental data will very likely need to be supplemented with data generated by numerical simulations of the structural response of the launch platforms to the anticipated flight environments. Efficient, cost-effective methods for generating non-linear structural models of CST platforms will result from this effort.

STATEMENT OF WORK
- Solicit Industrial Working Group feedback to guide implementation of system computational assembly methods.
- Generate non-proprietary code to extract relevant structural features from experimental test data i.e. modal extraction software using rational fractional polynominals (RFP)
- Provide Matlab™ scripts for combining finite element modelled components with experimentally defined (modal) components in structural assemblies.
- Provide help to commercial companies desiring to use modal extraction an assembly codes.

SUBSTRUCTURING



STATUS
- Experimental method was improved to yield reliable modal analysis using GMAP MATLAB code.
- Modal parameters of substructures were acquired using COMSOL beam model and experimentation.
- The developed MATLAB substructuring code was tested with COMSOL beam model substructures.

FUTURE WORK
- Improvement of accuracy of the MATALB substructuring code to substructure reduced-order computational model and experimentally derived model

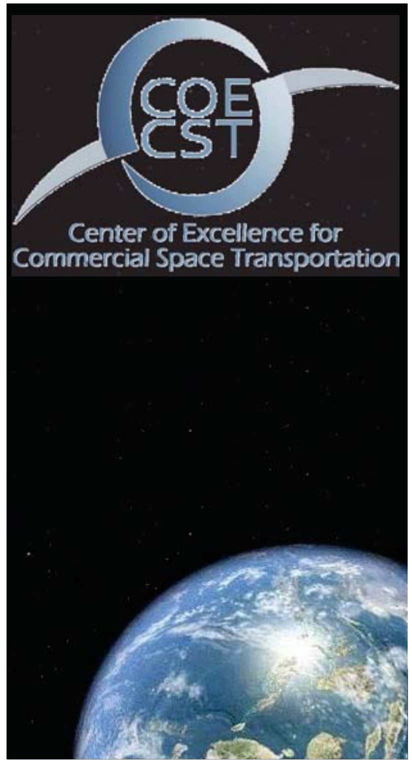
COE CST Fifth Annual Technical Meeting

Task 299: Nitrous Oxide Composite Case Testing

PI: Warren Ostergren
Co-PIs: Bin Lim, Andrei Zagrai

COE CST Program Manager: Ken Davidian (FAA)
Technical Monitor: Yvonne Tran (FAA)
Technical Monitor: Don Sargent (FAA)

October 27-28, 2015
Arlington, VA



Agenda

- Team Members
- Task Description / Goals
- Schedule
- Hypothesis
- Results
- Conclusions and Future Work

Team Members

- PI: Warren Ostergren (NMT)
- Co-PI: Seokbin (Bin) Lim (NMT)
- Co-PI: Andrei Zagrai (NMT)

- Student: Antonio Garcia (NMT)
- Student: Steven Sweeney (NMT)
- Test Engineer: Meliton Flores (EMRTC)

- COE CST Program Manager: Ken Davidian (FAA)
- Technical Monitor: Yvonne Tran (FAA)
- Technical Monitor: Don Sargent (FAA)

Task Description / Goals

- Objectives
  - Develop an understanding of fragmentation hazards from composite tanks used for fuel/oxidizer storage
  - Construction of hypothesis and experimental validation of how cracks form in test samples

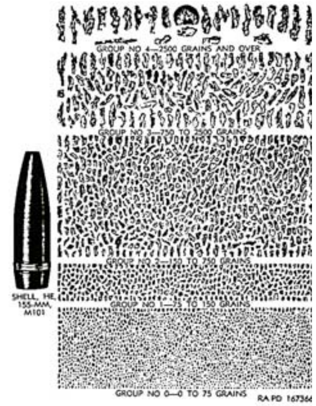
- Tasks
  - 5 tests each of Al 6061 & composite material tubes to understand the crack opening behavior (10 tests total)
  - Develop methods to predict crack opening behavior
  - Develop standard test procedures for composite materials under shock and high-rate loading
  - Numerical simulations to predict the fragmentation (in progress)

Schedule

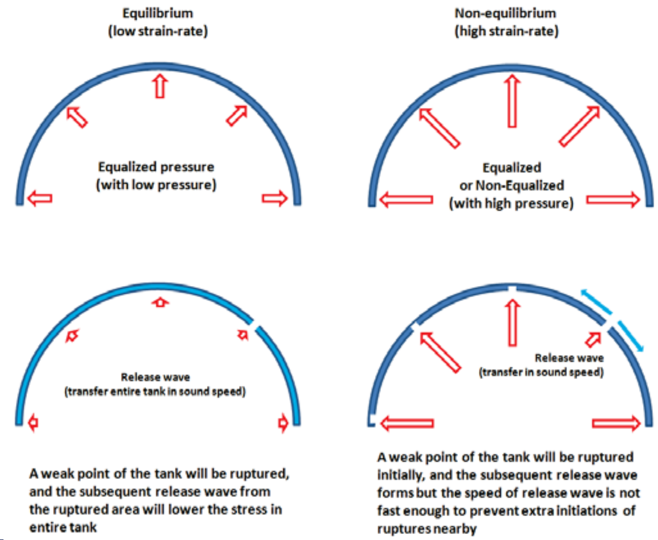
- Determination of sample thickness (numerical simulation): Jan 2015-Mar 2015
- Design of test fixture: Mar 2015-May 2015
- New test fixture construction: May 2015-July 2015
- 1st aluminum tube test: Aug 19, 2015
- 2nd aluminum tube test: Sep 10, 2015
- 3rd aluminum tube test: Sep 10, 2015
- 4th aluminum tube test: Sep 23, 2015
- 5th aluminum tube test: Oct 7, 2015

- 5 more composite tube tests are scheduled in late 2015

Hypothesis



Static vs. Dynamic
(Very slow loading Vs. Fast-Continuous loading)



Hypothesis

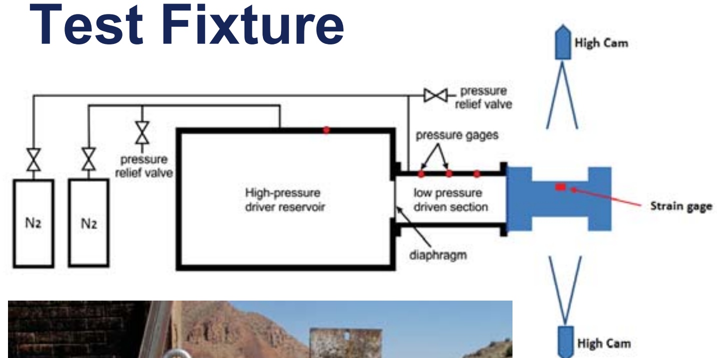
Expected damage/fracture patterns depending on the loading condition

	Equilibrium (low strain-rate)		Non-equilibrium (high strain-rate)	
	Non-brittle Material (Al)	Brittle Material (Composite)	Non-brittle Material (Al)	Brittle Material (Composite)
Plate test	Punching	Punching & Low fractures	Punching or High fractures	High fractures
Structural Tank Test (Tube)	Less number (or single) of opening	Less number (or single) of opening and fractures	Increased number of opening and shrapnel	Many number of opening and shrapnel

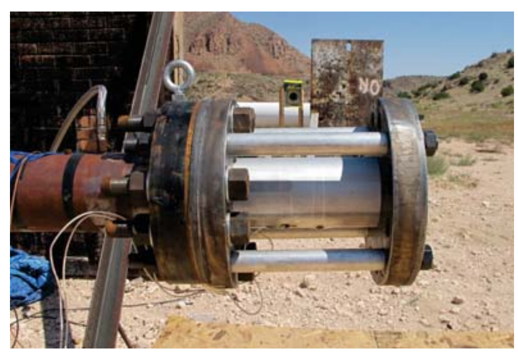
Pressure loading → **Opening** → **Secondary impact** → **Shrapnel**

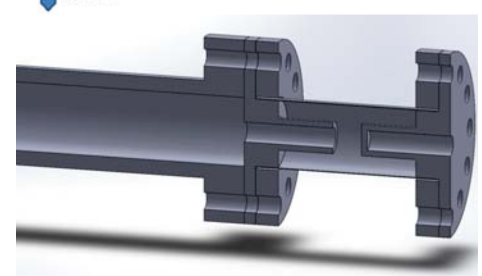
Current stage

Test Fixture

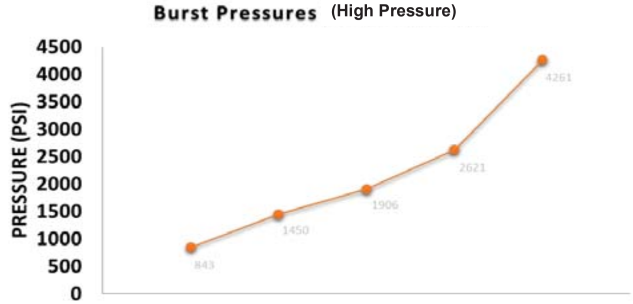


1/16 in. Wall thickness,
12 in. Long,
6 in. Diameter,
6061 Al Tube
Weight of tube: 1.65 lbs

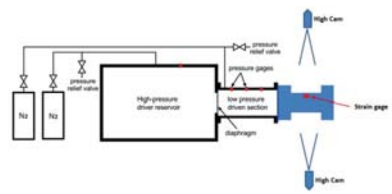




Test Matrix

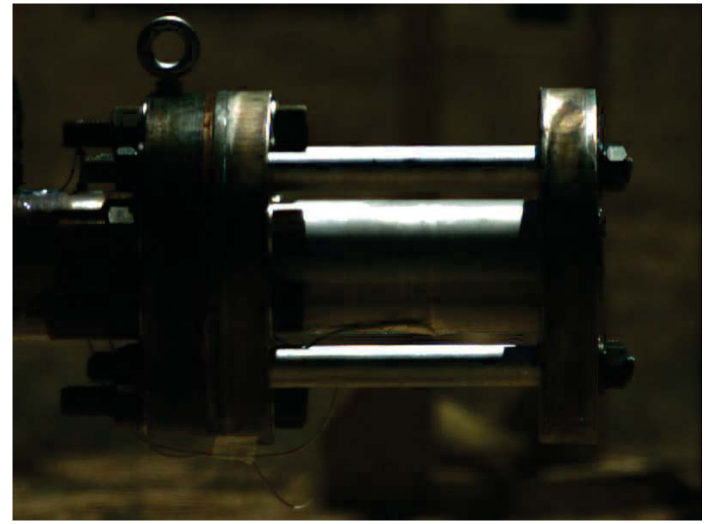


Test #	High	Low	Differential	Diaphragm	Sample
1	2621	692	1929	2008	Al tube
2	1906	699	1207	1195	Al tube
3	843	843	0	N/A	Al tube
4	4261	720	3541	3515	Al tube
5	1450	306	1144	1195	Al tube



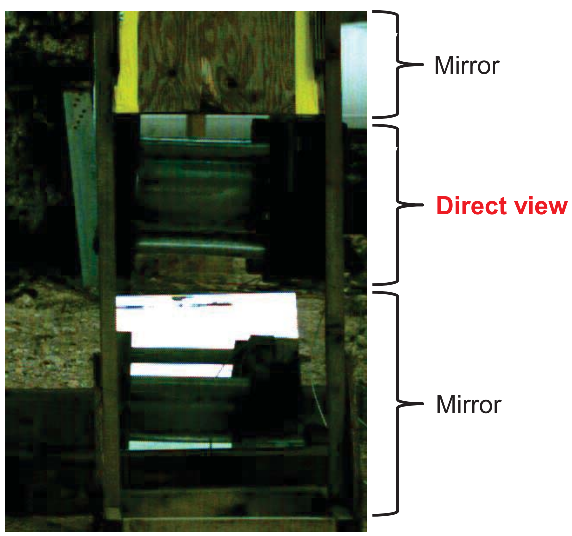
Test Results (Shot #1)

Two openings



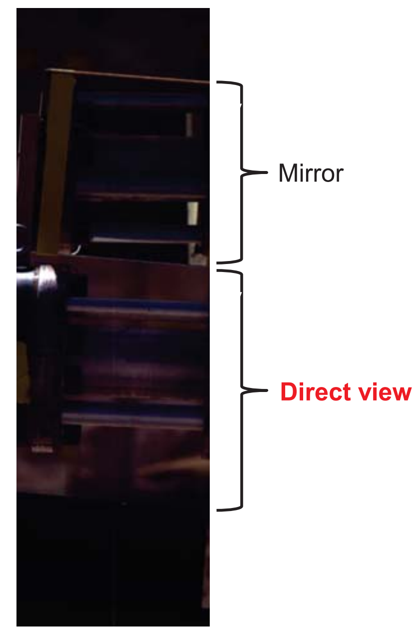
Test Results (Shot #3: static test)

Single opening

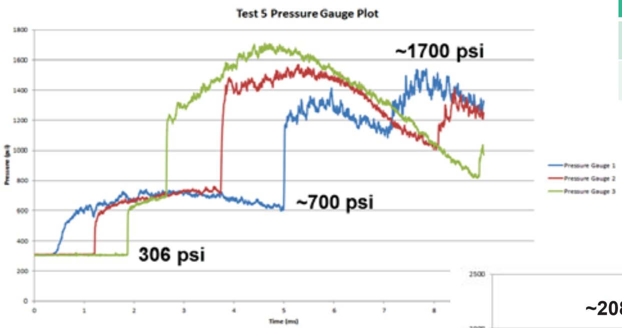


Test Results (Shot #4)

Two openings and many secondary fragments

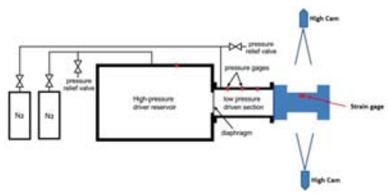


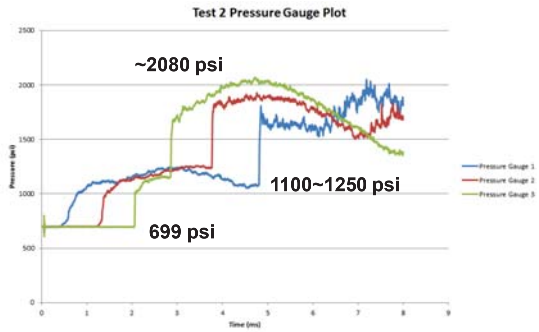
Results



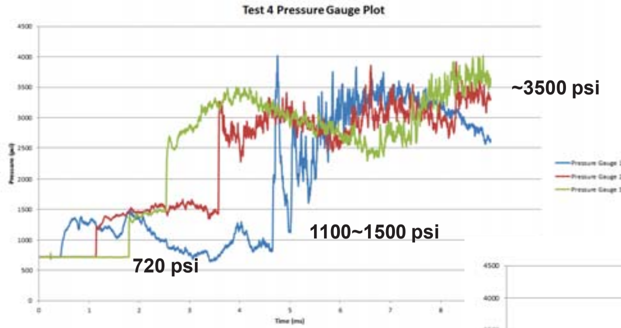
Test #	High (psi)	Low (psi)	Differential (psi)	# of opening
2	1906	699	1207	1
5	1450	306	1144	1

Single opening



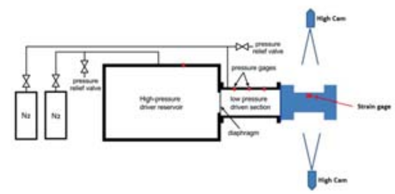


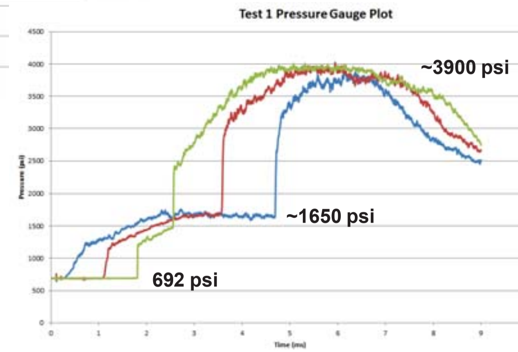
Results



Test #	High (psi)	Low (psi)	Differential (psi)	# of opening
1	2621	692	1929	2
4	4261	720	3541	2

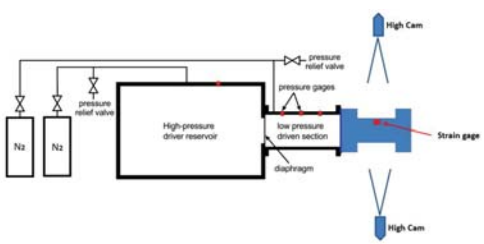
Two openings



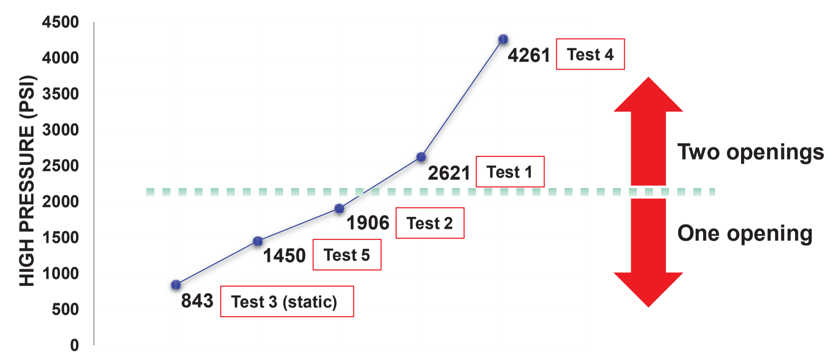


Results

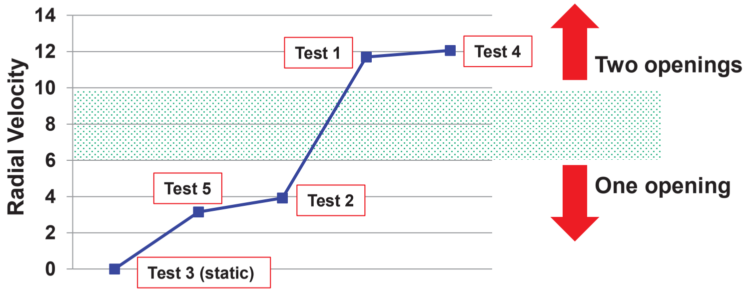
Test # (by date)	High (psi)	Low (psi)	Differential (psi)	Diaphragm (psi)	Radial vel. (m/s)	Circf. elong. vel. (m/s)	Radial strain rate (s^{-1})	# of opening	# of fragments
3	843	843	0	N/A	Too low	Too low	Too low	1	One large
5	1450	306	1144	1195	3.92	33.67	0.035	1	One large & small frags
2	1906	699	1207	1195	3.15	32.24	0.043	1	One large & small frags
1	2621	692	1929	2008	11.70	73.56	0.154	2	Approx. 20
4	4261	720	3541	3515	12.06	75.80	0.159	2	Many

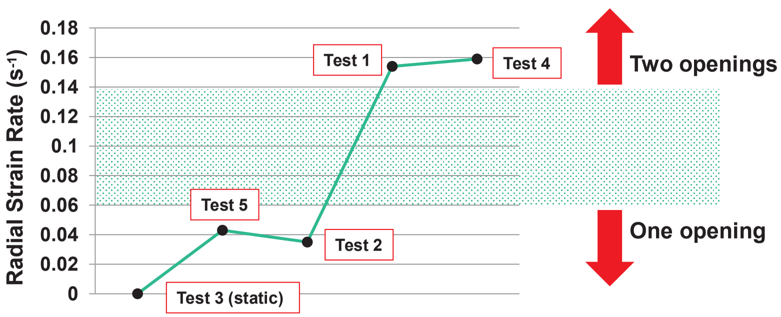


Results



Results





Conclusions

- Pressure tests on aluminum tubes show a clear tendency for the number of openings to be dependent on the input pressure
- The input pressure causes a similar trend in important deformation criteria: radial velocity, circumferential velocity, and strain rate
- The formation of small shrapnel in the aluminum is from secondary impact in the test structure
- The crack opening characteristic helps to predict the shrapnel kinetics (velocity, size, direction, etc.)

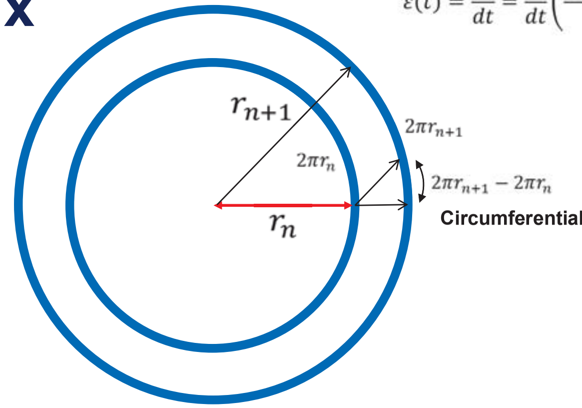
Future work

- Finalize quantification of the crack opening characteristics
- Investigation of the composite tube opening behavior
- Characterize the secondary impact and creation of small shrapnel (fragments)
- Understand the kinetics of the fragments

QUESTIONS?

Appendix

$$\varepsilon\dot{(t)} = \frac{d\varepsilon}{dt} = \frac{d}{dt}\left(\frac{L(t) - L_0}{L_0}\right) = \frac{v(t)}{L_0}$$



$$2\pi\frac{\Delta r}{\Delta t} = 2\pi\frac{r_{n+1} - r_n}{\Delta t}$$ Circumferential elongation velocity

$$\frac{\Delta r}{\Delta t} = \frac{r_{n+1} - r_n}{\Delta t}$$ Radial expansion velocity

Test	Cam	frame	size	size	surface a	surface a	speed measurem	speed measurem	speed measurem	speed measurem	speed measurem	speed measurem	avg speed	average spe
1	N	33	0.0554	0.0449	0.36	2.31	44.15	47.06	56.14	61.49	63.1		54.39	24.31
1	N	61	0.162	0.1772	4.13	26.67	88.49	77.95	78.42	76.68			80.39	35.94
1	N	63	0.0654	0.1024	0.96	6.22	145.63	137.337	136.94				139.97	62.57
1	S	24	0.2	0.1731	4.99	32.16	635	544.21					589.61	263.58
2	N	83	0.3394	0.1267	6.19	39.95	568.75	524.93	512.01	520.14			531.46	237.58
2	N	89	0.128	0.0527	0.97	6.27	359.92	401.64	395.96				385.84	172.49
2	N	88	0.1312	0.2443	4.62	29.78	204.13	200.05					202.09	90.34
2	N	98	0.3419	0.1517	7.47	48.19	159.32	160.27	159.86				159.82	71.44
2	S	78	0.1079	0.1015	1.58	10.17	167.99	165.24	160.64				164.62	73.59
2	S	71	0.0535	0.0433	0.33	2.15	93.02	96.8	107.88	115.29			103.25	46.16
2	S	86	0.1741	0.0779	1.95	12.60	532.12	547.32	558.79				546.08	244.12
2	S	72	0.1276	0.0605	1.11	7.17	132.91	136.45	140.89	141.96	144		139.24	62.25
2	S	74	0.043	0.0239	0.15	0.95	147.19	152.9	160.13	164.32	166.71		158.25	70.74
2	S	75	0.1861	0.0545	1.46	9.42	382.42	323.4	308.51	323.56	310.56		329.69	147.38
2	S	76	0.121	0.0348	0.61	3.91	359.93	384.14	374.54				372.87	166.69
2	S	72	0.1157	0.134	2.23	14.40	106.29	106.14	106.68	101.9	101.87		104.58	46.75
2	S	72	0.1581	0.0592	1.35	8.70	241.36	244.81	248.93	250.1984	255.05		248.07	110.90
2	S	72	0.1211	0.0624	1.09	7.02	62.47	64.51	74.19	74.89	81.41	85.66	73.86	33.02
2	S	79	0.0879	0.0508	0.64	4.15	393.74	366.79	370.32				376.95	168.51
2	S	73	0.0717	0.0492	0.51	3.28	125.7	128.95	133.73				129.46	57.87
3	N	-129	0.1155	0.0454	0.76	4.87	375.51	110.06	101.21	92.25			169.76	75.89
3	N	-130	0.1389	0.075	1.50	9.68	89.09	70.84	66.06				75.33	33.68
3	N	-99	0.0651	0.0601	0.56	3.63	117.35	90.79	82.14	79.87			92.54	41.37
3	S	-115	0.2331	0.1267	4.25	27.44	140.06	124.72	127.5	131.46	138.6		132.47	59.22
3	S	-77	0.2125	0.1314	4.02	25.94	225.76	242.12	250.72				239.53	107.08
3	S	-91	0.2081	0.1201	3.60	23.22	176.43	177.78	179.08	180.79	179.12		178.64	79.86
3	S	-24	0.238	0.2473	8.48	54.68								
3	S	-82	0.0853	0.2	2.46	15.85	85.97	88.93					87.45	39.09
3	S	-75	0.2363	0.2571	8.75	56.44								
3	S	-52	0.0894	0.052	0.67	4.32	104.06	109.22	107.87				107.05	47.86
4	N	92	0.1791	0.0543	1.40	9.03	248.22	245.73	247.41				247.12	110.47
4	N	108	0.4499	0.3145	20.38	131.45	163.38	163.38	157.6	160.44	162		161.36	72.13
4	N	103	0.1713	0.0455	1.12	7.24	151.8	150.16	148.4				150.12	67.11
4	N	86	0.0984	0.0785	1.11	7.18	341.27	288.83					315.05	140.84
4	N	122	0.1823	0.0895	2.35	15.16	193.27	176.83	184.56	185.65			185.08	82.74
4	N	97	0.0516	0.0552	0.41	2.65	319.99	315.84	320.19	319.34	318.92		318.86	142.54
4	N	198	0.1542	0.328	7.28	46.99	141.8	121.23	119.84				127.62	57.05
4	N	248	0.1223	0.1344	2.37	15.27	23.42	26.97	30.21	33.06	32.72		29.28	13.09
4	N	204	0.1315	0.0734	1.39	8.97	63.57	58.78	60.33	59.61	58.22		60.10	26.87
4	S	69	0.0336	0.062	0.30	1.94	354.35	313.25					333.80	149.22
4	S	69	0.1306	0.1614	3.04	19.58	408.04	406.99	415.96	406.69			409.42	183.03
4	S	68	0.064	0.064	0.59	3.81	190.43	216.15					203.29	90.88
4	S	80	0.3283	0.1835	8.67	55.97	126.69	142.67	139.9				136.42	60.99
4	S	103	0.0904	0.0407	0.53	3.42	35.06	36.48					35.77	15.99
4	S	106	0.1343	0.0593	1.15	7.40	28.1	56.08	68.04	73.24			56.37	25.20
4	S	173	0.1678	0.1007	2.43	15.70	76.1	84.04	92.67				84.27	37.67
5	N	69	0.1208	0.0614	1.07	6.89	244.82	254.64	258.9	258.68			254.26	113.66
5	N	70	0.2768	0.0427	1.70	10.98	362.63	257.5	255	256.35	255.99		277.494	124.05
5	N	66	0.0702	0.1073	1.08	7.00	432.29	419.75	433.09				428.37667	191.50
5	S	119	0.4565	0.1787	11.75	75.79	67.05	58.23	66.14	66.16	72		65.916	29.47
5	S	111	0.2791	0.102	4.10	26.45	126.12	166.2	181.11	190			165.8575	74.14
5	S	125	0.1806	0.1354	3.52	22.72	267.43	271.04	274.49	272.72			271.42	121.34
5	S	137	0.5183	0.1051	7.84	50.61	175.98	174.9	177.91	182.17			177.74	79.46
5	S	135	0.1426	0.0514	1.06	6.81	100.14	97.94	99.53	97.68	98.37	100.5	99.026667	44.27

COE CST Fifth Annual Technical Meeting (ATM5)
October 27-28, 2015
Center of Excellence for Commercial Space Transportation

Fire and Hazard Detection for Space Vehicles Using LEDs

[1]Justin Urso, [1]Michael Villar, [1]Kyle Thurmond, [1]Zachary Loparo,
[2]Dr. Bill Partridge Jr.,
[1]Dr. Jayanta Kapat, [1]Dr. Subith Vasu

[1]University of Central Florida, Orlando, FL
[2]Oak Ridge National Laboratory, Oak Ridge, TN

Presented at
FAA COE CST 2015
October 27, 2015
Arlington, VA

Agenda

- Team Members
- Introduction
- Sensor Overview
- Schedule
- Preliminary Results
- Current Work
- Conclusions and Future Work

Team Members

Principal Investigators

Dr. Subith Vasu
University of Central Florida


Dr. Jay Kapat (Co-PI)
University of Central Florida


Collaborators

Dr. Bill Partridge Jr.
Oak Ridge National Laboratory


Graduate Students

Justin Urso
University of Central Florida


Michael Villar
University of Central Florida


Zachary Loparo
University of Central Florida


Kyle Thurmond
University of Central Florida


Organizations

– Center for Advanced Turbomachinery and Energy Research (CATER), University of Central Florida
– Fuels, Engines, and Emissions Research Center, Oak Ridge National Laboratory

Matching Funds: Progress Energy Florida, UCF MAE Department & UCF Research and Commercialization. Support from ORAU and the Oak Ridge National Laboratory sponsored by US Department of Energy, Office of Energy Efficiency and Renewable Energy.

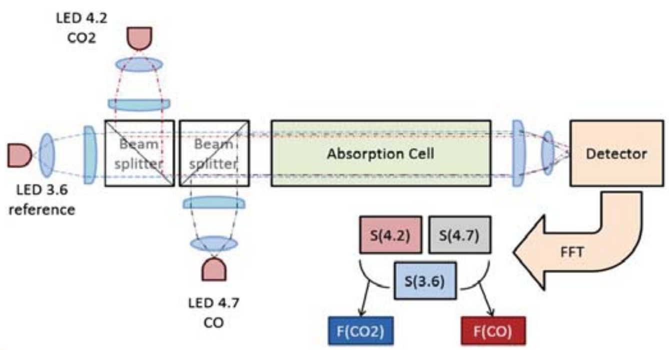
Motivation

Need for a new Sensor

- Current ISS and space shuttle sensors: false alarms and missed events
- Need multiple different sensor types to detect and characterize these events accurately
- Current fire detection sensors are particle based
  - Particle ionization smoke detector
  - NIR laser forward scattering particle detector
- CO_2 concentrations must be monitored in crew cabin for safety
- Time-resolved measurements of CO can be used as early indicator of fires

Technical Background

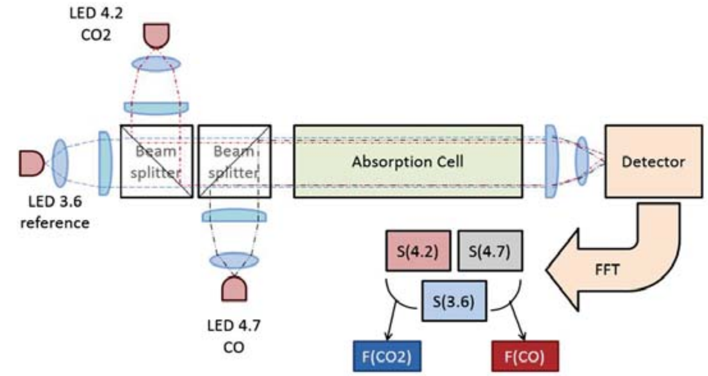
- Non-Dispersive Infrared (NDIR) absorption sensor using LEDs.
- Detects carbon monoxide (CO) and carbon dioxide (CO_2).
  - CO_2 center wavelength around 4.2μm
  - CO center wavelength around 4.7μm
- Implement as an early fire hazard detector for space vehicles



Sensor Design Using LEDs

- Three MIR LEDs centered at
  - 3.6μm (for reference)
  - 4.2μm (CO_2)
  - 4.7μm (CO)
- LEDs amplitude modulated at different frequencies

- Band pass filters
- Collimating lenses
- Pellicle beam splitters
- Thermo-electrically cooled photovoltaic detector



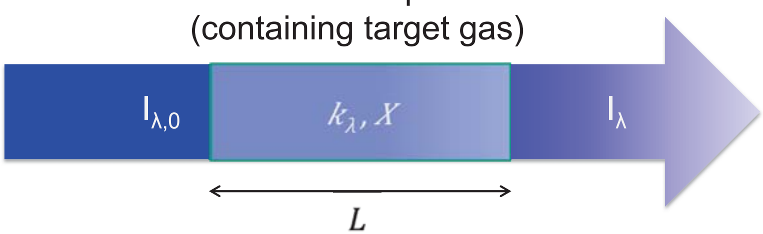
Absorption Spectroscopy and Beer's Law

Beer-Lambert Law of Absorption

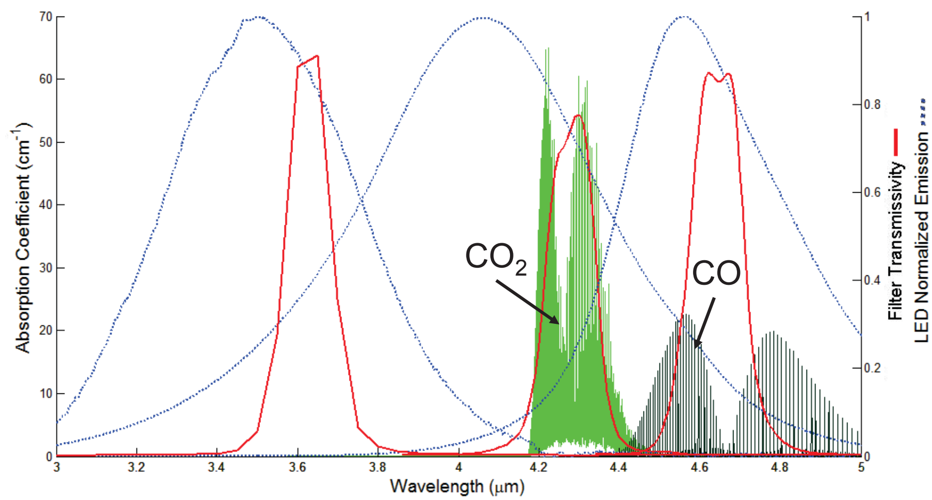
$$A_\lambda = \ln(I_\lambda/I_{\lambda,0}) = k_\lambda L X$$

A_λ = Spectral Absorbance (Typically 0-1)
I_λ = Transmitted Radiation at λ
$I_{\lambda,0}$ = Incident Radiation at λ
k_λ = Spectral Absorbance Coefficient (Intrinsic Property at λ)
L = Path Length of Gas Cell
X = Mole Fraction of Target Gas

Test Sample
(containing target gas)



Using LEDs in Absorption Spectroscopy



Schedule

Major Milestones

Achieved
- System integration of sensor components
- Sensor housing design for balloon test
- Convert system to run on cRIO DAQ

Ongoing
- Design gas delivery system
- Fabricate gas delivery system
- Integrate systems into final module
- Environmental Chamber Test Fall 2015
  - Preliminary run 10-12/2015
  - Full system diagnostic run 12/2015-4/2016

Planned
- Flight Test Summer/Fall 2016

Balloon Package
- House/weight/shield vital electronics

↓

Gas Controller
- For balloon flight

↓

Lab Characterization
- Calibration

↓

Environmental Chamber
- Calibration and evaluation
- -45°C, 1/100 atm

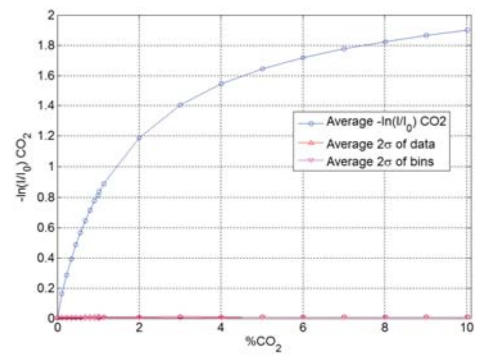
↓

Balloon Flight
- 30km flight

Neat Gas Results Early Proof of Concept

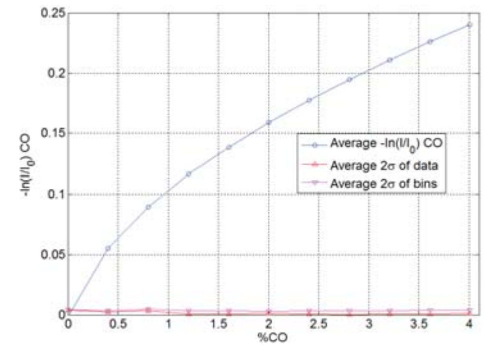
$$-ln(I/I_0) = kLX$$

Neat CO_2 Results



Detection Limit: 30ppm

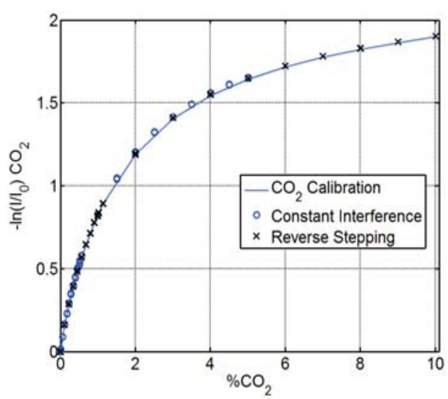
Neat CO Results

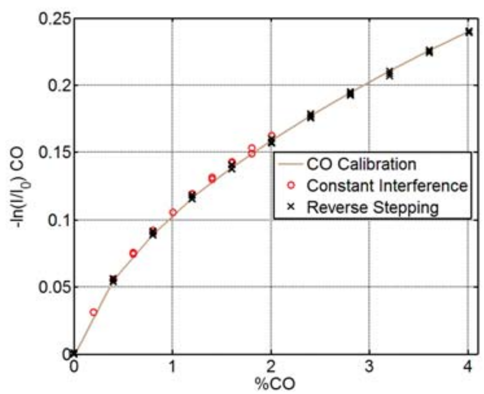


Detection Limit: 400ppm

Cross-Interference Study for CO and CO_2

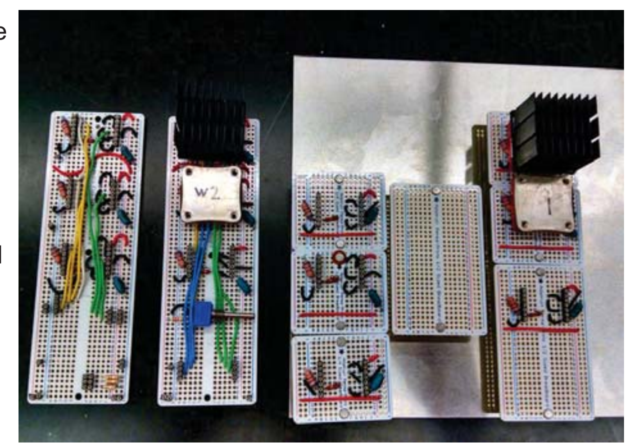
Simultaneous measurements of CO and CO_2 showed no cross-interference.





System Redesign

- Rebuilt circuitry to reduce feedback
- Signal leakage caused error in drivers
- New multi +/- current lines eliminate unwanted cross feed of LED and TEC signals



Why Environmental Chamber Tests?

- Validation of autonomous control systems
- Verification of system in low temperature/pressure environment
  - Lower pressure and temperature over an hour, maintain for two hours
- Troubleshoot prior to balloon test
  - Environmental analog to test system tolerance in extreme atmospheric conditions

Environmental Chamber Test

- UCF environmental chamber
- Test will verify system capabilities at 1/100 atm and -45°C
- Autonomous operation on ground will be achieved

NASA Flight Opportunities (Balloon Test): Proposal Pending

- Opportunity to test system in potential working conditions
  - 30km+ altitude flight
  - System designed for unmanned and manned space/air vehicles
  - Balloon test provides potential working environment
  - Autonomous operation in a high altitude environment

Future Work

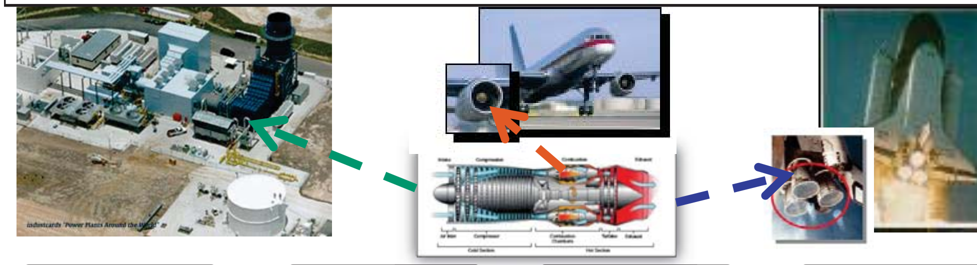
- Conduct balloon tests
- Characterize smoke of various space material to identify hazardous gases from fire onboard
- Extend range of species that sensor can measure (e.g. hydrocarbon fuels leak (~3.4μm), oxidizer N_2O (~4.5μm), HCN, etc.)
- Develop more accurate quantitative model for broad-spectrum absorption spectroscopy. Currently we rely on calibration models

Acknowledgments

- Research efforts at UCF have been supported by the **FAA Center of Excellence Commercial Space Transportation**.
- Additional financial assistance from **Florida Space Institute**, **Duke Energy**, **UCF Mechanical and Aerospace Department**, and the **UCF Office of Research and Commercialization**. The **Oak Ridge National Laboratory** work sponsored by the **U.S. Department of Energy.**

Questions?

Center for Advanced Turbomachinery and Energy Research

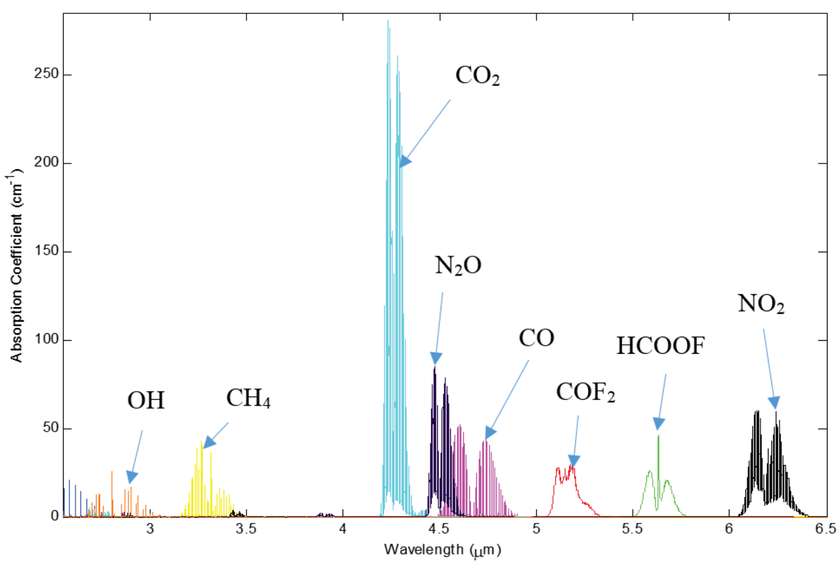


Aerodynamics & Heat Transfer | Combustion & Emissions | Alternative Fuels | Cycle Innovation

Extreme Temp Materials | **CATER 10 faculty members** | Mechanical Integrity

Design & Manufacturing | Polymer/Ceramic Composites | Dynamic Integrity | Plant & Grid Transients

Mid-Infrared Absorption Spectra

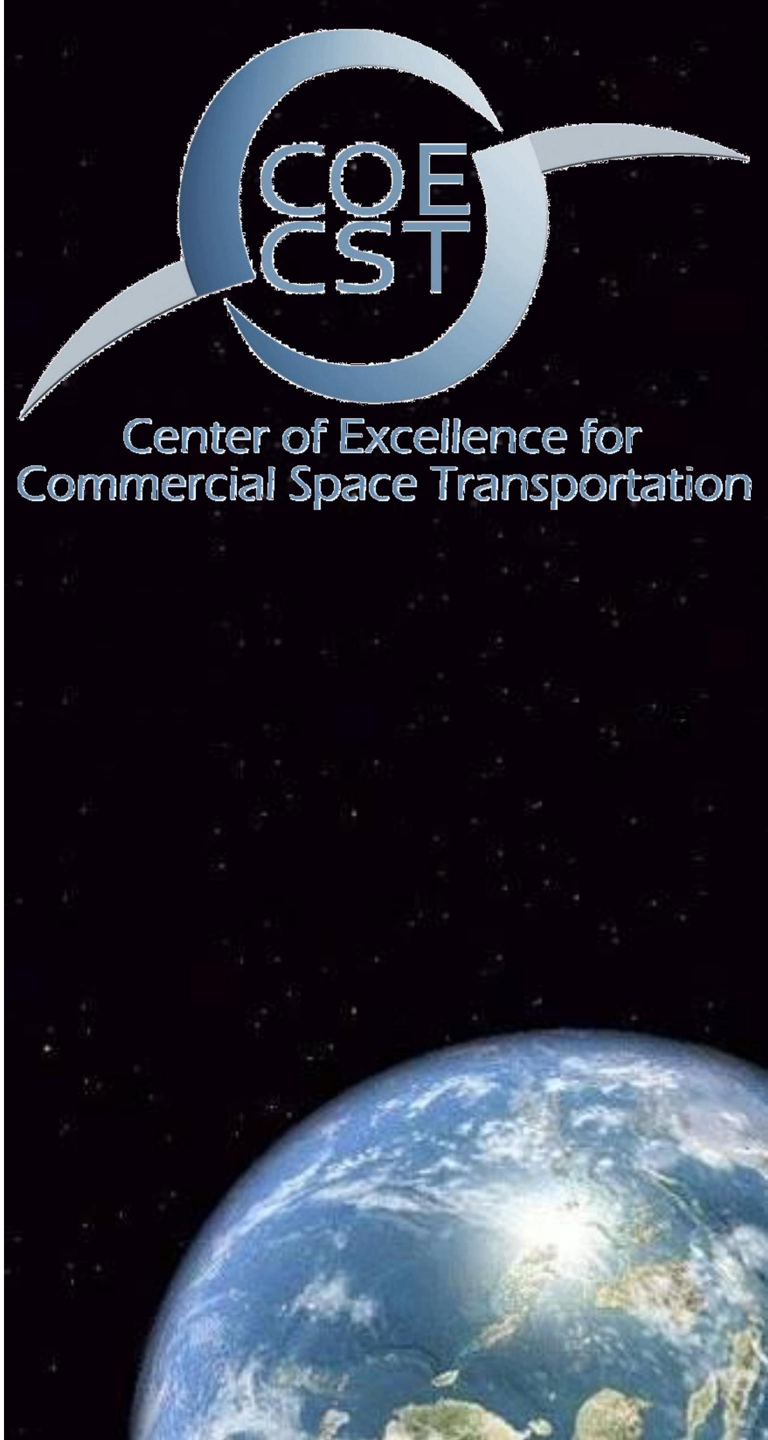


COE CST Fifth Annual Technical Meeting

Optical Measurements of Rocket Nozzle Thrust and Noise

PI (s): Rajan Kumar & Farrukh Alvi
Student: Griffin Valentich

October 27-28, 2015
Arlington, VA



Agenda

- Team Members
- Challenges and Motivation
- Task Description
- Test Facilities
- Schedule & Milestones
- Nozzle Design
- Future Work

Team Members

- Team
  - Rajan Kumar & Farrukh Alvi
  - Griffin Valentich
- Organizations Involved
  - FSU / FCAAP
  - Space Florida
  - SpaceX

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SPACE FLORIDA

FCAAP
FLORIDA CENTER FOR ADVANCED AERO-PROPULSION
TECHNOLOGIES FOR THE NEXT GENERATION

SPACEX

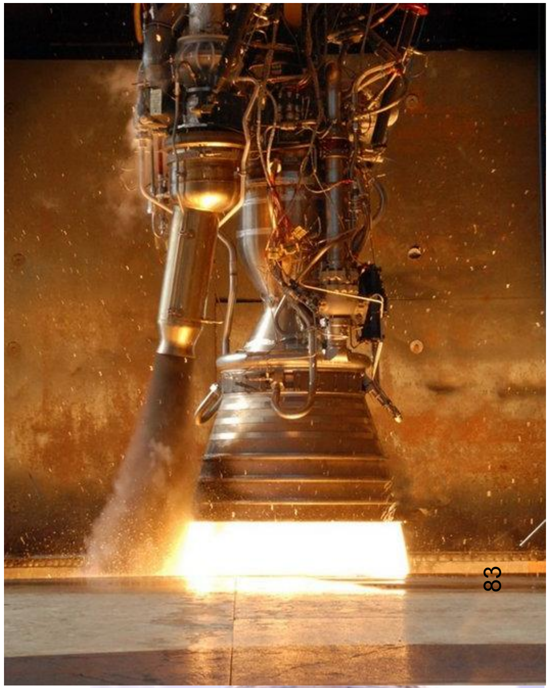
Challenges & Motivation

70% accidents in aerospace missions are due to engine malfunction or propulsion system failures!!

Rocket propulsion studies are limited (only National Labs. & big corporations)

- **High temperature and pressure environment**
- **Complex chemistry – unstable fuels**
- **Large scale tests are expensive & require specialized rigs**

- **Need to develop high temperature pressure sensors – activity initiated under COE-CST**
- **Measure steady and transient loading on the nozzle and ground surface – material characterization**
- **Jet plume development and flow field analysis**
- **Nearfield & farfield noise measurement and prediction tools**
- **Study of next generation hybrid fuels**



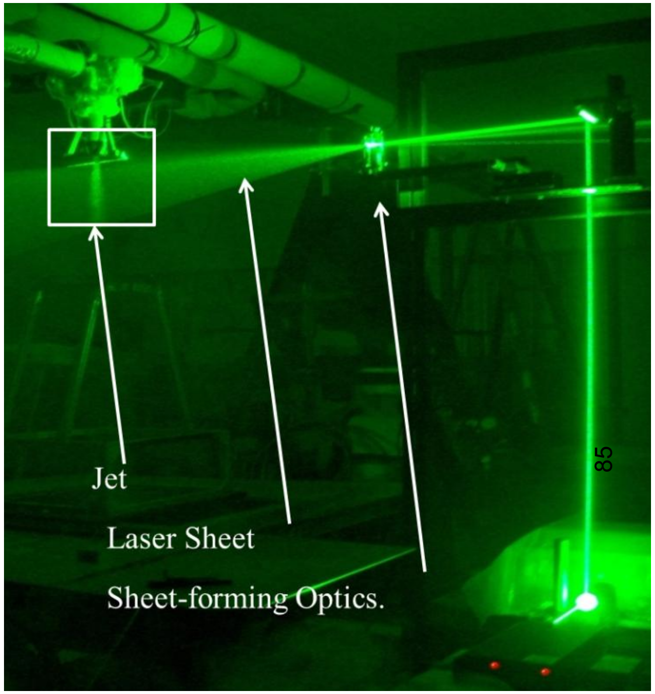
Tasks Description

- Development of a research plan based on state-of-art thrust and noise measurement techniques.
- Discussion with NASA /commercial launch engineers to ensure the transition of technology from laboratory to full-scale implementation.
- Design of a scaled nozzle and simulate realistic temperature and pressure conditions of the jet exhaust in the FSU jet facility
- Design and develop advanced optical techniques for thrust measurements and characterize its performance at controlled conditions.
- Refine and test the measurement techniques over a wide range of test conditions.

Test Facilities

Operational/Test Capabilities

- *Mach Number = 0.5 - 2.5*
- *T_o= 70 - 2000 F*
- *D_{Jet} = 25.4 – 76.2 mm*
- *NPR = Under-ideal-over expanded*
- *Anechoic chamber: 5.8 m x 5.2 m x 4.0 m, Calibrated to 100 Hz*



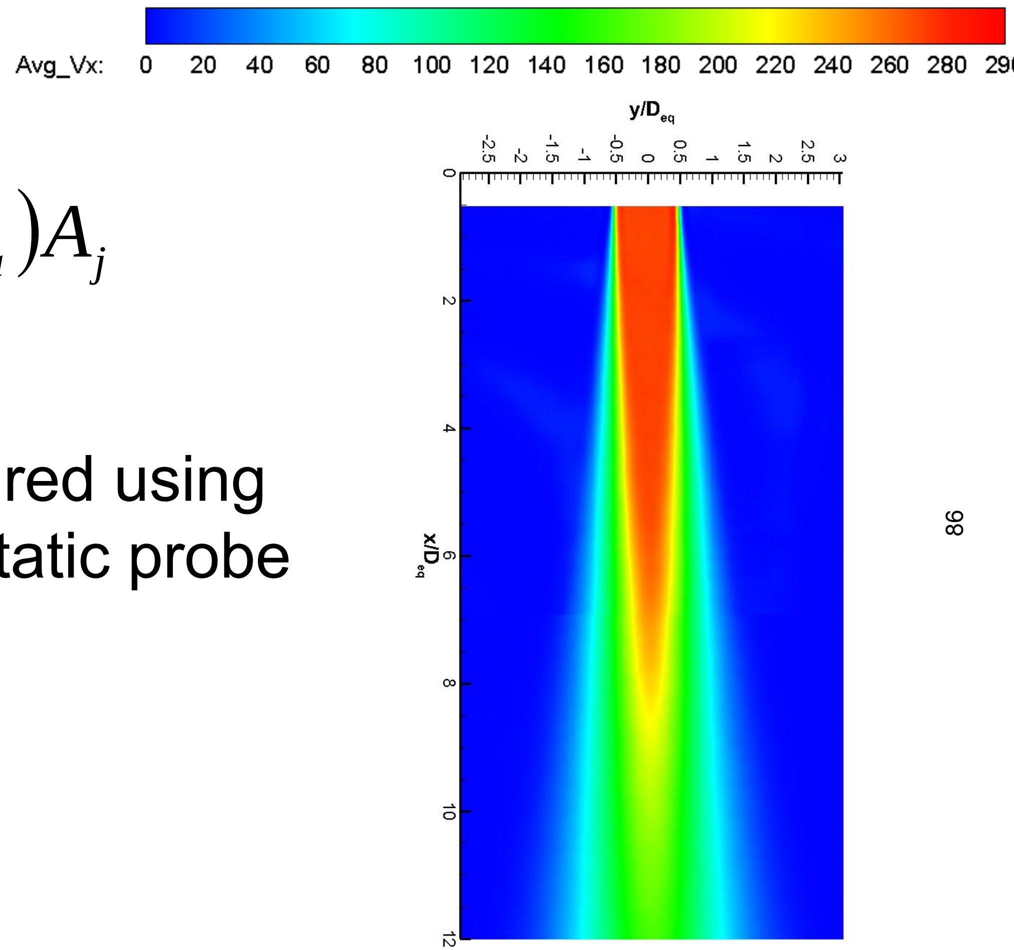
Thrust Measurements

$$F = F_m + F_p$$

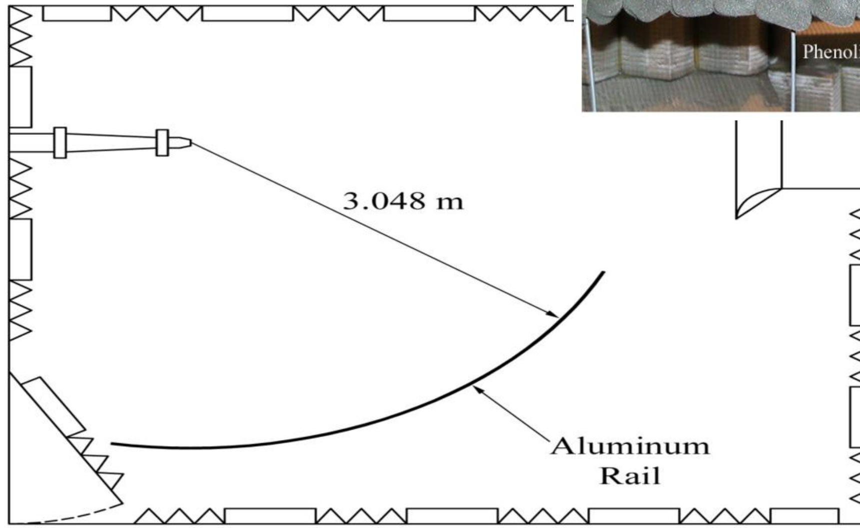
$$F = \dot{m}u_j + (p_e - p_a)A_j$$

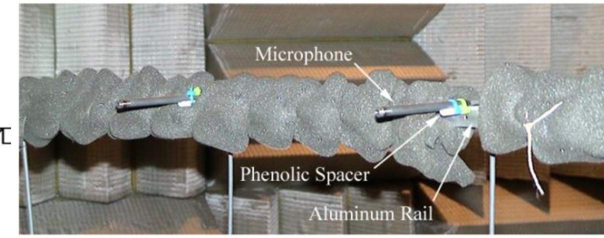
Measured using PIV

Measured using Pitot-static probe



Noise Measurements





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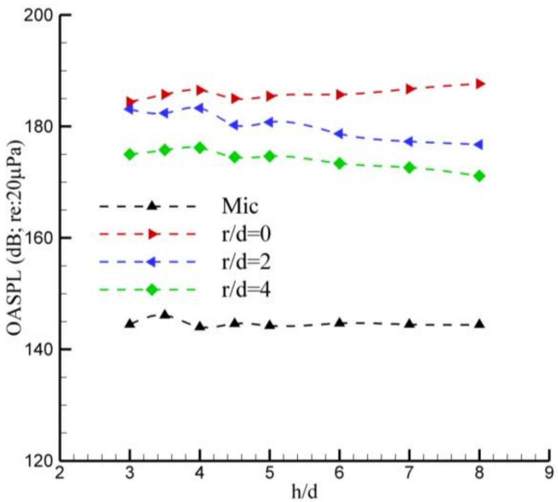
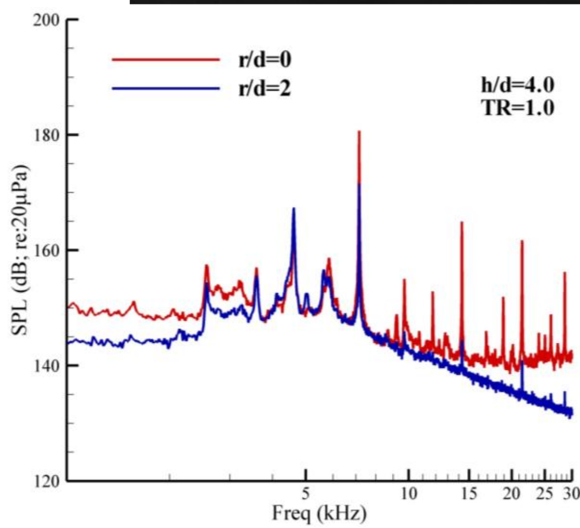
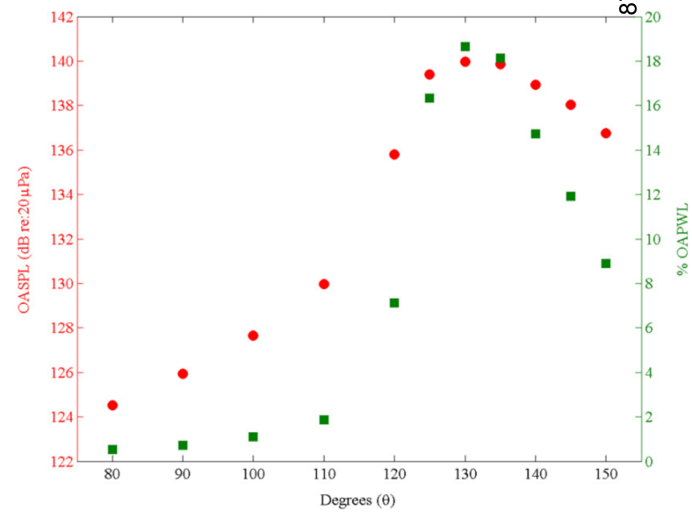


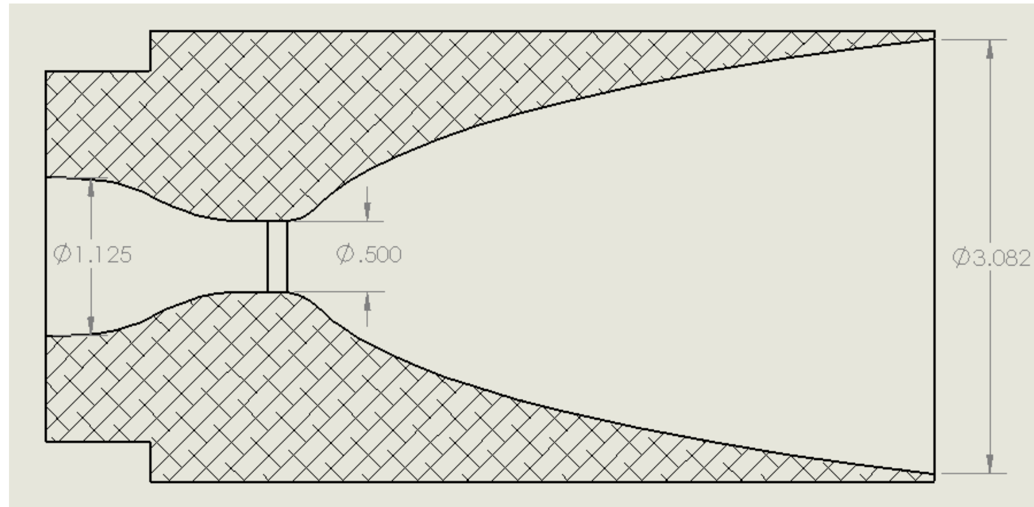




Schedule and Milestones

Task	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
Development of research plan												
Design and fabrication of nozzle												
Thrust measurements												
Noise measurements												

Preliminary Nozzle Design



Thrust optimized parabolic (TOP) contour nozzle

Design Mach Number: 5.6

A/A* = 38

Future Work

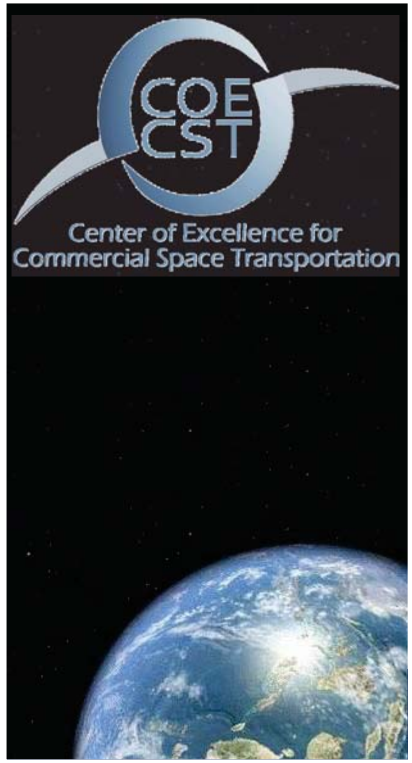
- Discussion with NASA / commercial launch manager (SpaceX).
- Detailed design to suit FSU jet facility and fabrication of TOP nozzle
- Instrumentation of jet facility to measure mass flow rate, exhaust velocity and pressure distributions at the nozzle exit

COE CST Fifth Annual Technical Meeting

Task 308: Assessment of Screening and Training Requirements for SFPs regarding Anxiety during Repeated Exposures to Sustained High Acceleration

James Vanderploeg, MD, MPH

October 27-28, 2015
Arlington, VA



Agenda

- Team Members
- Task Description
- Schedule
- Goals
- Results
- Conclusions and Future Work

Team Members

- Principal Investigator: James Vanderploeg, MD
- Co-Investigators: Rebecca Blue, MD; Tarah Castleberry, DO; Charles Mathers, MD
- Residents: **Robert Mulcahy, MD**; Ben Johansen, DO; James Pavela, MD; Rahul Suresh, MD
- Organizations
  - NASTAR Center – Matching Funds
  - Montclair University
  - Wyle

Task Description

- Space flight participant anxiety may present a significant problem for commercial spaceflight companies
- Currently no information about how to train SFP's for mental/physical challenges related to spaceflight environment
- Identify triggers for anxiety and mitigation approaches
- Identify optimum training methods to mitigate anxiety and enhance SFP enjoyment

Tolerance of centrifuge-simulated suborbital spaceflight by medical condition.

Aviat Space Environ Med. 2014 Jul;85(7):721-9.

Blue RS, Pattarini JM, Reyes DP, Mulcahy RA, Garbino A, Mathers CH, Vardiman JL, Castleberry TL, Vanderploeg JM.

RESULTS:

A total of 335 subjects registered for participation, of which 86 (63 men, 23 women, age 20-78 yr) participated in centrifuge trials. The most common causes for disqualification were weight and severe and uncontrolled medical or psychiatric disease. **Five subjects voluntarily withdrew from the second day of testing: three for anxiety reasons, one for back strain, and one for time constraints.** Maximum hemodynamic values recorded included HR of 192 bpm, systolic BP of 217 mmHg, and diastolic BP of 144 mmHg. Common subjective complaints included grayout (69%), nausea (20%), and chest discomfort (6%). Despite their medical history, no subject experienced significant adverse physiological responses to centrifuge profiles.

Subject anxiety and psychological considerations for centrifuge-simulated suborbital spaceflight

Aviat Space Environ Med. 2014 Aug;85(8):847-51.

Mulcahy RA, Blue RS, Vardiman JL, Mathers CH, Castleberry TL, Vanderploeg JM.

INTRODUCTION:
Anxiety and psychological concerns may pose a challenge to future commercial spaceflight. To help identify potential measures of anxiousness and indicators of flight-related stress, the psychiatric histories and anxiousness responses of volunteers exposed to G forces in centrifuge-simulated spaceflight acceleration profiles were examined.

METHODS:
Subjects completed a retrospective self-report anxiety questionnaire. Medical monitors identified individuals exhibiting varying degrees of anxiousness during centrifuge exposure, medical histories of psychiatric disease, and other potential indicators of psychological intolerance of spaceflight.

Subject anxiety and psychological considerations for centrifuge-simulated suborbital spaceflight

RESULTS:
The retrospective survey identified 18 individuals self-reporting anxiousness, commonly related to unfamiliarity with centrifuge acceleration and concerns regarding medical history. There were 12 individuals (5 men, 7 women, average age 46.2 yr) who were observed to have anxiety that interfered with their ability to complete training; of these, 4 reported anxiousness on their questionnaire and 9 ultimately completed the centrifuge profiles. Psychiatric history was not significantly associated with anxious symptoms.

DISCUSSION:
Anxiety is likely to be a relevant and potentially disabling problem for commercial spaceflight participants; however, positive psychiatric history and self-reported symptoms did not predict anxiety during centrifuge performance. Symptoms of anxiousness can often be ameliorated through training and coaching. Even highly anxious individuals are likely capable of tolerating commercial spaceflight.

Schedule

- Identify lay persons without acceleration experience
- Identify specific personality traits in individuals
- Identify response of personality traits to a range of training methods
  - Minimal training
  - Formal didactic
  - Experiential training
- Begin centrifuge runs in November 2015

Goals

- Provide data regarding how individuals with different personality types can best be prepared for suborbital spaceflight through training and anxiety mitigation techniques.
- Develop recommendations for optimum training protocols to reduce anxiety prior to and during suborbital flight

Results

- Pending

Conclusions and Future Work

- IRB approval completed
- 417 subjects registered
- 175 completed medical questionnaires
- 40 subjects scheduled
- Data collection will commence next month

Future Work

- Recruit and schedule120 more subjects

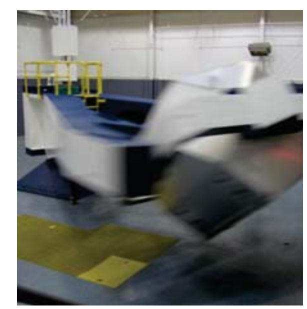
Task 308: Assessment of Screening and Training Requirements for SFPs regarding Anxiety during Repeated Exposures to Sustained High Acceleration

utmb Health Aerospace Medicine

Project At-A-Glance
- University: The University of Texas Medical Branch
- Principal Investigator: James Vanderploeg, MD
- Co-Investigators: Rebecca Blue, MD; Tarah Castleberry, DO; Charles Mathers, MD
- Residents: **Robert Mulcahy, MD**; Ben Johansen, DO; James Pavela, MD; Rahul Suresh, MD

Relevance to Commercial Spaceflight Industry
Psychological stressors can be significant challenges in the operational environment. This study will provide data regarding how individuals with different personality types can best be prepared for suborbital spaceflight through training and anxiety mitigation techniques.

Statement of Work
- Identify response of personality traits in individuals to a range of training methods
- Identify triggers for anxiety and mitigation approaches
- Develop recommendations for optimum training protocols to reduce anxiety prior to and during suborbital flight



Status
- IRB approval completed
- 40 subjects scheduled
- Data collection will commence next month

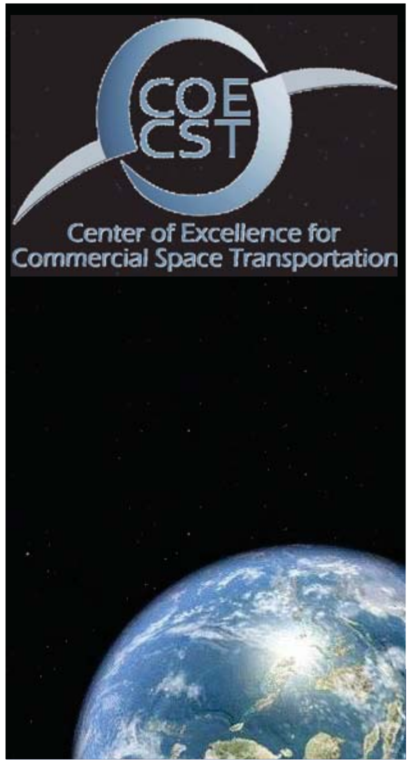
Future Work
- Conduct training and testing at NASTAR centrifuge through 12/2016
- Recruit 120 more subjects

COE CST Fifth Annual Technical Meeting

Task 309: Assessment of Screening and Training Requirements for Pilots with Repeated Exposures to Sustained High Acceleration

James Vanderploeg, MD, MPH

October 27-28, 2015
Arlington, VA



Agenda

- Team Members
- Task Description
- Schedule
- Goals
- Results
- Conclusions and Future Work

Team Members

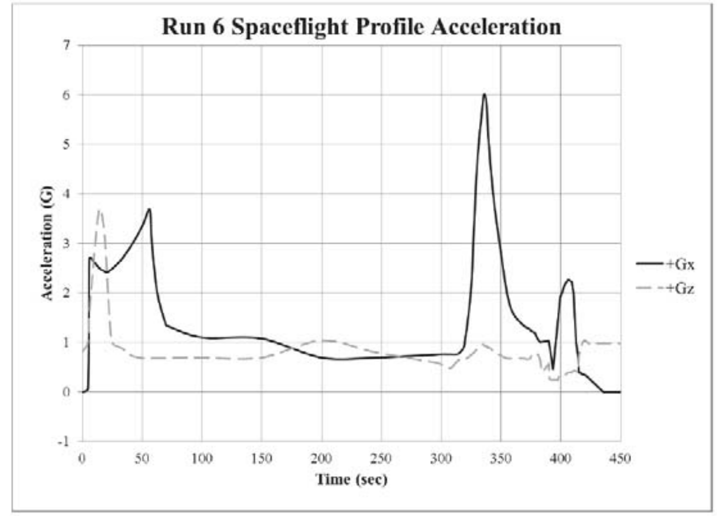
- Principal Investigator: James Vanderploeg, MD
- Co-Investigators: Rebecca Blue, MD; Tarah Castleberry, DO; Charles Mathers, MD
- Residents: **Benjamin Johansen, DO**; Robert Mulcahy, MD; James Pavela, MD; Rahul Suresh, MD

- Organizations
  - NASTAR Center – Matching Funds
  - Virgin Galactic

Task Description

- Repeated exposure of the flight crew to sustained high +Gx and +Gz acceleration in highly demanding spaceflight profiles is a new and untested paradigm.
- Identifying the unique physiological challenges and medical clearance requirements will enable spaceflight operators to ensure safe operations.

Vehicles



Task Description

Suborbital spaceflight profiles

- Combined +Gx and +Gz
- Peak +6.0Gx/+4.0Gz

Repeated exposures

Schedule

- Complete IRB approval process
- Recruit pilots for research study
- Conduct aerobatic flights and NASTAR testing throughout 2016
- Conduct physiological monitoring during spaceflights in 2016/2017

Goals

- Compare pilot performance and physiological response in aerobatic flights, centrifuge acceleration profiles, and actual spaceflight.
- Develop recommendations for pilot training and medical screening.

Results

- Pending

Conclusions and Future Work

- Collecting early data on acrobatic pilots flying sustained $+G_z$ exposures (i.e. prolonged G pull-outs from a dive or tight turns)
- IRB research protocol being prepared

Task 309: Assessment of Screening and Training Requirements for Pilots with Repeated Exposures to Sustained High Acceleration

utmb Health Aerospace Medicine

Project At-A-Glance

- University: The University of Texas Medical Branch
- Principal Investigator: James Vanderploeg, MD
- Co-Investigators: Rebecca Blue, MD; Tarah Castleberry, DO; Charles Mathers, MD
- Residents: **Benjamin Johansen, DO**; Robert Mulcahy, MD; James Pavela, MD; Rahul Suresh, MD

Relevance to Commercial Spaceflight Industry

- Repeated exposure of the crew to sustained high +Gx and +Gz acceleration in highly demanding spaceflight profiles is a new and untested paradigm. Identifying the unique physiological challenges and medical clearance requirements will enable spaceflight operators to ensure safe operations.

Statement of Work

- Compare pilot performance and physiological response in aerobatic flights, centrifuge acceleration profiles, and actual spaceflight.
- Develop recommendations for pilot training and medical screening.

Status

- Collecting early data on acrobatic pilots flying sustained G exposures
- IRB research protocol being prepared

Future Work

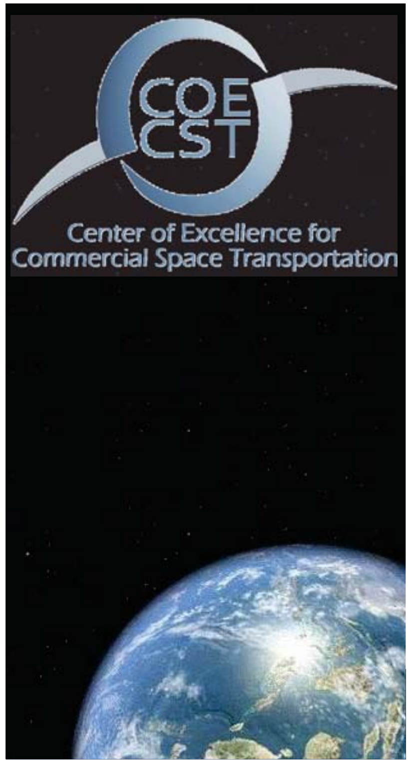
- Complete IRB approval process
- Recruit pilots for research study
- Conduct aerobatic flights and NASTAR testing throughout 2016
- Conduct physiological monitoring during spaceflights in 2016/2017

COE CST Fifth Annual Technical Meeting

Task 310: Assessment of methods, procedures, and technologies available for protection of SFPs in commercial spaceflight vehicles

James Vanderploeg, MD, MPH

October 27-28, 2015
Arlington, VA



Agenda

- Team Members
- Task Description
- Schedule
- Goals
- Results
- Conclusions and Future Work

Team Members

- Principal Investigator: James Vanderploeg, MD
- Co-Investigators: Charles Mathers, MD; Rebecca Blue, MD; Tarah Castleberry, DO
- Residents: Benjamin Johansen, DO; Robert Mulcahy, MD; Rahul Suresh, MD; James Pavela, MD

- Requesting data from commercial space flight companies

Task Description

- This project will evaluate methods to enhance the safety of the cabin environment and improve space vehicle crashworthiness, individual restraint systems, emergency evacuation systems, and survival equipment.

Schedule

- Complete literature review and analysis in 2015/2016
- Compare current spaceflight operators' interior cabin designs with historical precedents for cabin safety.

Goals

- Optimization of crew and passenger compartments to promote the survival of occupants during human spaceflight operations is a necessary component of vehicle interior fit out.
- Dedicated efforts towards the enhanced safety and advanced crashworthiness of spaceflight vehicles will improve the success of commercial space endeavors.

Results

- Pending

Conclusions and Future Work

- Literature search underway
- Students being trained in conducting and evaluating relevant literature review

Task 310: Assessment of methods, procedures, and technologies available for protection of SFPs in commercial spaceflight vehicles

utmb Health
Aerospace Medicine

Project At-A-Glance
- University: The University of Texas Medical Branch
- Principal Investigator: James Vanderploeg, MD
- Co-Investigators: Charles Mathers, MD; Rebecca Blue, MD; Tarah Castleberry, DO
- Residents: Benjamin Johansen, DO; Robert Mulcahy, MD; James Pavela, MD; Rahul Suresh, MD

Relevance to Commercial Spaceflight Industry
- Optimization of crew and passenger compartments to promote the survival of occupants during human spaceflight operations is a necessary component of vehicle interior fit out. Dedicated efforts towards the de-lethalization and advanced crashworthiness of spaceflight vehicles will improve the safety of commercial space endeavors.

Statement of Work
- This project will evaluate methods to enhance the safety of the cabin environment and improve space vehicle crashworthiness, individual restraint systems, emergency evacuation systems, and survival equipment.

Status
- Literature search underway
- Students being trained in conducting and evaluating relevant literature review

Future Work
- Complete literature review and analysis.
- Compare current spaceflight operators' interior cabin designs with historical precedents for cabin safety.

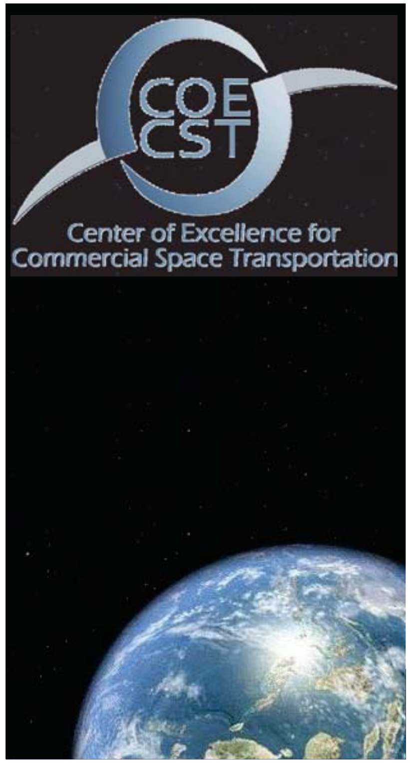
COE CST Fifth Annual Technical Meeting

TASK 320: Commercial Spaceflight Risk Assessment and Communication

Prof. David Klaus, Robert Ocampo

University of Colorado Boulder

October 27-28, 2015
Arlington, VA



Team Members

- Principal Investigator: **David Klaus**
- PhD Student: **Robert Ocampo**

University of Colorado Boulder

(no photo)

- FAA AST TM: **Henry Lampazzi**

Task Description

- **New Task 320 (2015-2016) Commercial Space Flight Risk Assessment and Communication**

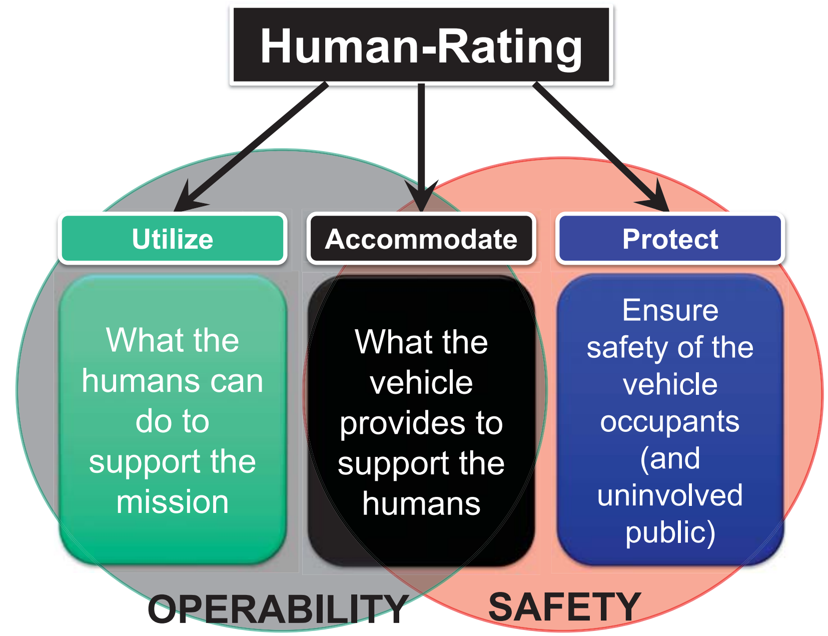
- *Prior Task 184 Human-Rating of Commercial Spacecraft (2011-2014) served as a baseline for this current research by addressing spacecraft human-rating processes and associated terminology*

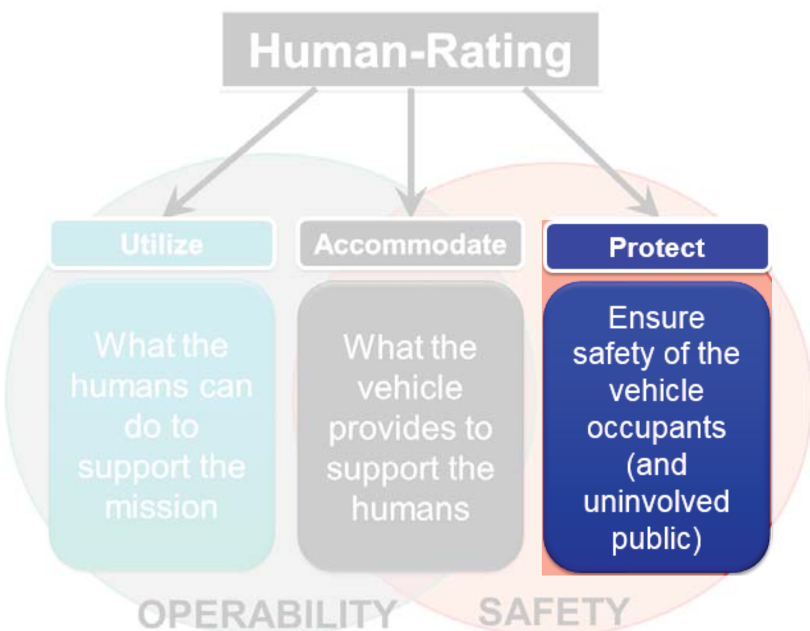
Prior Task 184 Results: COE Reports and Contributions to FAA Documents

1. Safe Return to Earth, 2012
2. Human Spaceflight Terminology and Definitions, 2013
3. Human Spaceflight Safety Terms and Definitions, 2013
4. Human Spaceflight Safety Perspectives, 2013
5. FAA Human-Rating Ground Rules and Assumptions Document (pre-decisional, 2013)
6. FAA Established Practices for Human Spaceflight Occupant Safety draft (7/31/13), with rationale (9/23/13)
7. Thoughts and Considerations on Necessary Levels of Care for Commercial Spaceflight Transportation, 2014
8. FAA Recommended Practices for Human Space Flight Occupant Safety Version 1.0, (8/27/2014)

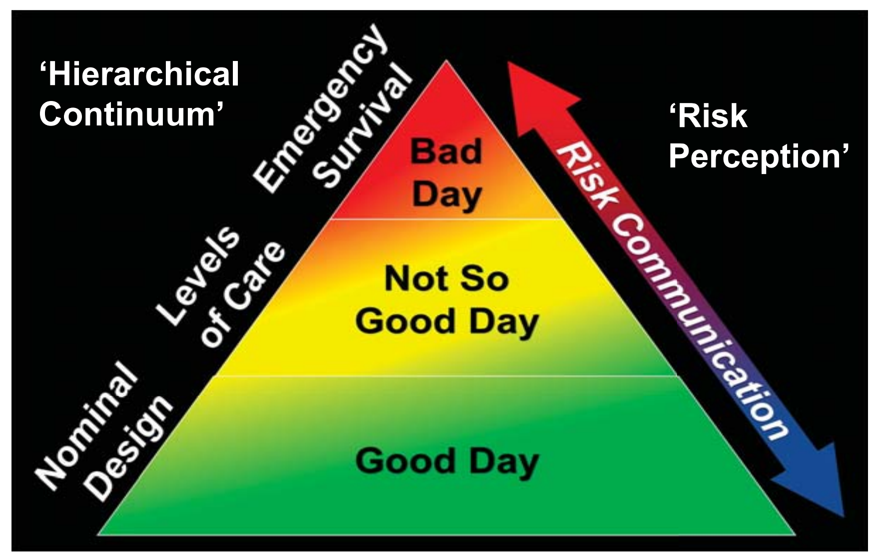
Prior Task 184 Results: Publications

1. Fanchiang, C. **Characterization and Evaluation of Manned Spacecraft Operability Factors**. *63rd IAC*, Naples, Italy, Oct 2012
2. Fanchiang, C., Johnson, M., and Ocampo, R. (2012) **Evaluation of Commercial Human Spaceflight Laws and Regulations in the United States**, IAC-12-D6.1.7 *63rd IAC*, Naples, Italy, Oct 2012
3. Klaus, D.M., Fanchiang, C. and Ocampo, R.P. (2012) **Perspectives on Spacecraft Human-Rating**. *AIAA* 2012-3419
4. Ocampo, R.P. and Klaus, D.M. (2013) **A Review of Spacecraft Safety: from Vostok to the International Space Station**. *New Space* 1(2): 73-80
5. Klaus, D.M., Ocampo, R.P. and Fanchiang, C. (2014) **Spacecraft Human-Rating: Historical Overview and Implementation Considerations**. *IEEE Aerospace Proceedings* (978-1-4799-1622-1/14, no. 2272)
6. Neis, S.M. and Klaus, D.M. (2014) **Considerations toward Defining Medical 'Levels of Care' for Commercial Spaceflight**. *New Space*, December 2014, **2(4)**: 165-177





Overall Task 320 Framework



Overall Task 320 Framework

- **Human-Rating Guidelines** – defined to help ensure likelihood of a ‘good day’ through risk mitigation and fault tolerant vehicle design
- **Medical ‘Levels of Care’** – intended to address minor (non-life threatening) injury or illness that might be considered a ‘not so good day’
- **Emergency Survival** – allow potential to deal with life-threatening illness/injury or recover from catastrophic vehicle failure to keep a ‘bad day’ from getting worse…

Task 320 Description

- **Commercial Spaceflight Risk Assessment and Communication**

- **Characterize** and **predict** risk factors of spaceflight and other transportation or adventure activities
- Develop effective, understandable ways to **identify**, **communicate** and **mitigate** the risks of spaceflight to space flight participants and the general public
- Summarize best practices with associated design safety **verification**

Schedule

June 1, 2015 through May 31, 2016

1) Provide a systematic framework for **characterizing risk** as a function of phase of spaceflight in terms of the range of scenarios from nominal ops to catastrophic vehicle failure and/or human illness or injury
2) Assess **risk prediction strategies**
3) Review prior spaceflight and terrestrial analogies to **effectively communicate risk** of space transportation to the public in a balanced, informing manner
4) Characterize **verification processes** aimed at ensuring the defined level of reliability (risk mitigation) is achieved for a given vehicle

Goals

- What does it mean for a spacecraft to be “Safe Enough”?
- How can “Safe Enough” be assessed using spacecraft risk progression statistics?
- How can we effectively communicate the relevant risks to space flight participants?
- What type of pre-hospital medical equipment and protocols are needed to assess and treat in-flight illness or injury and how is their implementation verified?

What is 'safe enough'?

Publication in prep for New Space

UNACHIEVABLE SAFE: System is free from all catastrophic hazards. Given that no practical (e.g. non-theoretical) system can ever be free of such hazards, this state is unachievable[2].

SAFE ENOUGH: System exhibits a mean probabilistic Loss of Crew—p(LOC)—value less than or equal to an established risk threshold (with a given level of statistical certainty)[2].

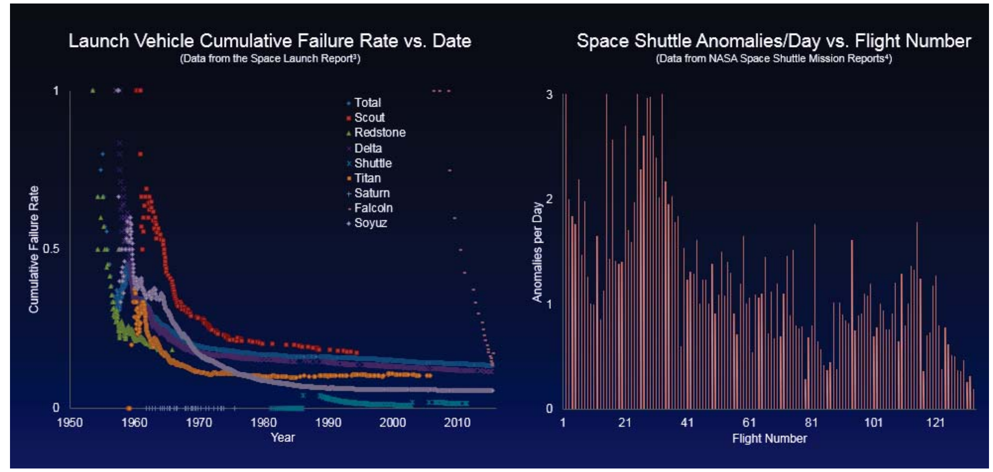
RISK THRESHOLD: A p(LOC) value chosen to distinguish "Safe Enough" from "Not Safe Enough". This value should attempt to balance what is acceptable with what is achievable[2].

UNSAFE: One or more catastrophic hazard(s) can occur. The likelihood of any one of these hazard(s) occurring is directly proportional to the degree to which the system is "Unsafe"[2].

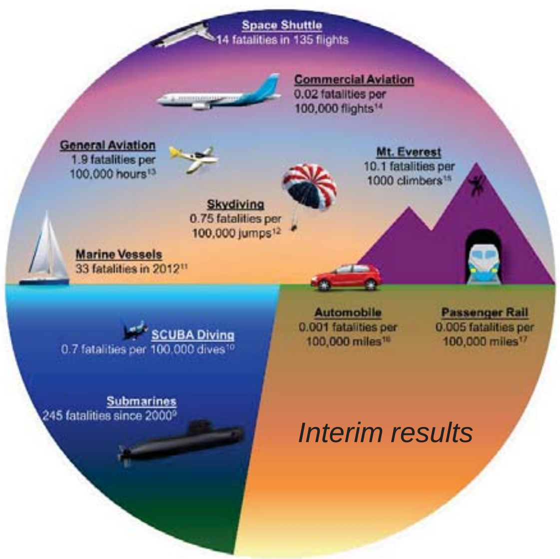
NOT SAFE ENOUGH: System that exhibits a mean p(LOC) value greater than an established risk threshold (with a given level of statistical certainty)[2].

RISK: The degree to which a system is unsafe[2].

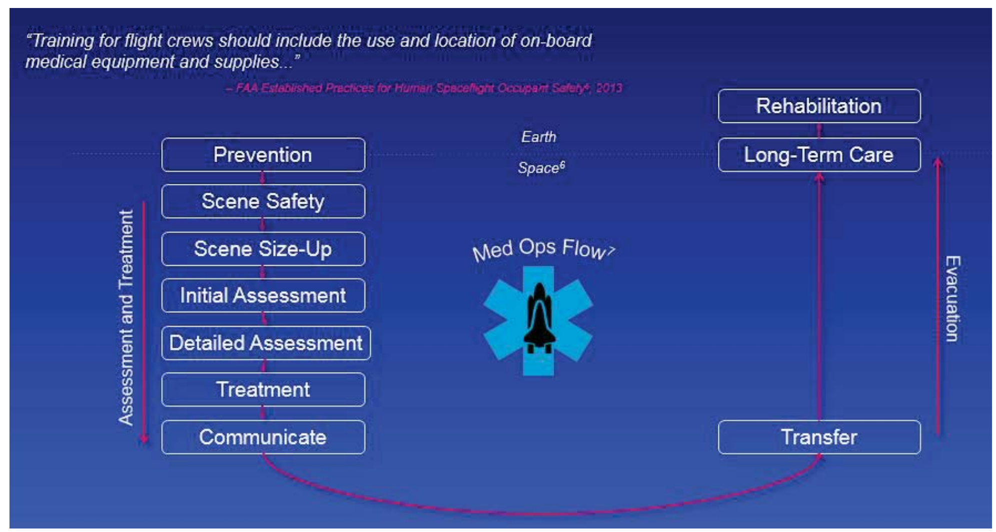
Risk Progression Analysis



Relative Risk Communication



Inflight Illness or Injury



Medical 'Levels of Care' for CST

- **Determining appropriate 'Level of Care' for commercial space flights should consider**
  - unique risks to each phase of suborbital or orbital flight
  - means of accommodating safety and medical concerns

- **Implementing an appropriate 'Level of Care'**
  - function of vehicle <u>design</u> and <u>operations</u>, including available <u>equipment</u> and personnel <u>training</u>

Results to date

- Ocampo, R.P. and Klaus, D.M. **A Quantitative Framework for Defining "How Safe is Safe Enough?" in Crewed Spacecraft** [in prep for submission to *New Space*]

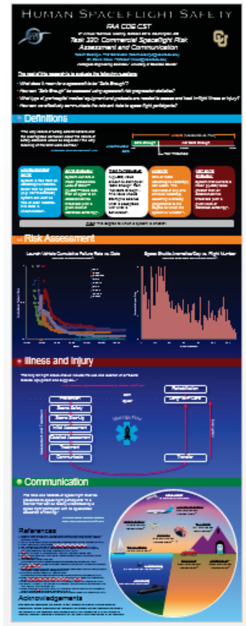
<u>Conclusions</u> and Future Work

- **The goal is not to ensure absolute freedom from hazards (not possible), rather an attempt to identify and minimize the risks incurred in the presence of hazards and failure potentials.**
- Risk is conveyed in terms *probabilistic prediction* of true (or actual) risk and ultimately realized as *actuarial outcome*.
  - <u>Actual risk decreases over time</u> as hazards are identified, mitigated, and controlled.
  - <u>Actuarial data</u> from U.S. and Soviet launch vehicles corroborate this claim, and indicate that risk tends to stabilize after a period of roughly 35 launches
  - <u>Assessment of risk</u> also becomes more refined over time as analysts gain both insight and experience with the system.
  - <u>Risk uncertainty</u>, as measured by PRA values, also showed a decline over the course of the Space Shuttle program. This suggests that as the total number of launches increase, the more accurately analysts can assess risk.

Conclusions and <u>Future Work</u>

- <u>Risk perception</u> strategies for effective communication to the general public in terms of more common, relevant terrestrial experiences will be addressed through literature review and analysis
- <u>Risk mitigation and verification</u> strategies will be evaluated
- <u>Human health-related</u> vehicle design concerns of interest within the proposed 'Good Day, Not So Good Day, Bad Day' framework will be coordinated with Dr. Jim Vanderploeg and colleagues at UTMB

TASK 320: Commercial Spaceflight Risk Assessment and Communication



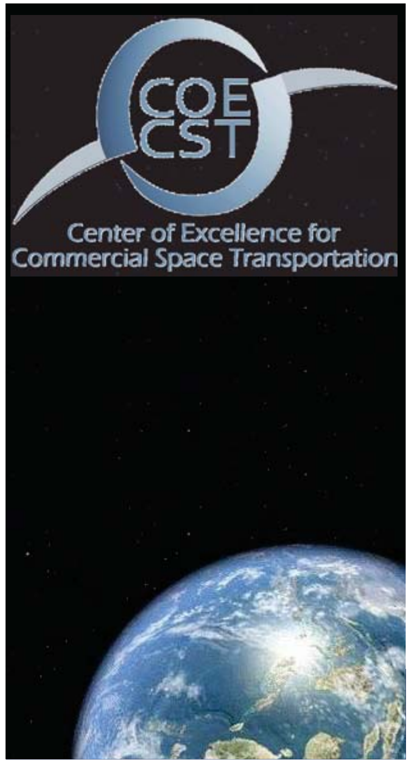
COE CST Fifth Annual Technical Meeting

Research Roadmapping Workshops

Task 193

Scott Hubbard, Jonah Zimmermann
Juan J. Alonso
Department of Aeronautics and Astronautics
Stanford University

October 27-28, 2015
Washington, DC

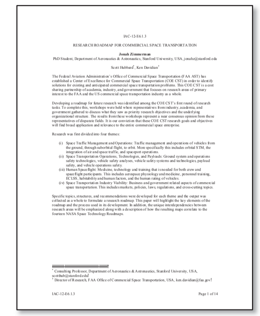


Background

In 2010, FAA established the FAA COE CST to identify research solutions to existing and anticipated CST problems. In addition:

- A research roadmap was identified as one of the first research tasks
- Workshops were held with representatives of industry, government, and academia
- A notional decomposition / program structure was created
- Results including research tasks (without prioritization) were compiled into a report in 2011

In 2015, it was recognized that the CST industry had undergone significant transformation and a revision of the roadmap (with prioritization in the research tasks) was needed.



Statement of Task

A summary of the updated (2015) research roadmap is described in this presentation

- It covers the same 4 major areas but modifications to the program structure were made
- Represents the consensus of experts in a host of interdisciplinary fields
- Revisits the prioritization of research tasks and includes near-term, high importance items
- Consensus achieved via discussion during five workshops held at different locations around the country, as well as virtually

The outcome represents the efforts of Prof. Scott Hubbard and (almost) Dr. Jonah Zimmermann, with the help of many.


Center of Excellence for Commercial Space Transportation
Research Roadmap Report

May/September 2015

Funded under FAA cooperative agreement 10-C-CST-SU-002
Prepared by: Scott Hubbard and Jonah Zimmerman

Contact Professor Scott Hubbard at Stanford University, Department of Aeronautics & Astronautics, Durand Building, 496 Lomita Mall, Stanford, CA 94305. Email: scotthub@stanford.edu

Research Themes

The basic structure of the research themes was taken from the 2011 roadmap and did not change significantly:

- Research Theme 1a: Space Traffic Management
- Research Theme 1b: Spaceport Operations
- Research Theme 2: Space Transportation Operations, Technologies & Systems
- Research Theme 3: Human Spaceflight
- Research Theme 4: Space Transportation Industry Viability

- Cross-Cutting Tasks and Integration

High-Priority Research

Sample, near-term high-priority research tasks in each of the themes:

- **Space Traffic Management**: Dynamic de-confliction for nominal and off-nominal operations and integrated procedures above / below FL600.
- **Spaceport Operations:** Provide guidance to spaceport operators and launch operators on emergency response and communications in the event of an incident
- **Space Transportation Operations, Technologies & Systems:** Develop, test, and refine promising flow control methods to reduce flow unsteadiness in rocket plume interactions with launch pad structures.
- **Human Spaceflight:** Research to determine the highest risk medical conditions that would require more data and need monitoring
- **Space Transportation Industry Viability:** Determine the government regulatory structure that will minimize cost to the industry while maximizing safety.

Research Theme 1a: Space Traffic Management

Focuses on two major areas:

1. Ideas, methods, and operations to safely and equitably share the NAS with minimal disruption caused by commercial space traffic (outbound and inbound), and
2. Space situational awareness of resident space objects and the potential safety implications of lack of separation.

Priority Research Tasks

Air/Space Traffic Management:

- Dynamic de-confliction for nominal and off-nominal operations
- Integrated procedures above / below FL600

Space Situational Awareness / Space Debris:

- Debris monitoring and forecasting methods
- Debris impact modeling and risk assessments

Example of a Current Research Task

Task 185: Unified 4-D Trajectory Approach for Integrated Traffic Management

Principal Investigator: Dr. Juan J. Alonso, Stanford University

The projected growth in demand for the use of the traditional airspace by commercial space transportation entities will make it increasingly difficult to accommodate launches on a Special Use Airspace basis. The purpose of this project is to use 4-D time-space probabilistic trajectories and safety assessments to develop the foundation of a plausible Integrated Airspace Management System. In the figure below, an example is shown of a compact envelope for a suborbital commercial spaceflight vehicle.

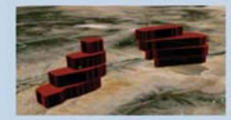


Figure 3. Example of a compact envelope for a Lynx-like vehicle

Research Theme 1b: Spaceport Operations

Facilitate the development, utilization, and operation of commercial spaceports by developing a framework to capture knowledge for spaceport operation best practices.

Priority Research Tasks

- Guidance to spaceport and launch operators on emergency response and communications in the event of an incident
- Expand the sections on insurance, indemnification, and waivers
- Query the users to identify information gaps by using survey techniques
- Encourage transparency in the agreements between spaceports and launch operators

Example of a Current Research Task

Task 220: Spaceport Operational Framework

PI: Pat Hynes, New Mexico State

The commercial space industry has not assembled a body of knowledge for commercial spaceports. The purpose of this task is to develop a framework for the body of knowledge, encompassing the activities conducted at a commercial spaceport. Below, the top level breakdown of the framework is shown.

Reference	Topic
1.0	AIRFIELD & LAUNCH OPERATIONS
2.0	SITE SECURITY
3.0	EMERGENCY RESPONSE
4.0	VISITOR MANAGEMENT
5.0	GROUND AND FLIGHT SAFETY
6.0	ENVIRONMENTAL MANAGEMENT
7.0	MISSION READINESS
8.0	ITAR REQUIREMENTS
9.0	INTERNATIONAL COORDINATION AMONG SPACEPORTS
10.0	SELF-INSPECTION

Figure 4. Top level breakdown of the commercial spaceport framework

Research Theme 2: Space Transportation Operations, Technologies & Systems

Focuses on enabling and enhancing the safety, reliability, and efficiency of commercial space vehicles.

Priority Research Tasks / Areas

- Devices: Sensors and Actuators for Enhanced Aircraft Safety
- Advanced Materials and Structures
- Aerothermal Environment – Test and Simulation
- Technology Transition

Including (near term): advanced materials, structures, and sensors that have shown promising results; modeling the space vehicle environment; leveraging the distributed capabilities of the COE members.

Example of a Current Research Task

Task 299: Nitrous Oxide Composite Case Testing

PIs: Warren Ostergren, Robert Abernathy, Michael Hargather, Andrei Zagrai, New Mexico Tech

Nitrous oxide is a popular oxidizer for rocket propulsion systems in commercial spaceflight, and is commonly stored in lightweight composite tanks. The purpose of this task is to develop an understanding of fragmentation hazards from such tanks in order to set guidelines for proper safe distances. In the picture below, a composite panel is mounted in a test setup that can produce shock waves.

Figure 5. Test fixture for shock wave loading of composite panels

Research Theme 3: Human Spaceflight

Concerned with the physiology, medicine, technology and training that impact safety and performance of both crew and spaceflight participants (SFPs). Research is in two primary areas:

1. Protection of the health and safety of crew and spaceflight participants, and
2. Identification and reduction of avoidable risks of human spaceflight.

Priority Research Tasks / Areas
- Vehicle life support and survivability
- Medical standards for crew and acceptance criteria for spaceflight participants
- Training and adaptation
- Operational support
- Physiological monitoring
- Data analysis and database repository

Example of a Current Research Task

Task 256: Tolerance of Centrifuge-Induced G-Force by Disease State

PI: James Vanderploeg, University of Texas Medical Branch

There is currently little to no data on how individuals with chronic diseases will perform in a high-performance environment such as commercial spaceflight. The purpose of this task is to produce such data by testing participants with various common medical conditions in the NASTAR centrifuge and use these resulting data to develop risk mitigation strategies. Below, the types of medical conditions tested are shown.

Figure 6. Past medical history of participants in the study

Research Theme 4: Space Transportation Industry Viability

Support effective policy decision-making in the accomplishment of the dual regulatory and promotional missions of FAA AST. Includes economic, legal, legislative, regulatory, and market effects.

Priority Research Tasks / Areas
1. What defines an industry and does the commercial space transportation have an accepted definition of the industry?
2. **Adoption of CST and the adoption of the aviation industry.**
3. Cross-over of aviation and space transportation regulatory authority domestically and internationally
4. Industry access to public data and lessons learned for human space flight.
5. Identify macro level trends across multiple industries that consistently effect rapid industry proliferation.
6. What is an appropriate amount of government regulation that will stimulate growth in the industry while achieving the objective of protection of public safety?
7. **What government regulatory structure will minimize cost to the industry while maximizing safety concerns?**

Example of a Current Research Task

Task 193: Role of COE CST in EFP

PI: George Born, CU Boulder

The FAA COE program has three primary goals: research, training, and outreach. This activity emphasizes COE CST's outreach goal by engaging students in graduate seminar activities, conference attendance that emphasizes commercial space topics, and the execution of specific research work for presentation at professional space conferences in commercial space paper sessions. In Figure 5, students are shown at the first Emerging Space Industry Leaders Conference.

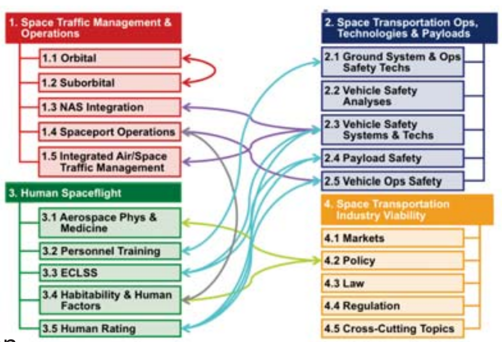
Figure 7. ESIL-01 Conference in Boulder, CO

Cross-Cutting Tasks & Integration

- Multiple tasks belong under more than one theme
- Interaction may be one-way or two-way.
- Different paradigms for interaction

Some examples:

- Equipage and STM
- Flight diagnostics & ECLSS
- Payload safety & occupant protection
- SV safety & spaceport ops
- ECLSS & Policy
- Human rating & vehicle/ops safety
- Passengers and space transportation operations, technologies and payloads



Acknowledgements

This roadmap was made possible through the efforts of:

- **Research Roadmap PM**: Ken Davidian
- **PI:** Scott Hubbard, SU with help from Jonah Zimmermann
- **Workshop Theme 1a:** Juan J. Alonso, SU
- **Workshop Theme 1b:** Patricia Hynes, NMSU
- **Workshop Theme 2:** Farrukh Alvi, FSU
- **Workshop Theme 3:** Jim Vanderploeg, UTMB Galveston
- **Workshop Theme 4:** Tristan Fiedler / Scott Benjamin, FIT

… and the participation and contributions of nearly 70 experts from academia, government, and industry.

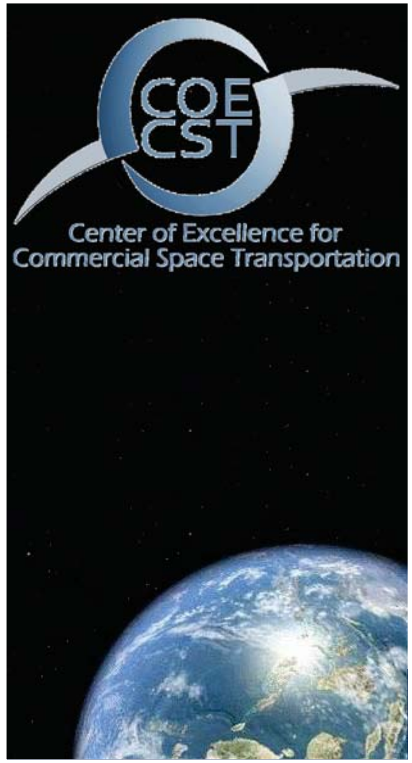
Thanks!

COE CST Fifth Annual Technical Meeting

Task 193:Role of COE CST in EFP

PI: George H. Born
Bradley Cheetham

October 27-28, 2015
Washington, DC



Agenda

- Team Members
- Purpose of Task
- ESIL
- Other Support
- Publications
- Next Steps
- Contact Information

Team Members

- **George H. Born** – Director Emeritus, Colorado Center for Astrodynamics Research
- **Bradley Cheetham** – Instructor/Researcher, CU Boulder, Aerospace Engineering Sciences

Team Members – Sponsors

LOCKHEED MARTIN

SNC SIERRA NEVADA CORPORATION Space Systems

Team Members – Supporters

- William Pomerantz – Virgin Galactic
- Greg Autry – UC Irvine
- Scott Hubbard – Stanford Univ.
- Dan Lopez – Urthecast
- Julian Mann – Skybox
- Art Anisimov – Dauria Aerospace
- Jordon Croom – SSL
- Ward Hanson – SIEPR
- Bruce Pittman – NASA
- Steve Jurvetson – DFJ
- Robert Lightfoot – NASA
- George Nield – FAA
- David Brandt – LMCO
- A.C. Charania – Virgin Galactic
- Charles Miller
- Mischa Fisher
- Carissa Christensen – Tauri Group
- Richard Dalbello - OSTP
- Lori Garver - ALPA

Task Purpose

Objectives:

- Identify key industry characteristics to facilitate EFP efforts
- Host targeted workshops to engage students and young professionals
- Support conferences to educate students and young professionals
- Incorporate young professional perspectives in ongoing industry planning efforts

COE Research Objectives

Research

- Products of workshop and ongoing EFP supporting activities

Training

- Emerging Space Industry Leaders Workshop Series

Outreach

- Disseminating activity results, promoting a broader understanding of commercial space

ESIL Workshops

- Emerging Space Industry Leaders Workshop series
- Objectives:
  - Inform – perspective, background, context
  - Perform – group analysis
  - Network – internal and external to industry
- Impact:
  - 83 participants
  - 3 publications complete

ESIL-01 – October 2011

- 26 participants
- Industry segments:
  - Point-to-point
  - Lunar Mining
  - Hosted Payloads
- Guest Contributors
  - Dennis Stone – NASA JSC
  - Max Vozoff – mv2space
  - Diane Dimeff - eSpace

ESIL-02 – March 2012

- 12 Participants
- Industry focus:
  - Government role in commercial space
- Guest contributors
  - Richard Dunn – DoD Acq.
  - Chris Shank – dCoS L. Smith
  - Alan Ladwig – NASA HQ
  - James Finch – OSD
  - Jim Van Laak – FAA AST
  - Clay Mowry - Arianespace

ESIL-03 – November 2012

- 10 Participants
- Industry focus:
  - Commercial human spaceflight training
- Guest Contributors
  - Brienna Henwood

ESIL-04 – June 2013

- 14 Participants
- Industry focus:
  - Microgravity utilization
- Guest contributors:
  - Sirisha Bandla – CSF
  - Cassie Kloberdanz – SNC
  - Dan Durda – SwRI
  - Khaki Rodway – XCOR

ESIL-05 – November 2013

- 5 Participants
- Industry focus:
  - Smallsat dedicated launcher
- Guest Contributors:
  - William Pomerantz – Virgin Galactic

ESIL-06 – May 2014

- 7 Participants
- Industry focus:
  - Commercial remote sensing
- Guest Contributors:
  - Greg Autry – UC Irvine
  - Scott Hubbard – Stanford Univ.
  - Dan Lopez – Urthecast
  - Julian Mann – Skybox
  - Art Anisimov – Dauria Aerospace
  - Jordon Croom – SSL
  - Ward Hanson – SIEPR
  - Bruce Pittman – NASA
  - Steve Jurvetson – DFJ

ESIL-07 – May 2014

- 12 Participants
- Industry focus:
  - Student non-profit strategy
- Guest contributors:
  - Robert Lightfoot – NASA
  - George Nield – FAA
  - David Brandt – LMCO
  - A.C. Charania – Virgin Galactic
  - Charles Miller
  - Mischa Fisher
  - Carissa Christensen -Tauri Group
  - Richard Dalbello - OSTP
  - Lori Garver - ALPA

Impact

Support Other Events

- SpaceVision Conference (2011, 2012, 2014, 2015)
  - Logistics/planning/speaker support
- Space Generation Fusion Forum (2012, 2013, 2014)
  - Logistics/planning/speaker support
  - Video recording support

Publications/Presentations

- Bandla, Sirisha, Bradley Cheetham, Rachel Hakeem, and Luis Zea, **Applying Insights of Game Theory to the Microgravity Utilization Market**, 65th International Astronautical Congress, Toronto Canada, IAC-14,E6,3,3,x24346
- Henwood, Brienna, Nathan Wong, John Stark, Ken Davidian, Bradley Cheetham, Kaizad Raimalwala, Matt Cannella, Liz Kennick, Sirisha Bandla, Jules Feldhacker, and Jim Crowell, **"The 'Game' of Training Humans for Commercial Suborbital Spaceflight,"** 64th International Astronautical Congress, Beijing China, IAC-13-E6.2.3
- Cheetham, Bradley, Juliana Feldhacker, Angela Peura, Ashley Chandler, Cassie Kloberdanz, and Lewis Groswald, **"Government's Role in Commercial Space from the Perspective of Emerging Industry Leaders,"** 63rd International Astronautical Congress, Naples Italy, IAC-12-E6.4-D4.2.1.

Next Steps

- Get to ESIL-10
  - Planning stages of 3 more ESIL workshops
  - Considering
    - DC in March
    - NYC, LA, and/or Seattle as destinations
- Seeking partner organizations to continue efforts
  - Multiple expressions of interest
  - Goal is to continue with "franchise model"

Contact Information

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Bradley.Cheetham@Colorado.edu

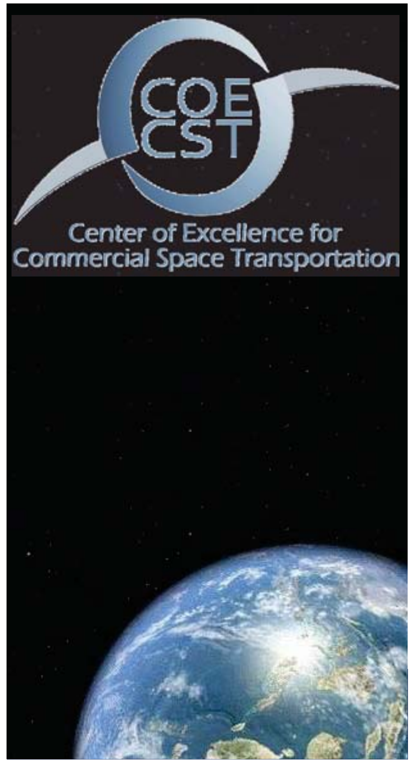
Bit.ly/ESIL_Home

COE CST Fifth Annual Technical Meeting

Space Transportation Industry Viability

Dr. Scott Benjamin
Taylor Smith
Arion Gray

October 27-28, 2015
Arlington, VA



Agenda

- Team Members
- Task Description
- Schedule
- Goals
- Results
- Conclusions and Future Work

Team Members- People

Dr. Scott Benjamin

Principal Investigator- Associate Professor at Florida Institute of Technology, Director for the Center of Entrepreneurship and New Business

Taylor Smith

Student- Current Graduate Student Studying for her MBA, Expected Graduation is Fall 2015

Arion Gray

Student- Current Undergraduate Student Studying Aerospace Engineering, Expected Graduation is Spring 2017

Team Members- Partner

Greg Autry

Assistant Professor of Clinical Entrepreneurship at USC Marshall School of Business

Task Description

- To understand the industry structure, conduct and performance of firms in the suborbital space transportation industry by using Porter's Five Forces Model to help develop a general understanding of profitability given the interaction of stakeholders.

Schedule

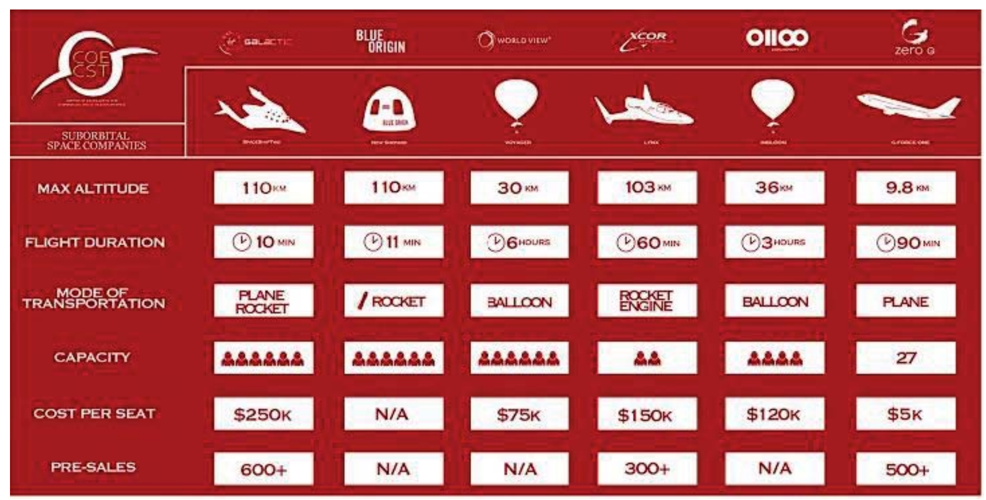
Semester and Year	Completed Tasks
Fall 2014	Understanding the Industry Needs
Spring 2015	Literature Review and Data
Summer 2015	Interviews Conducted and Data Analyzed
Fall 2015	Interviews Conducted, Writing Conclusions and Publishing Results

Goals

- To define the industry and its competitors
- Conduct a Porter's Five Forces analysis in order to evaluate competitive rivalry and industry profitability

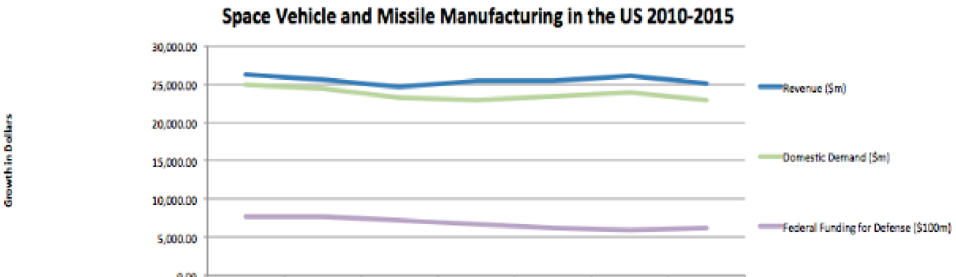
Results

The Current Competitors Within The Industry



Results

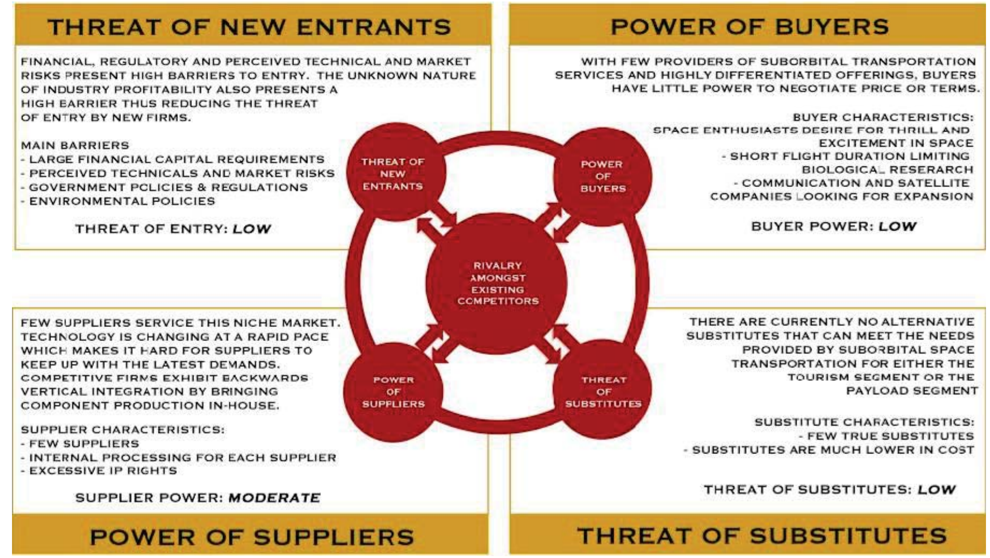
Industry Current and Future Growth



	2010	2011	2012	2013	2014	2015	2016
Revenue ($m)	26,289.30	25,514.20	24,645.30	25,343.50	25,469.40	26,098.80	25,053.10
Domestic Demand ($m)	24,851.20	24,342.40	23,268.50	22,938.10	23,503.10	23,888.40	22,855.00
Federal Funding for Defense ($100m)	7,688	7,663	7,230	6,661	6,217	5,975	6,155

Years

Results



Conclusions

- Oligopolistic industry in nature
- Growth has remained flat within the industry, though the progression of commercial space flights could bring growth to the industry
- Rivalry among competitors will not be price competitive, instead they will compete on differentiation factors, such as flight path

Conclusions and Future Work

- Future work
  - Industry Adoption: A Comparative Analysis Between Commercial Aviation and Commercial Space Transportation

ATM5 - October 2015

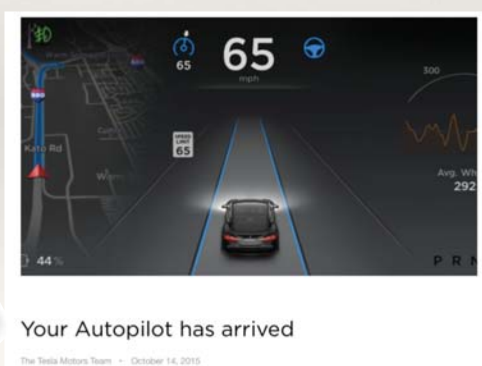
Deregulation Lessons from the Internet

Dr. Ward Hanson
Dr. Greg Rosston

Stanford Institute for
Economic Policy Research

Idea 1: Interesting Things Happen When Industries Collide

Vehicles + Machine Learning



Space + Television

Launch of DirectTV 12

+

Broadcast television is the Dominant share of Current Commercial Space Service Revenues

What commercial space marketing looks like:
"High voice" Peyton Manning, due to cable.

Idea 2: Deregulation is a powerful force of change.

What industry?

Grew slowly for 25 years, fostered primarily by military, scientific, and governmental agency support?

Developed powerful capabilities in research labs, with access by only a select few?

Prohibited a wide range of commercial activities, as incompatible with its core missions?

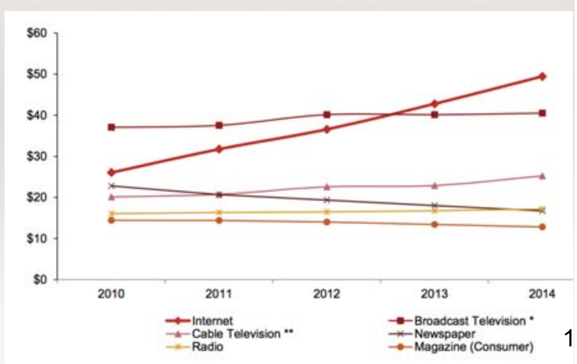
Had core aspects of its infrastructure controlled by a monopoly, very skeptical of entry and capable of persuading government officials to hinder competition?

Internet Has Been Commercial for (only) 20 years

October 1994: Very first Internet Ad

By 2014, Internet advertising surpassed television as the #1 advertising venue in the United States.

Worldwide, more than 2 billion users and rising rapidly.



Key Deregulation Steps

- Judge Greene follows *U.S. Justice Department* and breaks up the Bell system in the 1980s,
- *National Science Foundation* spins off the Internet backbone, and drops its *Acceptable Use Policy. (1992-1993)*
- *Federal Communication Commission* auctions spectrum and allows wide use of unlicensed spectrum *(mid 1990s onward)*
- *National scientific laboratories* (mostly) encourage open source usage of its intellectual property - especially *World Wide Web* (CERN, 1990) and *Browser (1993, NCSA)*
- *U.S. Congress* alters tax code, encouraging venture capital funds. (late 1980s)
- *Policy consensus* of Congress & Executive Branch encourages end-to-end neutrality, limits Internet taxes, and allows informal governance of Internet standards. (1990s onward)

Current Efforts

Synthesizing Internet lessons, applying to commercial space.

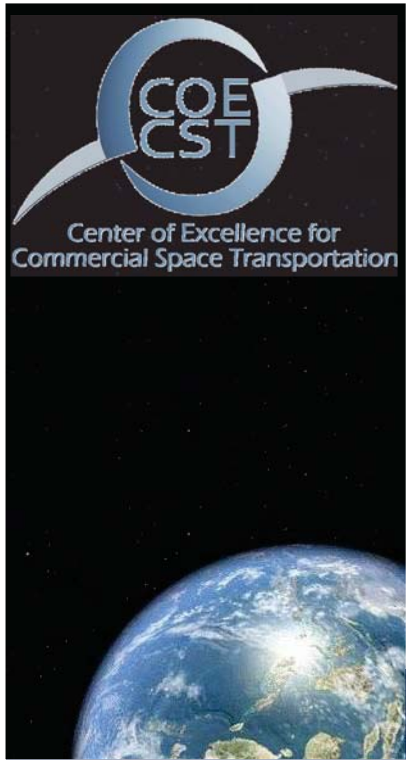
The collision of commercial space and high speed Internet access.

COE CST Fifth Annual Technical Meeting

Insurers as Regulators of Space Safety and Sustainability

Dr. Ram Jakhu
Andrea Harrington

October 27-28, 2015
Arlington, VA



Agenda

- Team Members
- Task Description
- Schedule
- Goals
- Results
- Conclusions and Future Work

Team Members

Dr. Ram Jakhu

Peace Through Governance
Arsenault Family Foundation

Andrea Harrington

Task Description & Context

- Lack of political will for new binding international requirements, national or agency requirements are not necessarily harmonized
- Technology is changing and advancing; Need exists to balance safety and sustainability with commercial viability
- Insurance is the 3rd greatest cost
- Space insurance industry needs to evolve
- Insurers can set requirements to obtain insurance or premium levels for levels of compliance
- Precedent for insurer-led regulation exists

Schedule

- Area of research was proposed by Andrea Harrington for supervision by Ram Jakhu in 2013
  - Since then, presentations have been made at a half dozen conferences with papers produced on the topic, significant progress has been made
- Discussed and accepted as a topic for CoE CST attention in early 2015 following completion of last year's CoE CST research goals

Goals:

- Explore issues inherent in the offering, procurement, and handling of traditional areas of space insurance
- Provide public policy and regulatory explanations and recommendations
- Compare aviation and space insurance in the context of reusable craft
- Analyze the role of informed consent and liability waivers / insurance for spaceflight participants

Goals: Evaulate possibility of insurers:

<u>Setting standards for debris mitigation:</u>

- Limitations on mission-related debris
- End-of-life requirements to meet or exceed other guidelines
- Technical capability evaluation: evasion, graveyarding, shielding

<u>Providing collision avoidance services:</u>

- Purchase situational awareness services, act as point of contact for all insureds
- Provide technical guidance re: possible maneuvers

Results (Presentations with Papers)

- *Spaceflight Participant Liability and Insurance*, DCL Research Series (Montreal) November 2014
- *Risk Management in the Intermediate Frontier*, 3rd Manfred Lachs International Conference on NewSpace Commercialization and the Law (Montreal) March 2015
- *Leveraging Insurance for Commercial Space: Managing Legal and Regulatory Challenges*, 31st Space Symposium (Colorado Springs) April 2015
- *Debris Mitigation as an Insurance Imperative*, IAC (Jerusalem) October 2015
- *Innovations for Insurers in Space Traffic Management and Weather Forecasting*, Space Traffic Management (Daytona Beach, FL) November 2015

Results (Related Publications)

- *Legal Considerations for Commercial Space: An Overview* in New Space Volume 3: Issue 2 (2015)
- *State Spaceflight Liability and Immunity Acts in Context in Emerging Space Activities*, Leuven Global Governance Series, Edward Elgar Publishers (accepted and awaiting publication)
- *Legal And Regulatory Challenges To Leveraging Insurance For Commercial Space*, submitted and under review by Journal of Space Law

Conclusions and Future Work

- Final Remarks: Important not to underestimate the role of insurance in the development of the commercial space industry

- Next steps: Completion of Andrea's Thesis & Thesis Defense (1st half of 2016), *Risk Management in Space: Insurance and Legal Issues in the Growth of Commercial Space Activities*; publication of comprehensive volume

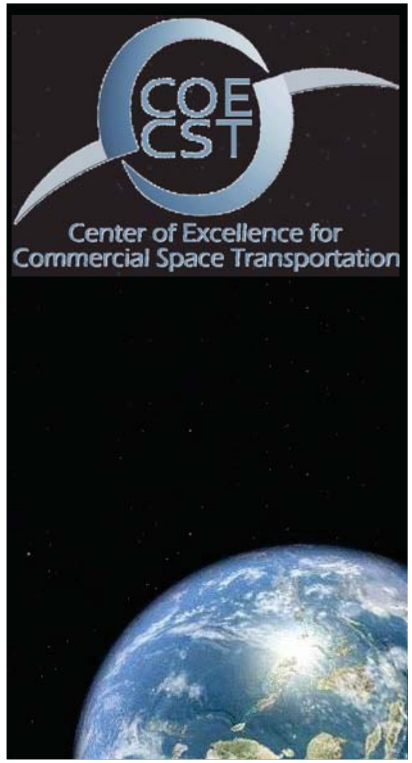
COE CST Fifth Annual Technical Meeting

UAT ADS-B Research and Demonstration for Commercial Space Applications: Progress Report

Richard S. Stansbury

Student:
Brandon Neugebauer
Dominic Tournour
Dylan Rudolph
Richard Day
Yosvany Alonso

October 27-28, 2015
Arlington, VA



Agenda

- Team Members
- Project Overview
- Collaboration with Terminal Velocity Aerospace
- Maturation plan and follow-on research plans

Team Members

- **<u>People</u>**
  - Principal Investigators: Richard S. Stansbury
  - Students: Brandon Neugebauer, Richard P. Day, Yosvany Alonso, Dyland Rudolph, and Dominic Tournour
  - Other faculty: William C. Barott, Massood Towhidnejad
  - FAA: Nick Demidovich, Chuck Greenlow, John Dinofrio, and others.
  - MITRE: Dave Edwards
- **<u>Organizations</u>**
  - Terminal Velocity Aerospace, LLC.
    - Dominic Depasquale
  - NASA Flight Opportunities Program
    - Up Aerospace
    - Near Space Corporation

EMBRY-RIDDLE Aeronautical University

Terminal Velocity Aerospace, LLC
A SpaceWorks Company

Goals

- Enhance tracking of vehicles as they traverse through the national airspace system to mitigate the impact of commercial space operations on routine aviation operations
- Sub-goals goals:
  - Determine suitability for ADS-B for commercial space
  - Determine boundary conditions of system performance
  - Assess performance of prototypes on space vehicles and suitable analogues
  - Identify areas of improvement in ADS-B standard to accommodate ADS-B operation
  - Provide stakeholders with information regarding suitability of ADS-B as a primary or secondary tracking source

MITRE UBR-TX

- UAT Beacon Radio – Transmit Only (UBR-TX)
  - Broadcasts state vector once per second
  - Supports both barometric and GPS-based altitudes
- Balloon / Rocket Flight Tests
  - 2008 Red Glare V (amateur rocket)
  - 2009 Red Glare VII (amateur rocket)
  - 2010 AFRL research balloon
  - 2010 NASA Wallops sounding rocket
  - 2012 Up Aerospace Spaceloft 6
  - 2012 Team America Rocket Challenge
  - 2013 Up Aerospace Spaceloft 7
  - 2013 Masten Xombie

MITRE TECHNOLOGY APPLIED

Past Flights:
- **NSC Nano Balloon System**
- **NSC High Altitude Shuttle System**
- **Up Aerospace SpaceLoft-8**
- **NSC Small Balloon System w/ TVA Spacecraft**

Maximum Altitude: 349,700 ft (SL-8)

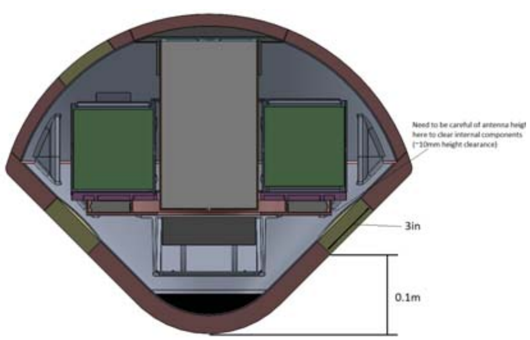
Parameter	Specification
Length	5.75" (14.6 cm)
Width	2.5" (6.35 cm)
Height	2.5" (6.35 cm)
Weight (UBR board, daughter board, GPS, battery, and enclosure)	790 g (27.9 oz)
Weight (cables, antennas, etc.)	85-300g est.
Nominal power Consumption	840mA @ 3VDC
Nominal battery capacity	7.75 Ah

UBR-ERAU Advanced ADS-B Transmitter for sRLVs

Upgraded firmware and GPS hardware

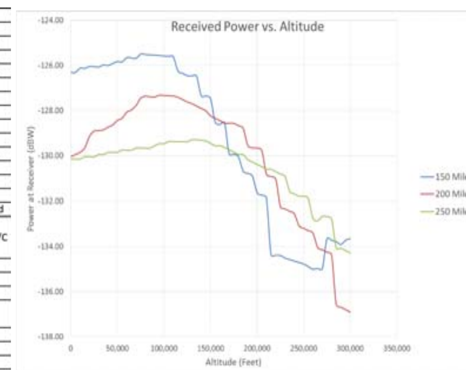
Terminal Velocity Aerospace

- Integration of Advanced ADS-B Unit onboard reentry vehicle
- Funded by NASA Ames
- Goals:
  - Evaluate performance of ADS-B broadcasting through experimental TPS material
  - Demonstration of UBR on new vehicle type



Link Budget Analysis

Link Budget ADS-B				
	Symbols	Data	Units	Deviation
Frequency	f	978	MHz	0.3125
Wavelength	λ	0.30654	m	0.000006
Modulation Rate	B	1.041667	Megabits/sec	
Altitude	h	45.72	km	
Distance	d	241.4	km	
Offset Angle	ϴ	10.72	degrees	
	Symbols	Gain/Loss	Units	Equation
Transmitter	P	8.5	dBW	
Transmitter Cable	L	0.9	dB	
Transmitter Antenna	G	4.6	dBi	
TPS Window	L	0	dB	Not Disclosed
Free Space	L	140.1	dB	FSPL=20 log_10[(4*π/C)*f*d]
Pointing Loss Tran		1.0	dB	
Pointing Loss Rec	L	1.0	dB	
Polarization Loss	L	3.0	dB	
Receiver Antenna	G	7.0	dBi	
Receiver Cable	L	0.9	dB	
Signal Present at	P	-123.8	dBW	
Receiver		-126.8	dBW	
Margin		-2.8	dBW	
		-5.8	dBW	

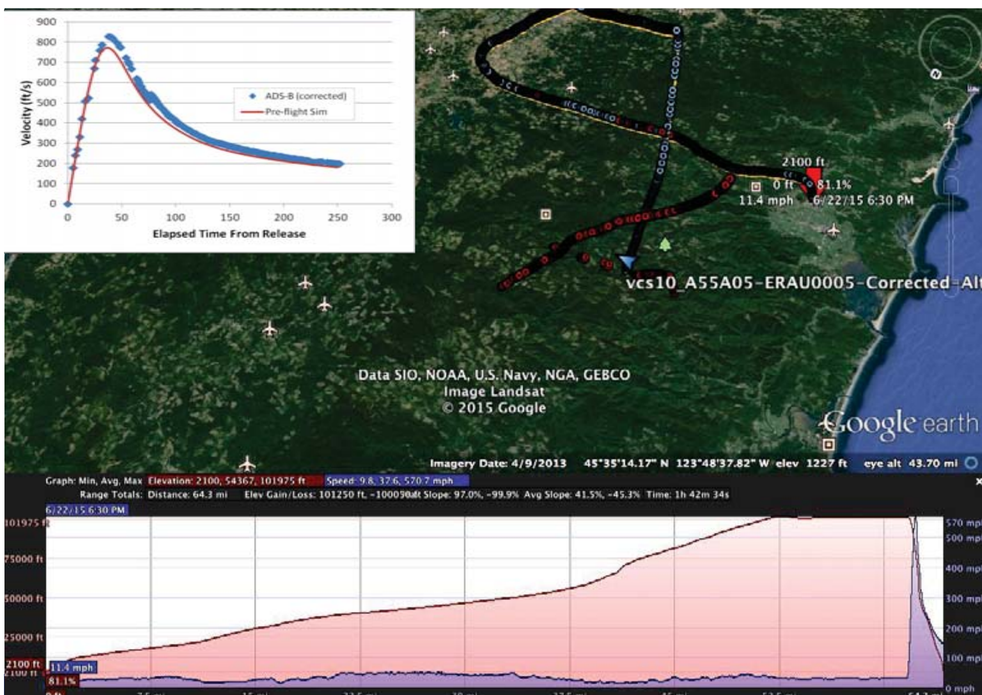


Amplification needed with TPS material added as altitude is increased.
Note: TPS material unknown and not included in models shown.

Terminal Velocity Aerospace Reentry Vehicle
Drop from stratospheric balloon


Terminal Velocity Aerospace Reentry Vehicle
Drop from stratospheric balloon

- Dropped from 100Kft - ADS-B payload reported at all times in flight
- Was useful in finding vehicle in landing location in forest!
- Balloon gondola also had ERAU ADS-B out payload
- First known flight with
  - ADS-B on both balloon and ballistic payload
  - Tranmission through heat shield

Technology maturation plan

- Project goal to demonstrate viability and test functional envelope of experimental ADS-B payload for sub-orbital commercial space operations
  - TRL-7, proven within its operational environment
- Additional flights needed before transition to TRL-8 (i.e. move out of prototype phase)
- Diversity of new vehicles is desirable to get operator feedback
- Conduct research to address issues with current ADS-B message standards as no message type for space vehicle yet developed / approved.

Planned Future Commercial Space Flights with Experimental ADS-B Payloads

- Near Space Corporation's High Altitude Shuttle System
  - Surrogate winged suborbital vehicle performing a descent into NAS (from above 60, 000 feet) - ASAP
- SL-11 reflight with GPS through boost phase (16Gs for 12 seconds with FOP – Spring 2016
  First time to pull high-g's with live data
- TVA vehicle –upgrades proposal developed
- Large amateur rocket to >100 miles in consideration
- SL-12 mixed airspace demo with UAS TBD
- Virgin Galactic SpaceShip 2 (TBD)

Source: Near Space Corporation

Planned Future Commercial Space Flights with Experimental ADS-B Payloads

Source: Near Space Corporation

- Expendable Launch Vehicle
  - Currently in planning stages for first stage
  - fly back booster
  - expendable
- Cubesat or International Space Station
  - Investigating opportunities for cubesat integration or a ISS flight
  - Proof of concept for on-orbit application

Questions?

Image courtesy of UpAerospace Inc.

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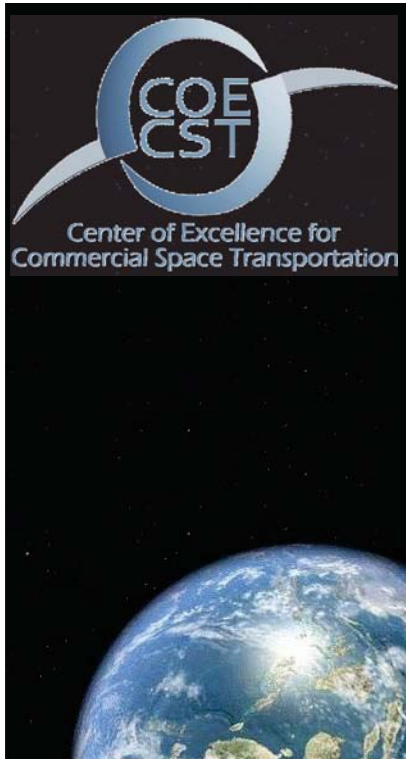
COE CST Fifth Annual Technical Meeting

TASK 332-SIM/SU: Assessing rural airports for drone and RLV use using the Draper-Santos projection methodology

Prof. Aaron Santos, Dr. Chris Draper, Kristina Smith, Nick Joslyn, and Mackenzie Finnegan

October 27-28, 2015
Arlington, VA



Agenda

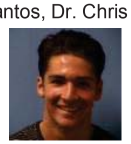
- Team Members
- Task Description
- Schedule
- Goals
- Results
- Conclusions and Future Work

Team Members

- People

  - Prof. Aaron Santos, Dr. Chris Draper,

  - Kristina Smith, Nick Joslyn, and Mackenzie Finnegan
- Organizations

SIMPSON COLLEGE   Emerge Incubator in a box   meidh

Task Description

- Determine which rural airports are suitable for supporting RLV and drone operations based on the proximity and density of population centers.
  - Use the Draper-Santos projection methodology to develop airspace volumes where unrestricted vehicle operation will not unreasonably endanger the public
  - Examine population clustering and sheltering model strategies that ensure suitable data fidelity in rural or sparsely populated areas
  - Integrate Stanford tools RSAT and SU-FARM to increase efficiency of analysis
  - Assess how specific results could be used to benefit FAA regulatory activities

Schedule

- The near term tasks and target completion dates are as follows:

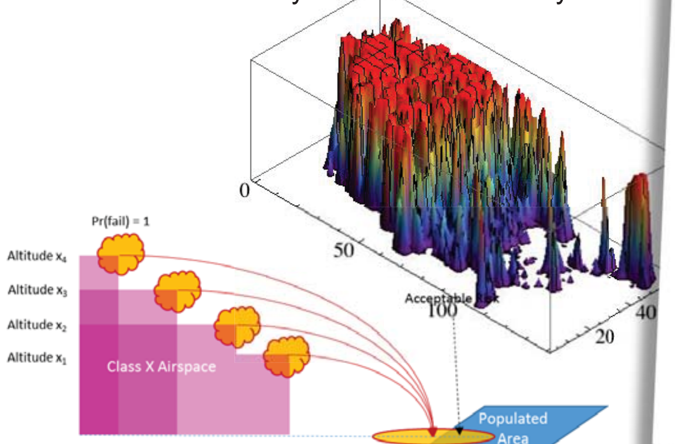
	Start	Target
Assessment of accessible population data sources	1JUN15	15DEC15
Examination of population cluster modelling strategies	1AUG15	15APR15
Development of population data around test site	1NOV15	15DEC15
Development of catastrophic risk assessment for test site	1DEC15	15DEC15
Integration of catastrophic risk assessment into Draper-Santos projection model	15JAN16	30MAY16
Application of catastrophe-based Draper-Santos model to multiple test locations	15APR16	30MAY16
Examination of Stanford tool integration	1JUN16	1OCT16

Goals

- Goal:
  - Demonstrate that a risk-based flight envelope designed to containing any hazards from unconventional launch profiles can be efficiently built for rural areas
- Relevance to Commercial Space Industry:
  - Demonstrating that we can identify volumes of airspace where any failure will not violate an appropriate level of safety means we can remove mission-specific restrictions for RLV and UAS tests or missions operating in these volumes

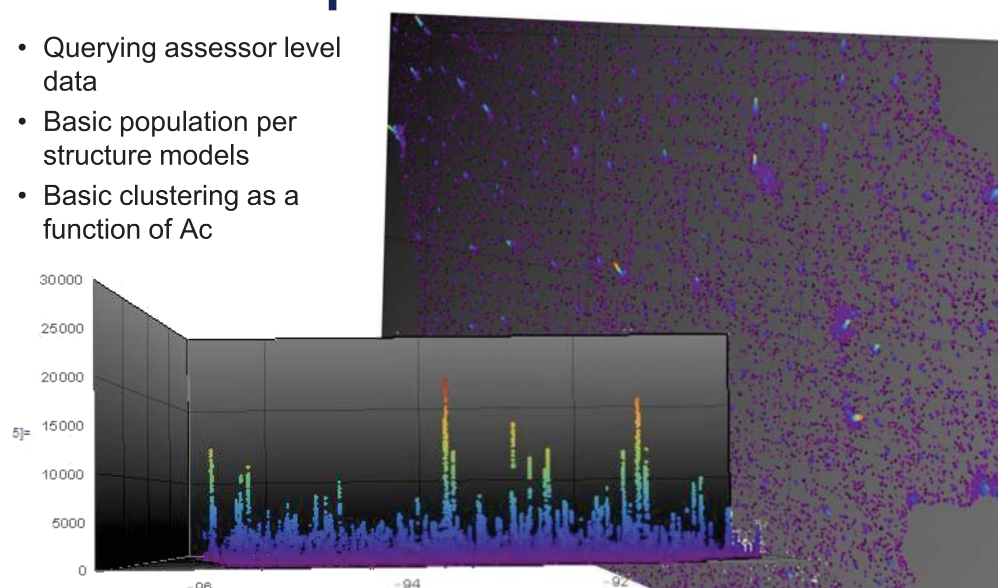
Results: Concept

- Created MVP
- Ran census-level populations
- Demonstrated ability to create a boundary

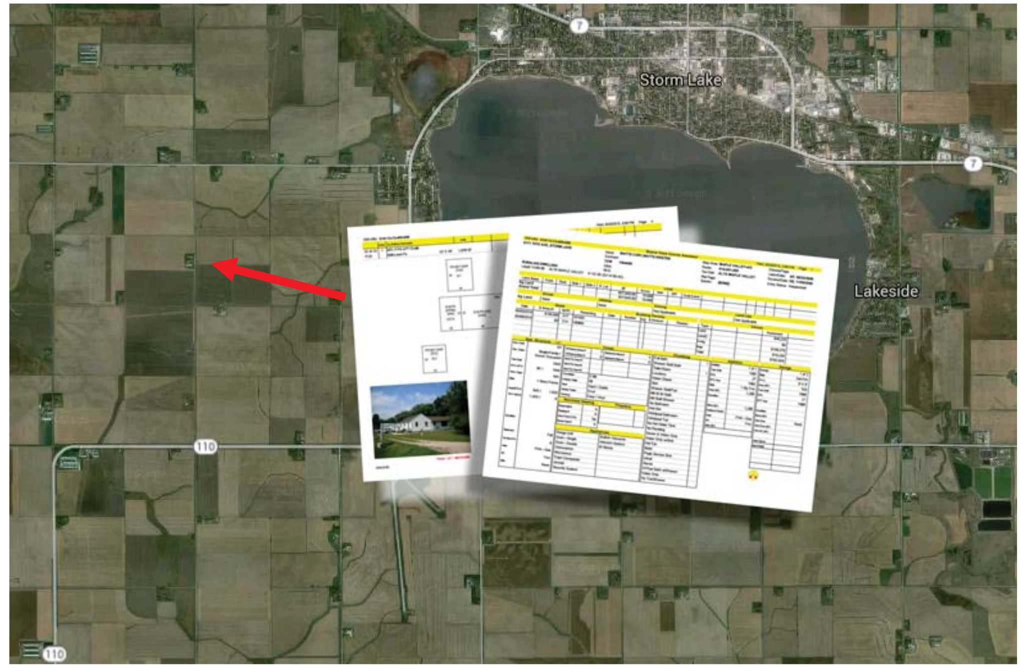


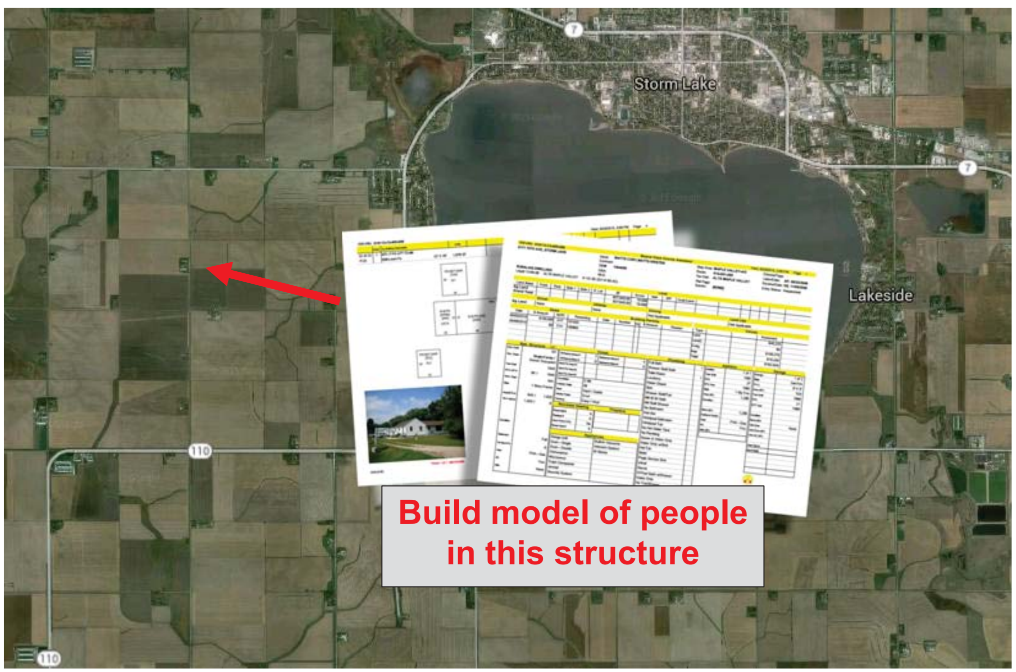
Results: Population

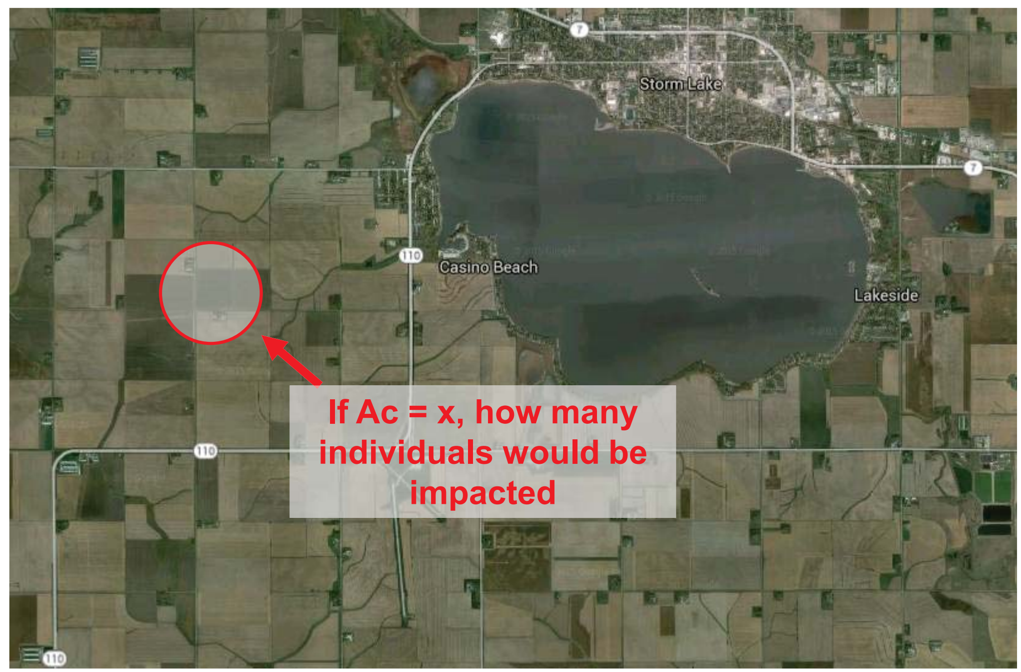
- Querying assessor level data
- Basic population per structure models
- Basic clustering as a function of Ac




Storm Lake
Casino Beach
Lakeside

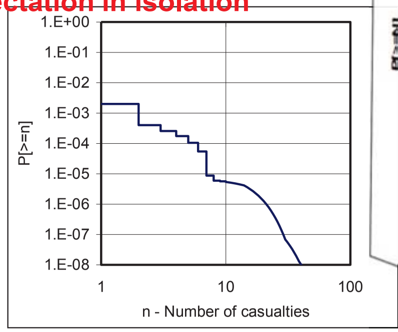

Storm Lake
Lakeside

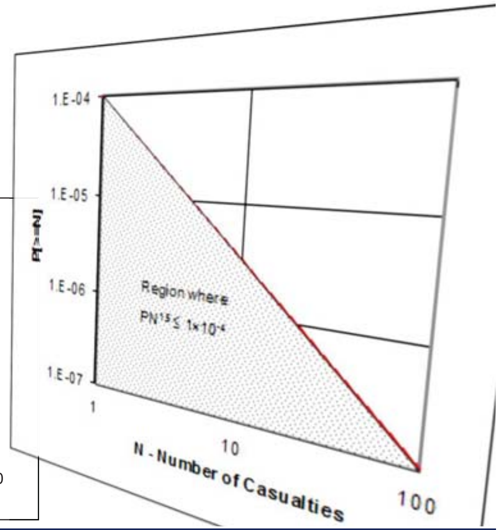

Storm Lake
Lakeside
Build model of people in this structure


Storm Lake
Casino Beach
Lakeside
If Ac = x, how many individuals would be impacted

Results: Risk Modelling

- Apply risk profile
- Build boundaries based on acceptable catastrophe level
  - **Should open up more reasonable opportunities than applying casualty/fatality expectation in isolation**





Conclusions and Future Work

- Team
  - Young, growing team
  - Mathematics, modelling focus
  - At least 3 years with current core
- Focus
  - Population modelling in rural areas
  - Catastrophic verses Expected
  - Demonstrate the opportunity
- Next Steps
  - Integrate with Stanford tools
  - **Develop industry accessible database for population models**

Evaluating Space Launch Vehicle / Reentry Vehicle (LV/RV) Separation Concepts and Standards

Zheng Tao
Ganghuai Wang

COE CST Fifth Annual Technical Meeting

October 27-28, 2015
Arlington, VA

MITRE

MITRE: Established to serve the Public Interest

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Team Members

Zheng Tao
Principal Investigator

Ganghuai Wang
Algorithms

Tudor Masek
Modeling

Ashley Williams
Developer

Tom St. Clair
ATC SME

Mark Banyai
Space SME

Jonathan Schwartz
Algorithms

MITRE

Collaboration with COE CST

- **Juan Alonso - PI**
  - Francisco Capristan
  - Tom Colvin
- **Research/Industry Member**
- **Research Roadmap**
- **Office of Comercial Space Transportation**
  - Nick Demidovich
  - Dr. Paul Wilde

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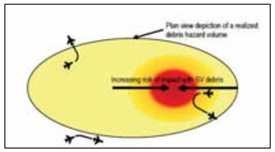
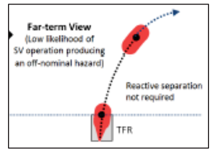
Research question

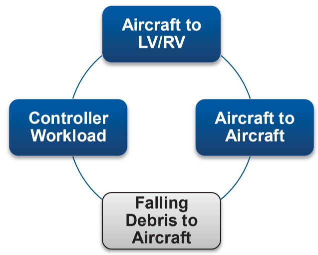
How to evaluate the safety of Launch Vehicle / Reentry Vehicle (LV/RV) separation concepts and associated standards?

- **FAA NextGen Separation Concepts**

FAA, "Management of Space Vehicle Operations in the National Airspace System Concept of Operations," Version 1.1, August 2014.

- **Separation Standards for:**
  - Suborbitals
  - Flyback ops
  - Hybrid vehicles
  - Generic hazard areas



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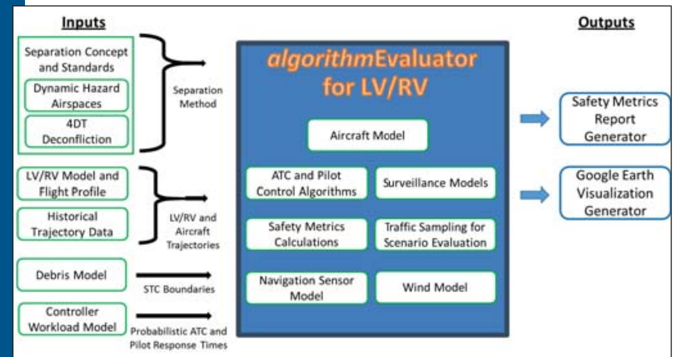
Approach

Develop a flexible, fast-time analysis capability to provide operational measures of safety to evaluate LV/RV separation concepts and standards



- **Insight into requirements for**
  - Surveillance, communications, navigation performance
  - Automation tools
- **Supports FAA's Safety Management System process**
- **Evaluate procedures and traffic flow considerations**

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Debris Modeling

Developed in-house debris trajectory estimator

- Adapted and enhanced from Stanford's debris propagator in their Range Safety Assessment Tool
  - Integrated into MITRE's space vehicle trajectory estimation tool
  - Other enhancements

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Metrics

- **Defined 8 operationally focused metrics to measure:**
  - Separation between Aircraft to LV/RV and Aircraft to Aircraft
  - Time and number of aircraft in hazard airspace and debris filed
  - Time to provide and execute commands
- **Qualitative metrics from observing visualizations**
  - Workload
  - Sector loading
- **Preliminary findings to be published at Space Traffic Management Conference**

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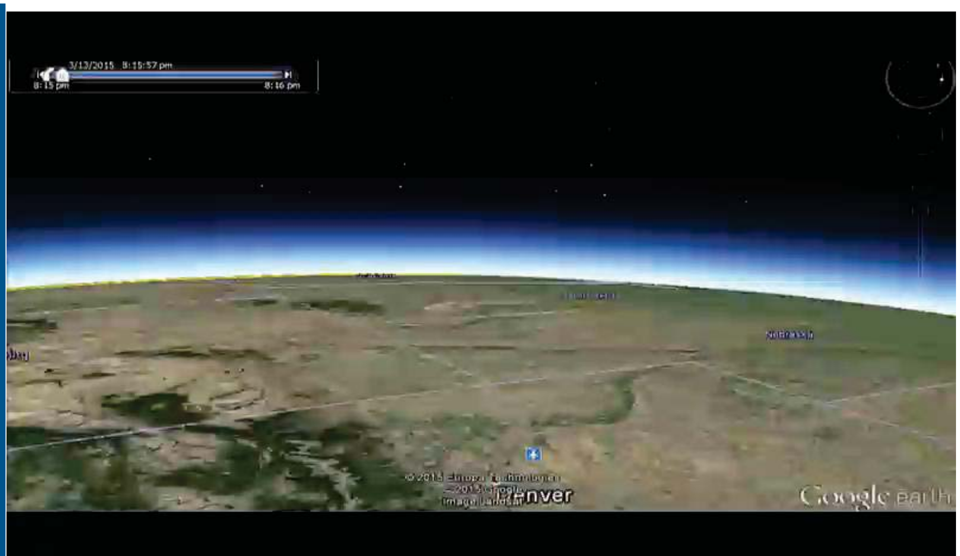
Debris Model Visualization



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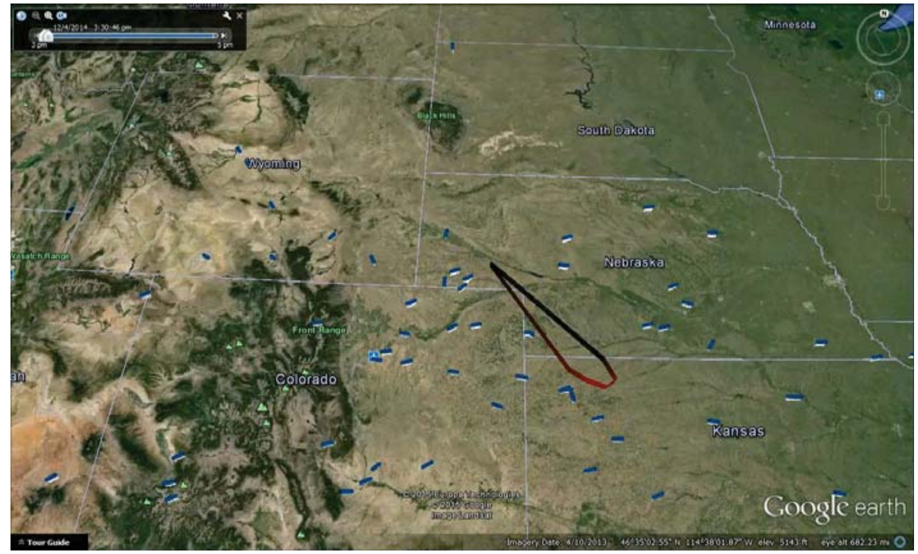
Capsule Re-entry Scenario Visualization



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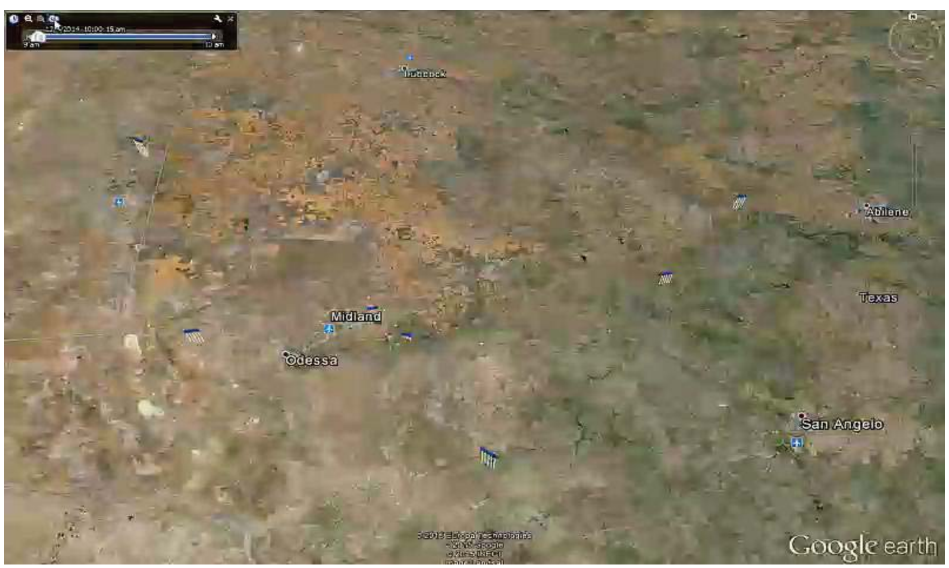
Spaceplane Arrival Scenario Visualization



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Status and Future Work

- **Developed an initial capability that can run and evaluate safety of LV/RV separation concepts and standards**
  - Outputs safety metrics and Google Earth visualizations
  - Preliminary findings to be presented at Space Traffic Management Conference (November 2015)
- **FY16 plan**
  - Confirm and assessing the model's performance
  - Improve trajectory models and algorithms
  - Evaluate potential separation standards for large generic hazard areas, flyback ops, suborbitals, or hybrid vehicles
  - International scenarios

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Launch Vehicle/Reentry Vehicle (LV/RV) National Airspace System (NAS) Effect Assessment

Center of Excellence for Commercial Space Transportation

5th Annual Technical Meeting
October 26-28, 2015

CAASD

MITRE

Background

Demand for space access for commercial, civilian and military use has been rising rapidly.

FAA accommodates space launches often by blocking large volumes of airspace from traditional National Airspace System (NAS) usage. This results in flights routing around blocked airspace resulting in extra flying distance and delays.

FAA has asked for insights into the effects of upcoming launches on the NAS to balance competing demands in a safe and efficient manner

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What is the Effect of A Proposed Future LVRV Operation on the Other NAS Users?

Example of Flight Rerouting During Actual Launch

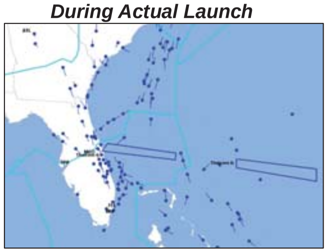

Image source: All NAS Display, MITRE Corporation

Current FAA Practice:

- Use manual analysis of Traffic Situation Display (TSD) replays for a few sample days to estimate impact of proposed operation on future day in terms of flight counts
- This analysis is input to decision making process and in any negotiations between the FAA and the space operator

MITRE recommended to the FAA the following improvements:

- Use objective, repeatable, model-based approach to look at the distribution of likely impacts over a large sample of historical dates similar to the proposed date
- Consider number of impacted flights, expected increase in flying time, or possible ground delay, and the likely range for these values
- Include ability to perform detailed time period and sensitivity analysis
- FAA accepted these recommendations

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Technical Approach

- **Historical Date Selection for Input to Simulation Model**
  - Pick sample of 30 historical days most similar to the proposed launch date
- **Simulating Effect of the Launch on Other NAS Users Over the Selected Dates**
  - Avoid active Aircraft Hazard Area (AHA) by ground delay, or by routing around them
  - Reroute using minimum deviation around AHAs
  - Impact metrics
    - Number of affected flights
    - Extra distance travelled
    - Delay experienced
  - For each metric
    - The average value
    - Likely range of the average
    - The likely maximum value
  - Model Performance
    - Completes on "standard PC" in 1-2 hours or less
    - Preprocessing to speed-up run time
  - Based on Alternative TFM Actions Model (ATAM) software
    - Developed previously for AJR
    - Extensively revised for LVRV application

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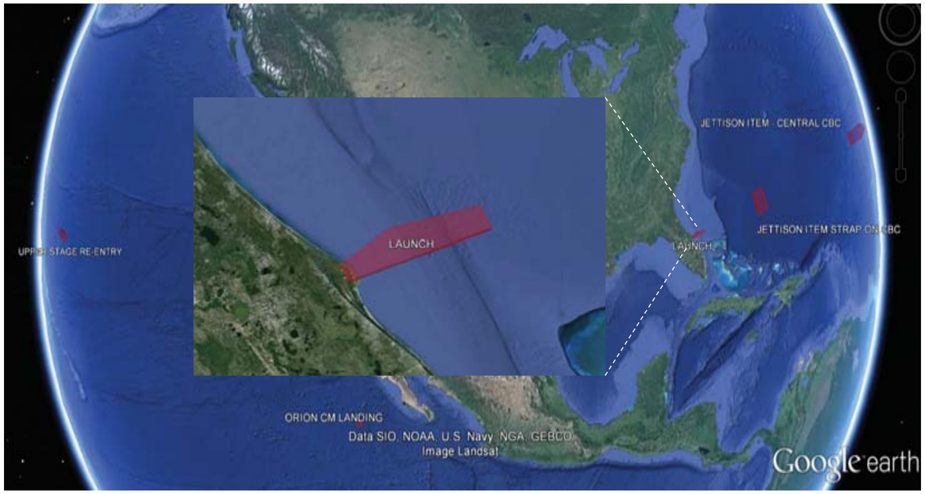
Example: NASA ORION Launch

(Launched from Cape Canaveral on 5th December, 2014)



Background Image source: Google Earth, product of Google Inc.

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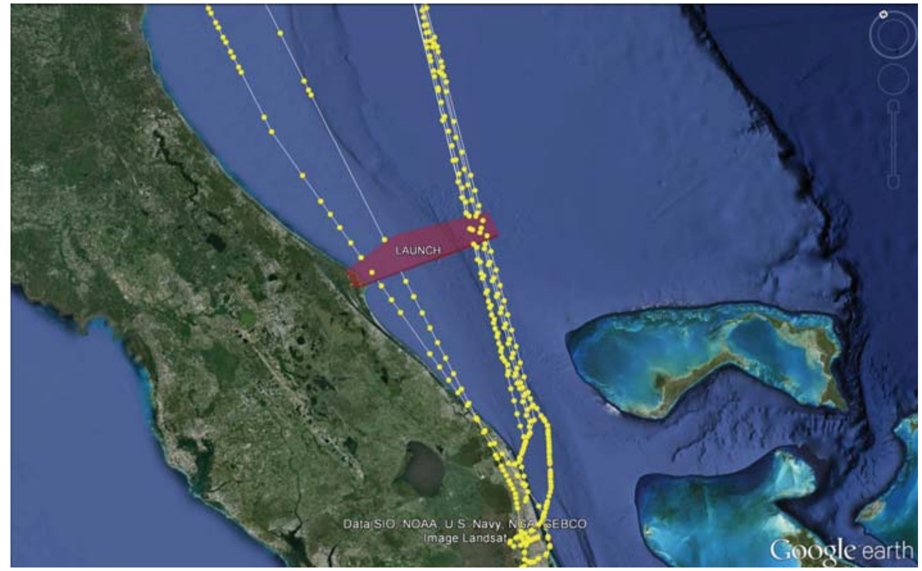
Example: Actual Flights Intersecting Launch AHA on Historical Date



Background Image source: Google Earth, product of Google Inc.

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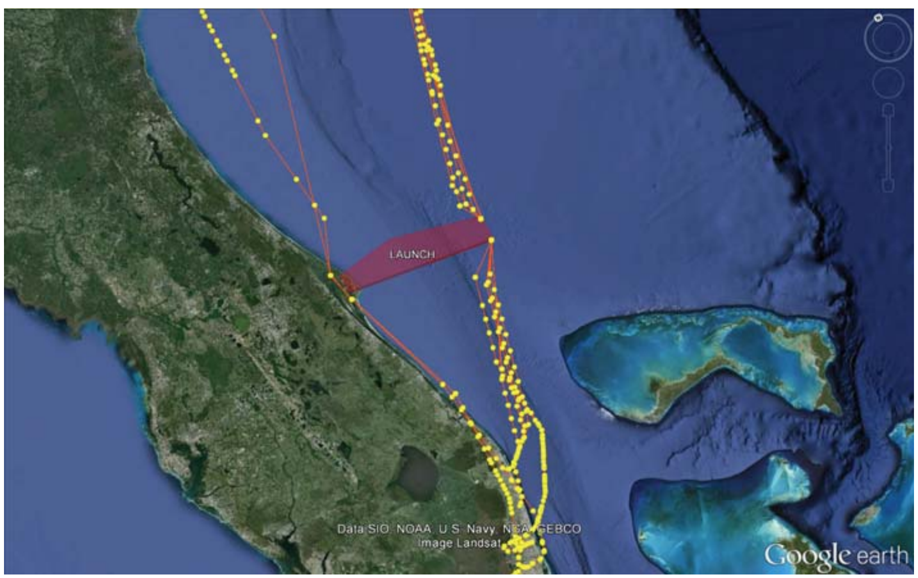
Example: Flights Rerouted Around Launch AHA and SUAs



Background Image source: Google Earth, product of Google Inc.

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What Happens if the Launch Or Recovery Time Window is Changed?

Base CaseAnalysis

Alternative Dates

Alternative Start Times

- *Base Ana*lysis: Impact on 30 similar historical dates
- *Alternative Dates?*: Look at likely back-up dates
- *Alternative Start Times*?: Change time by +/- 3 hours
- *Time Period Analysis?*
  - Look at effect by 15-minute interval in within base case time window
  - See impact of each AHA separately
- *Data to answer all these questions is pre-generated during the simulation run*

Alternative Durations

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NOTICE

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