Overview of Recent EAST Testing, Modeling & Analysis

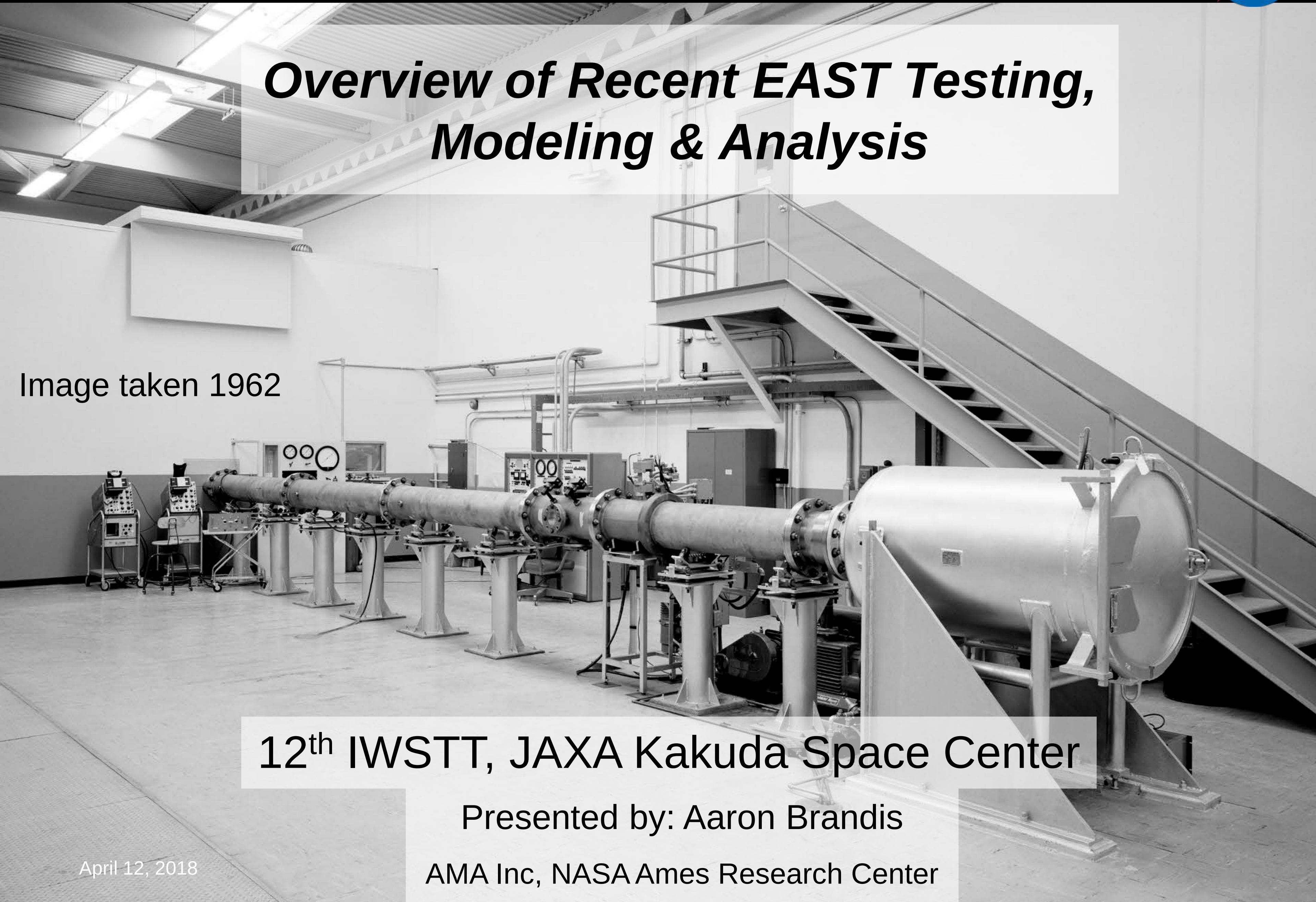


Image taken 1962

12th IWSTT, JAXA Kakuda Space Center

Presented by: Aaron Brandis

AMA Inc, NASA Ames Research Center

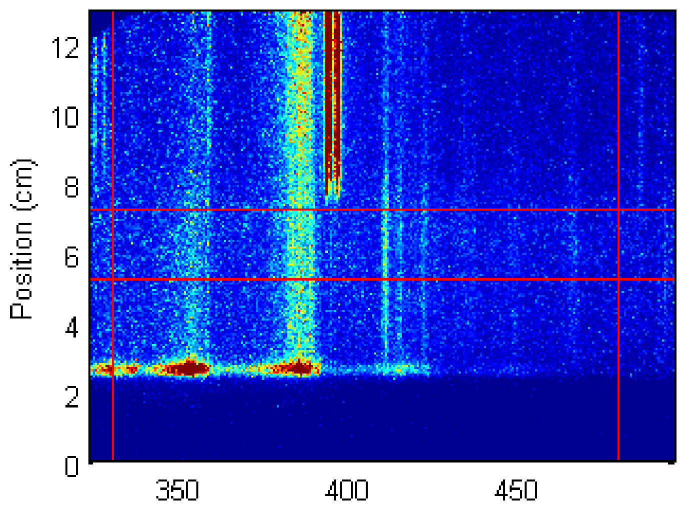
April 12, 2018

Shock Layer Radiation Group & Associates

- This presentation contains work for a large number of NASA’S Entry Systems Modelling (ESM) team members & affiliates, including:
- NASA Ames:
  - Brett Cruden, Rich Jaffe, David Schwenke, Khalil Bensassi, Jeff Hill
- NASA Langley:
  - Tom West
- University of Minnesota:
  - Durgesh Chandel, Graham Candler

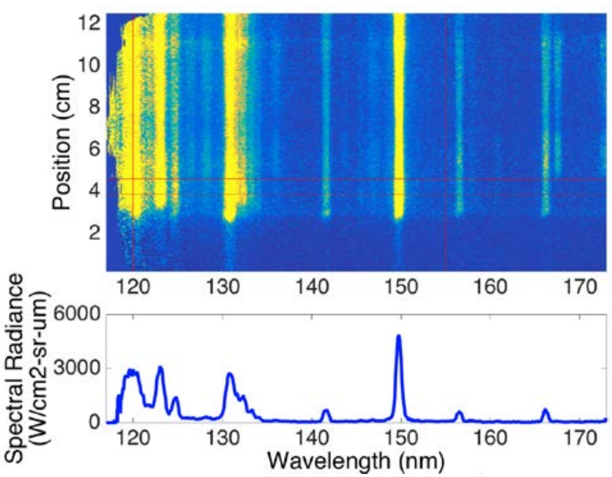
Shock Layer Radiation at NASA Ames

- Background: Complex aerothermal and thermochemical phenomena of planetary entry define convective and radiative heating. A spacecraft's TPS mitigates heat transfer to substructure. Successful TPS design relies on verifiable characterization of these phenomena in the anticipated flight environment.
- Approach: EAST simulates high-enthalpy, real-gas phenomena encountered by hypersonic vehicles entering planetary atmospheres by spectrally imaging a the flow behind a moving shock wave.
- Goal: Validate aerothermal models (DPLR & NEQAIR), inform model improvements, reduce uncertainty and quantify design uncertainties.
- Recent Relevant Projects: MSL & Mars 2020, InSight, OSIRIS-REx, Orion EFT-1 & EM-1 and New Frontiers

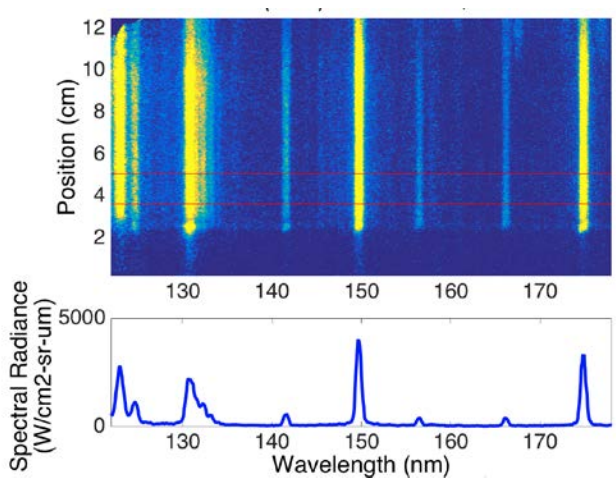


Radiance Obtained in Different Spectral Regions

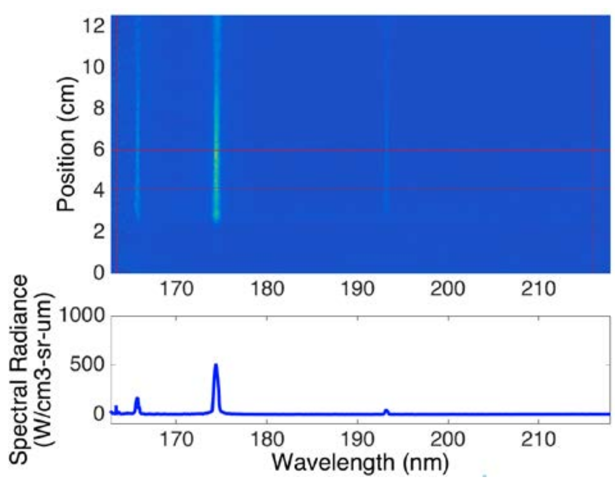
Deeper VUV



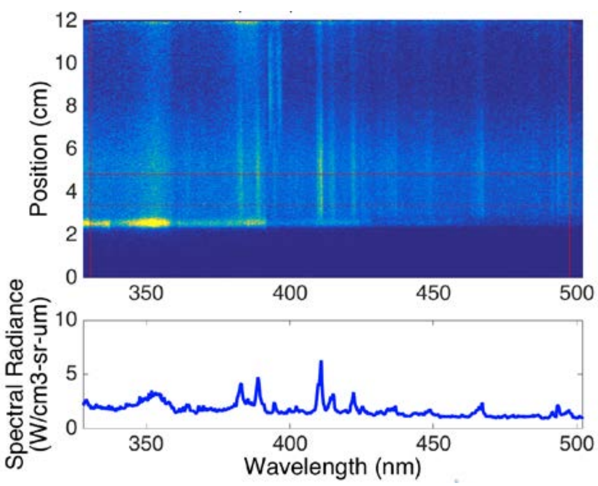
VUV



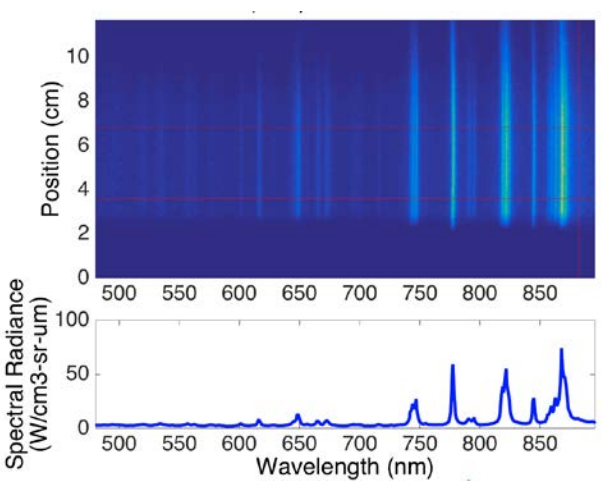
VUV/UV



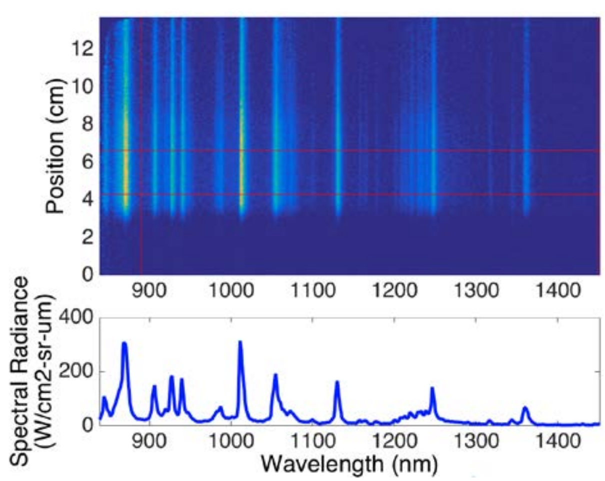
UV/Vis



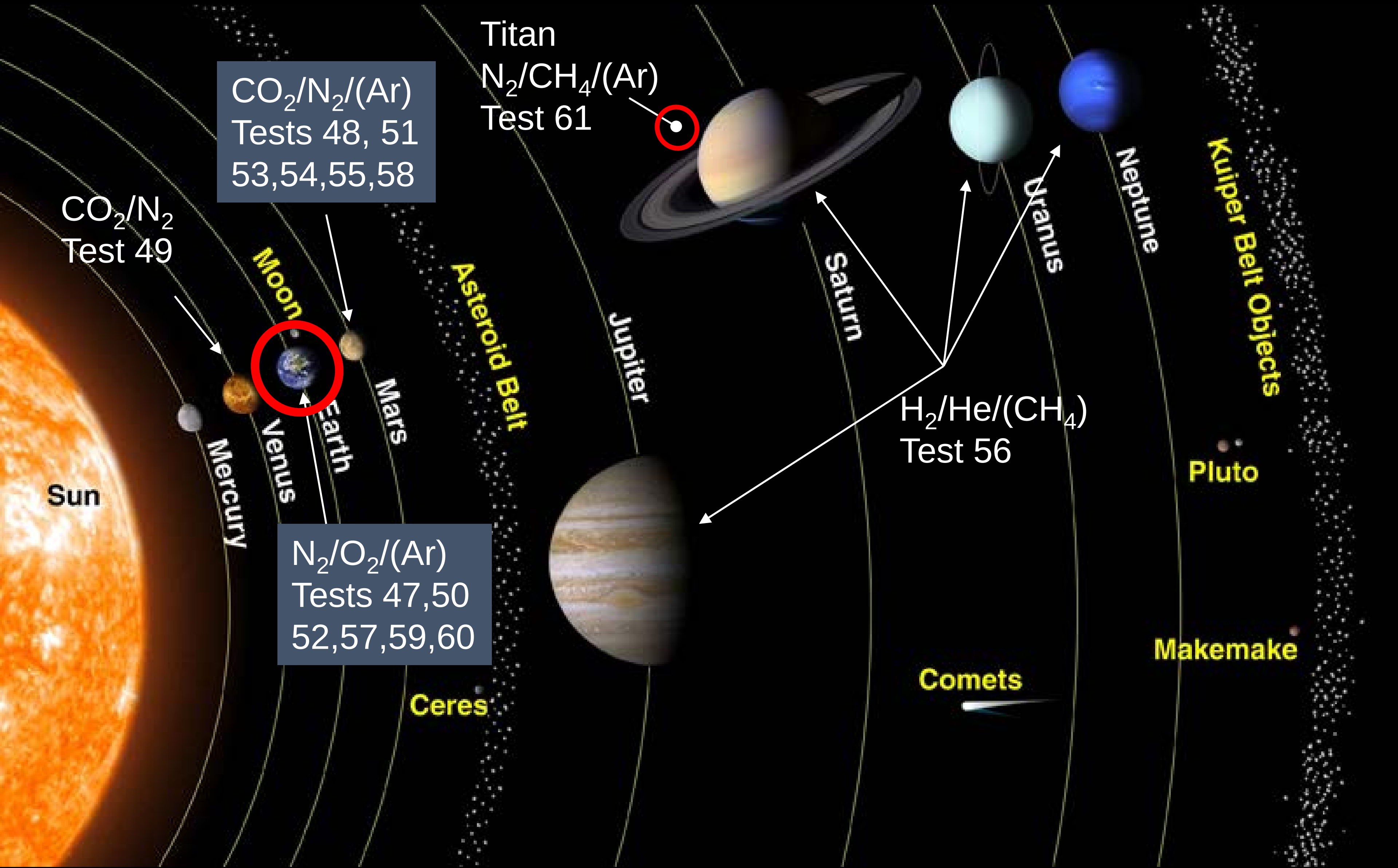
Vis/NIR



NIR/IR



Planetary Atmospheres



Recent Significant Achievements

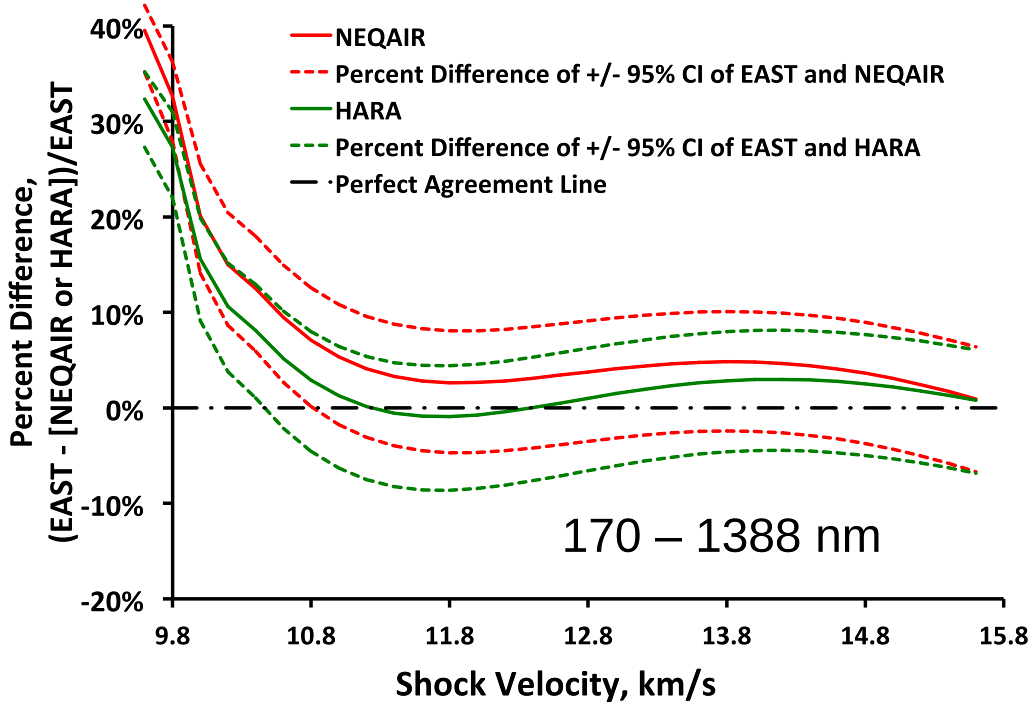
- **Margin Policies**
  - Rigorous approach to radiation margin developed for Earth re-entry **Orion: EM1**
  - Similar approach applied to Mars entry **Mars 2020**
- **FT1 Radiometer Discrepancy**
  - Significant under-prediction of FT1 radiation with baseline simulations
  - EAST testing allowed for the construction of a new model **Orion: FT1, EM1**
  - Model updates show good agreement with FT1 data
- **Titan Radiation Discrepancy** **New Frontiers: Dragonfly**
  - Radiation predictions for Titan entry have historically greatly over-predicted shock tube measurements
  - Newly measured radiation is substantially larger compared to literature experiments
  - Good agreement with simulations observed for peak radiance, while discrepancy in decay rate is still present
- **New Validation Data for Martian Entries** **Future Mars missions**
  - TDLAS measurement provides new avenues for understanding Martian reaction kinetics
- **Backshell Radiation** **Mars 2020, Orion, InSight**
  - ESM research implementing and validating backshell radiation for both Mars/Venus and Earth entries has directly influenced mission design – leading to EAST expansion testing

Recent EAST testing has driven significant model improvements and multiple infusions with flight projects

Investigation of Earth Entry Radiation

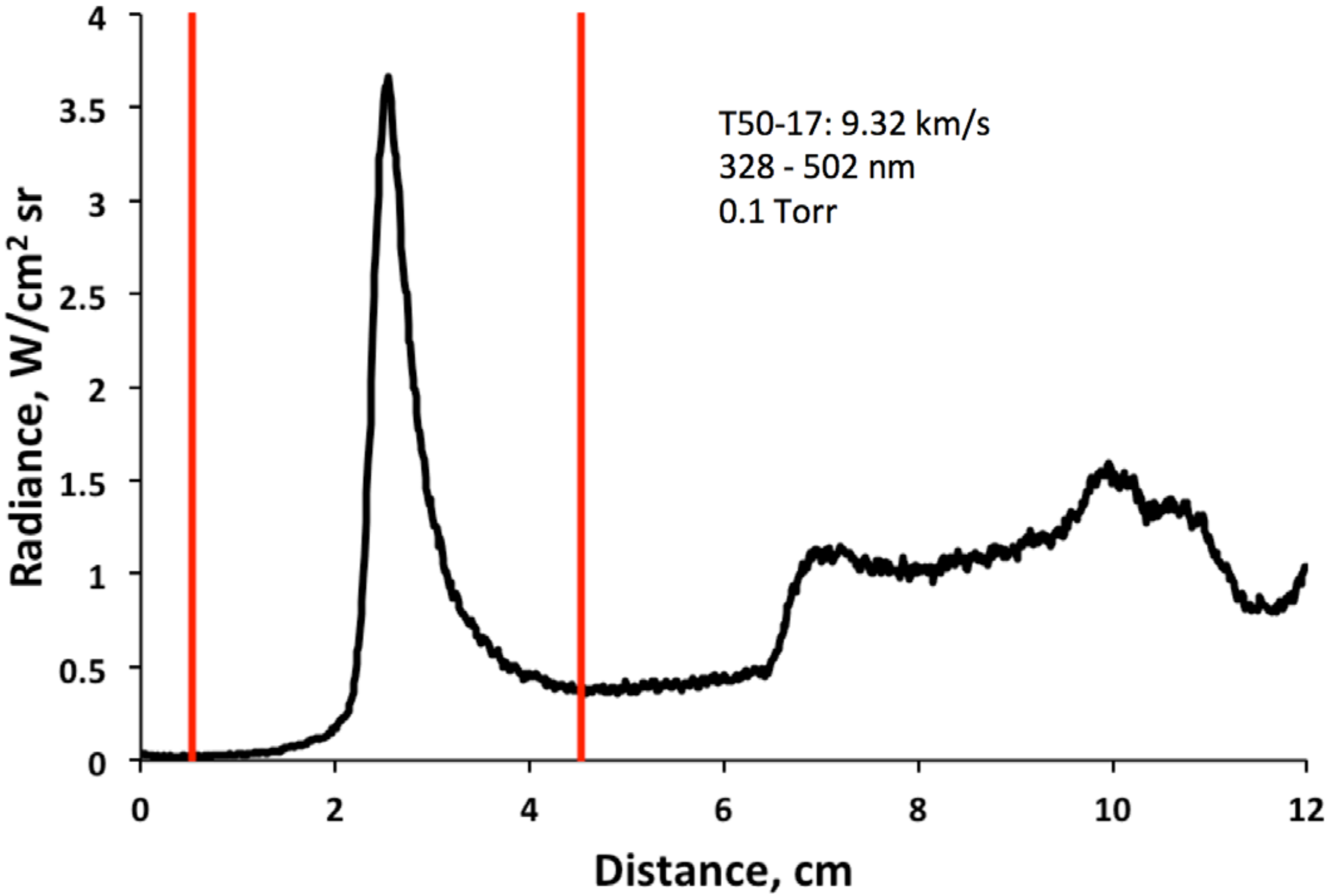
Equilibrium Summary

- Uncertainty for model predictions of EAST as a function of velocity for Earth entry up to 15.5 km/s.
- 1 Standard deviation in scatter of EAST: 17%.
- Disagreement of models w.r.t. to mean EAST result from 11 – 15.5 km/s on average [9.0%, -6.3%].



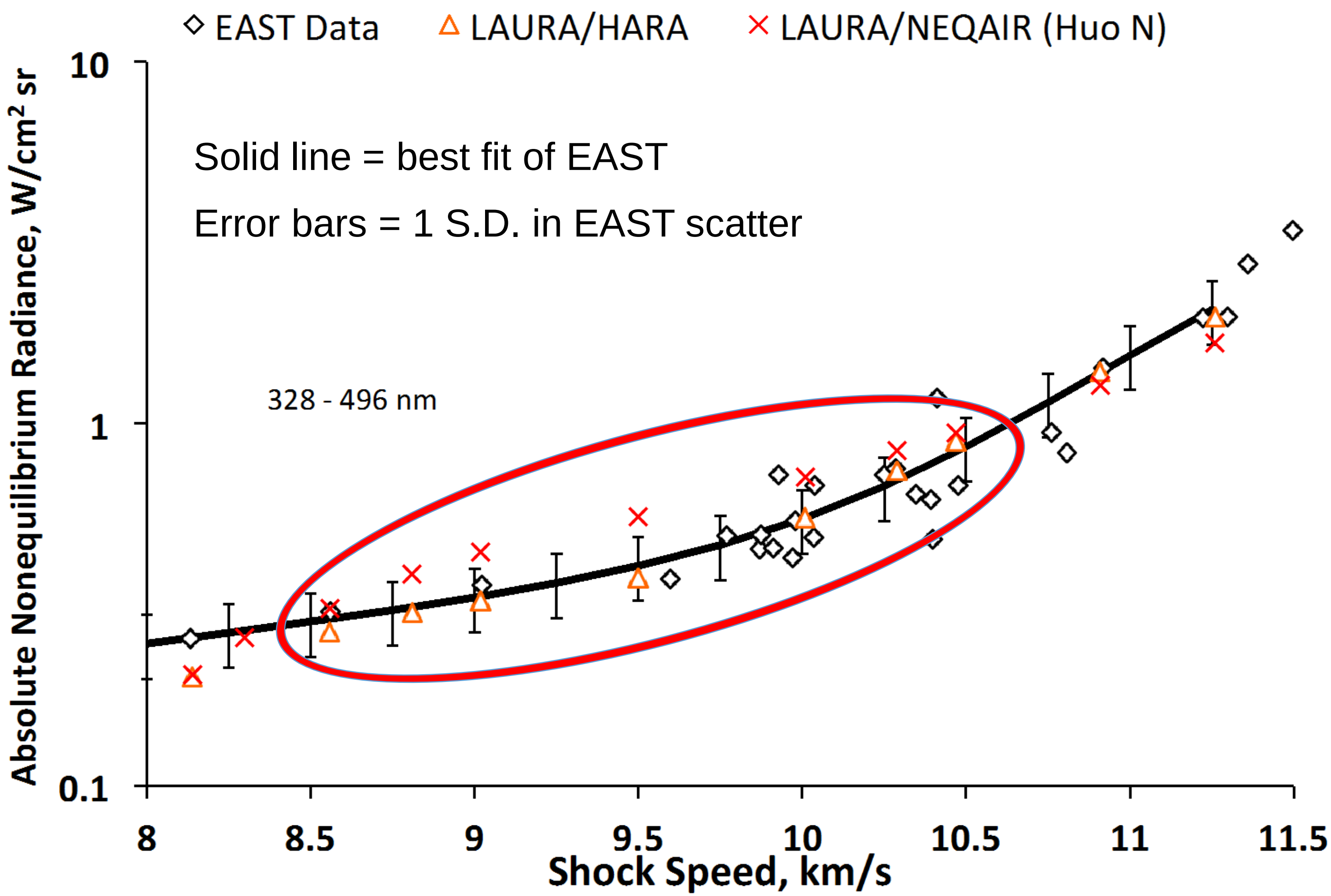
Non-equilibrium Metric

Absolute Non-Equilibrium Radiance



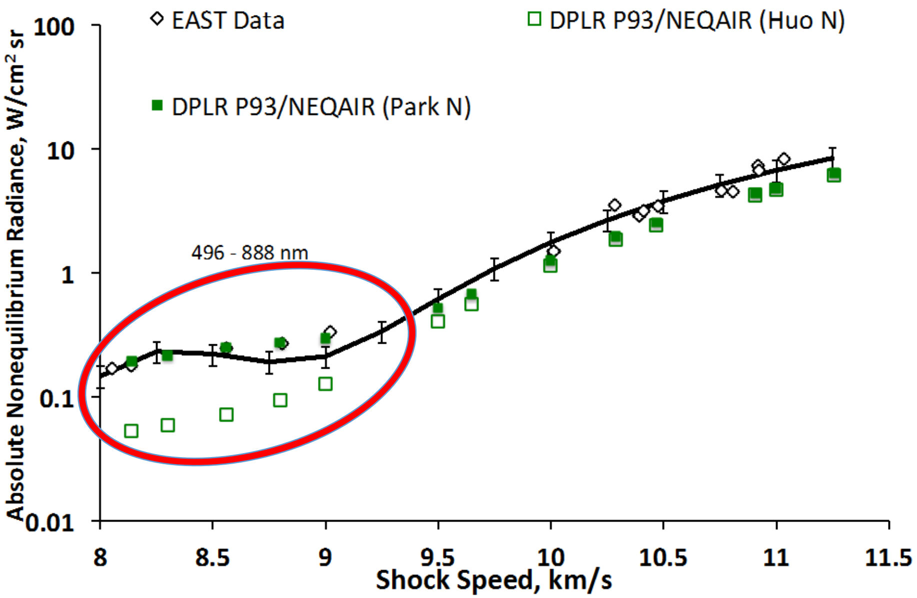
Integrate radiance ±2cm either side of shock front.
Normalized by shock tube diameter

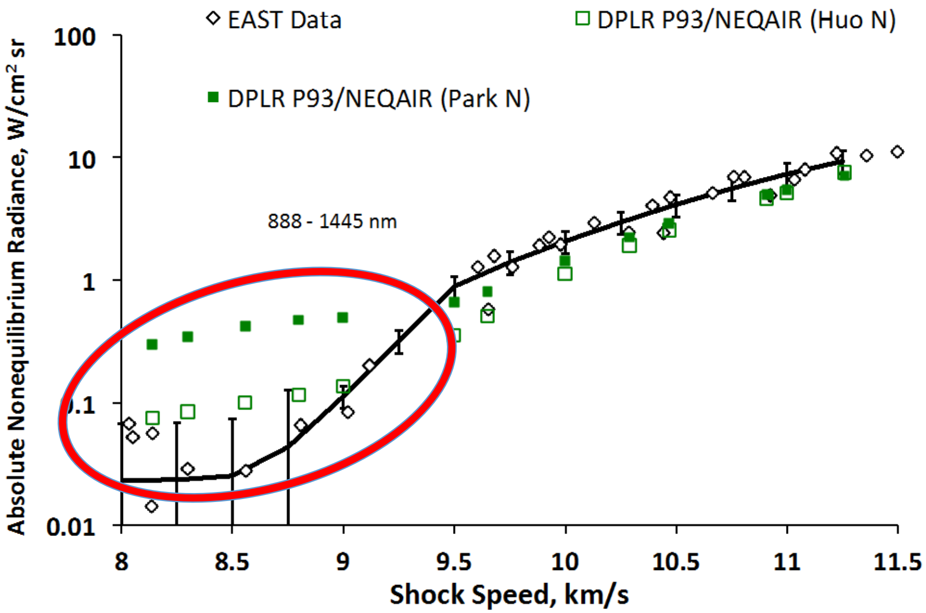
Simulations vs EAST: UV



- In the UV, NEQAIR and HARA show a difference between 8.5 and 10.5 km/s when based on the same (LAURA) flowfield

Using EAST to Validate Excitation Models

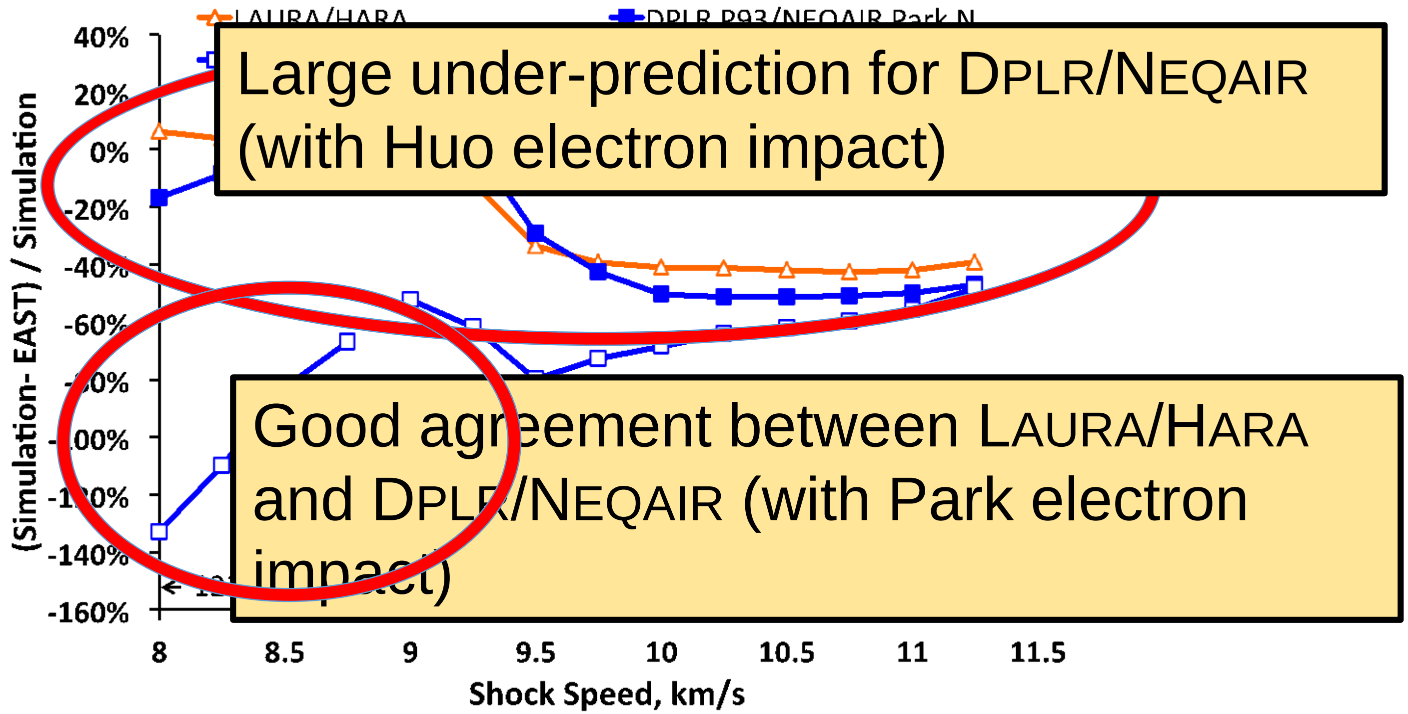




- In the Vis/NIR, the nitrogen electronic impact excitation rates from Park match well with EAST, while there is an under-prediction with those from Huo
- Other spectral regions show the inverse, such as the IR, with better agreement observed using the Huo data

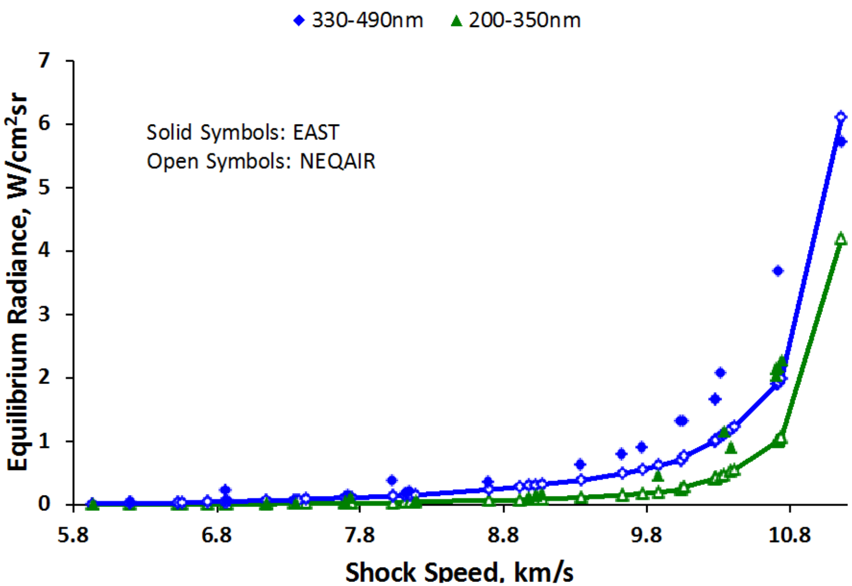
Overall Summation

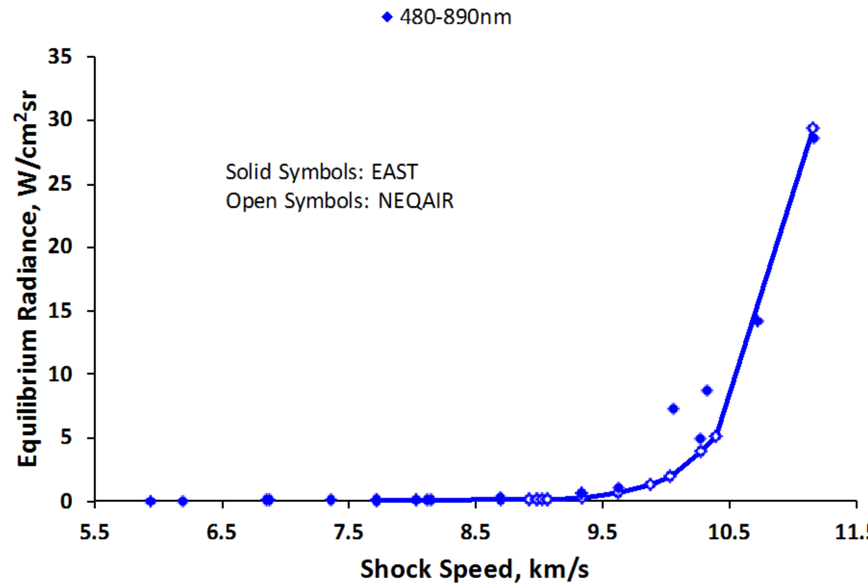
- The summation of the weighted discrepancies (overall difference) is shown below.

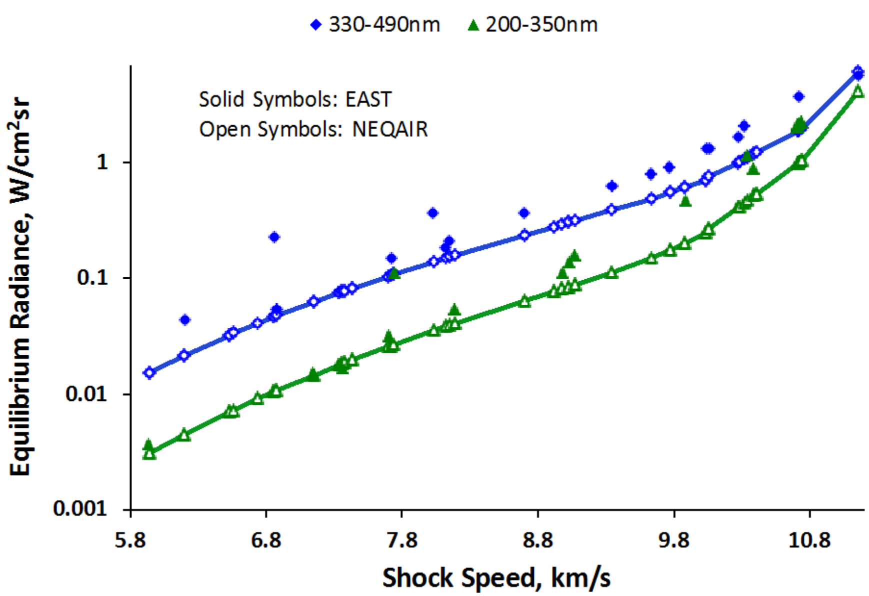


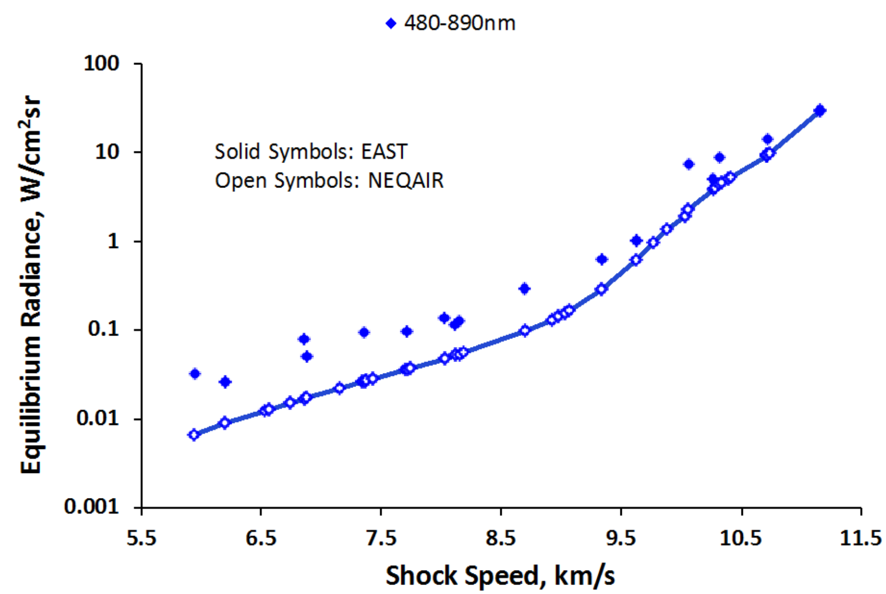
- Large differences at lower speeds, where non-equilibrium is more significant
- Improving agreement between the codes as shock speed is increased

Equilibrium EAST: N_2 & 0.2Torr

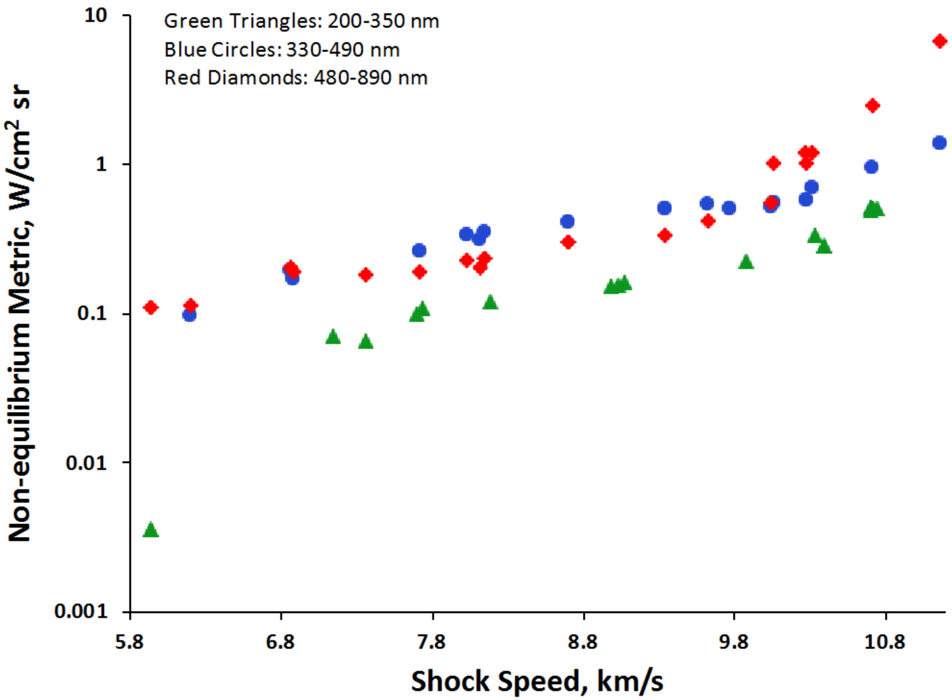


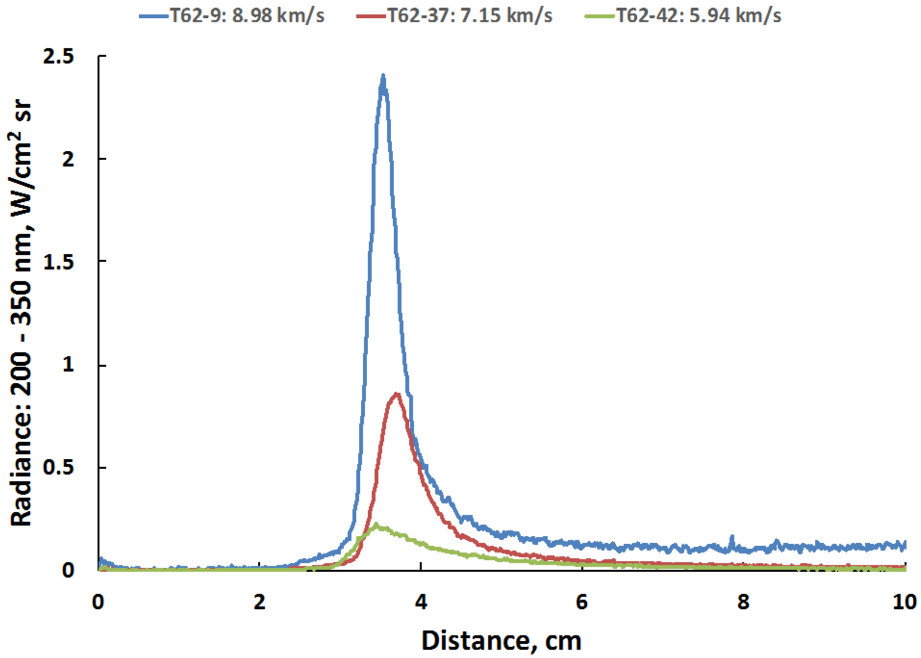






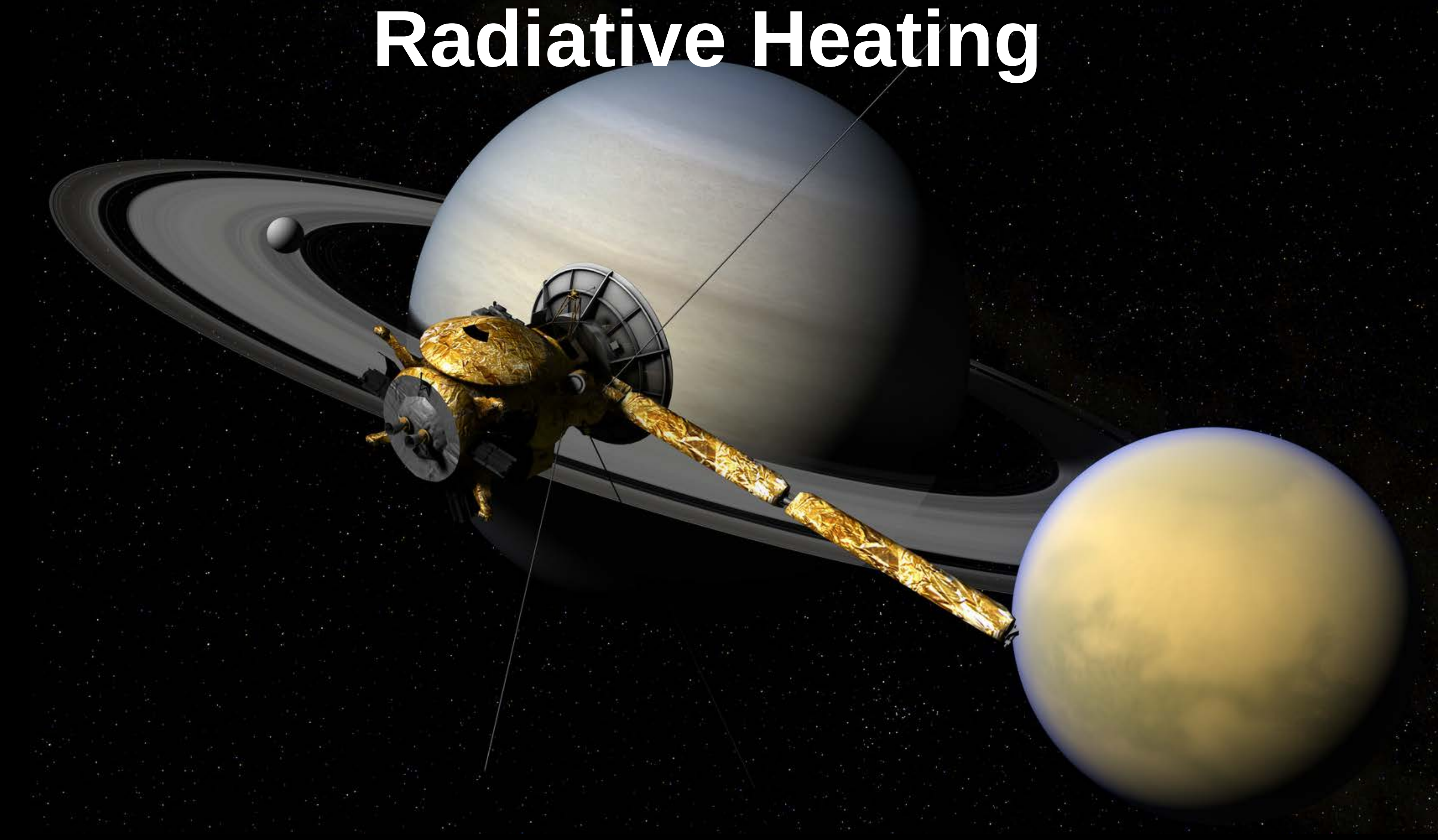
Nonequilibrium EAST: N_2 & 0.2Torr





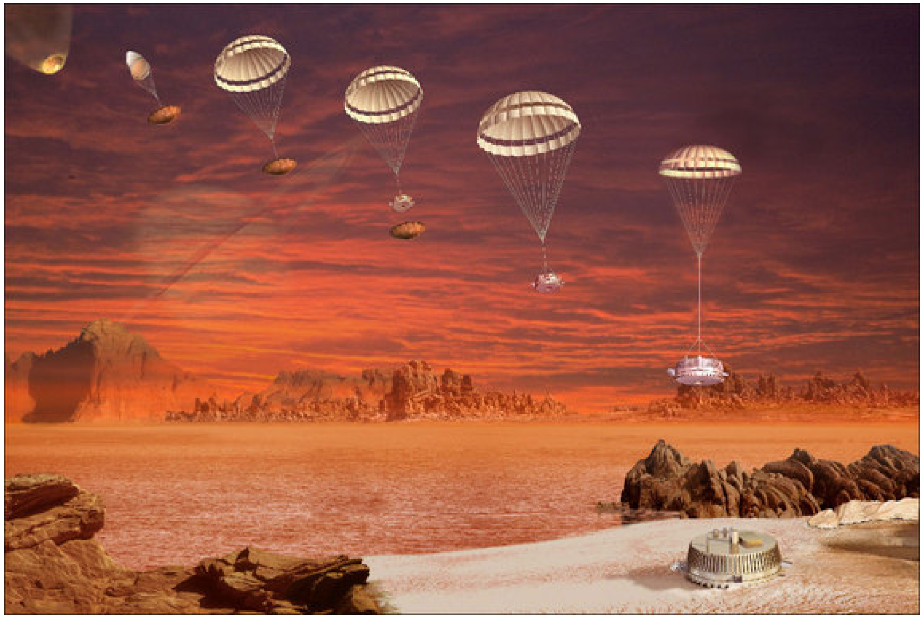
- Goal is to provide a fundamental database for validation of N_2 models, such as dissociation.
- Identify benchmark datasets.
- The insights gained from examining this dataset can then be applied to our air flight simulation capability.

Titan Atmospheric Entry Radiative Heating



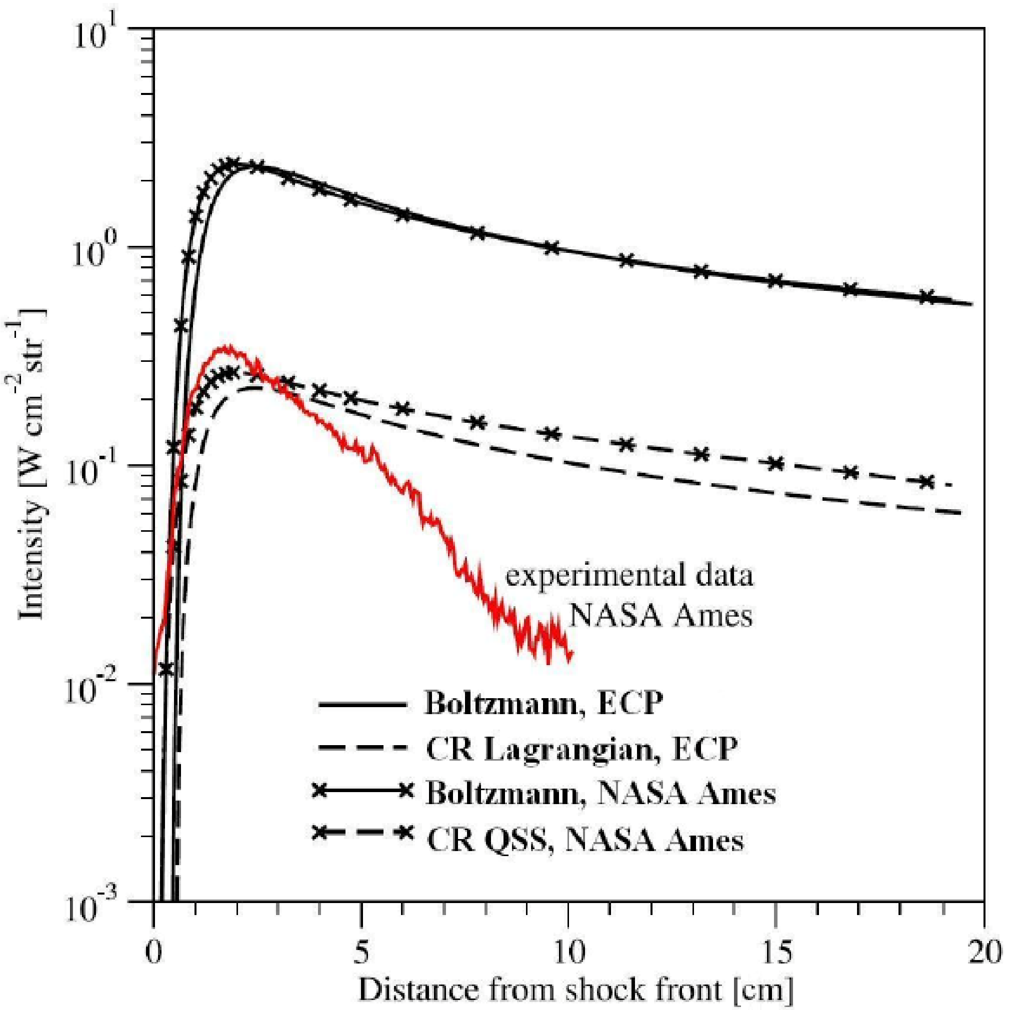
Previous Titan Radiation Studies

- The joint NASA/ESA Cassini/Huygens mission resulted in significant efforts to understand radiative heating for Titan.
- Post flight simulations were conducted assuming a Boltzmann distribution of cyanogen (CN) excited states
  - If this were to be the case, Huygens may have burnt up during entry
- Consequently, experiments were performed in shock tubes and QSS/CR models developed.
- Reasons to believe there were issues with previously reported Titan (pre-upgrade) EAST data.
- Current interest in heading to Titan with two New Frontiers proposals
- Warranted to update published data due to improvements available with the current EAST set up



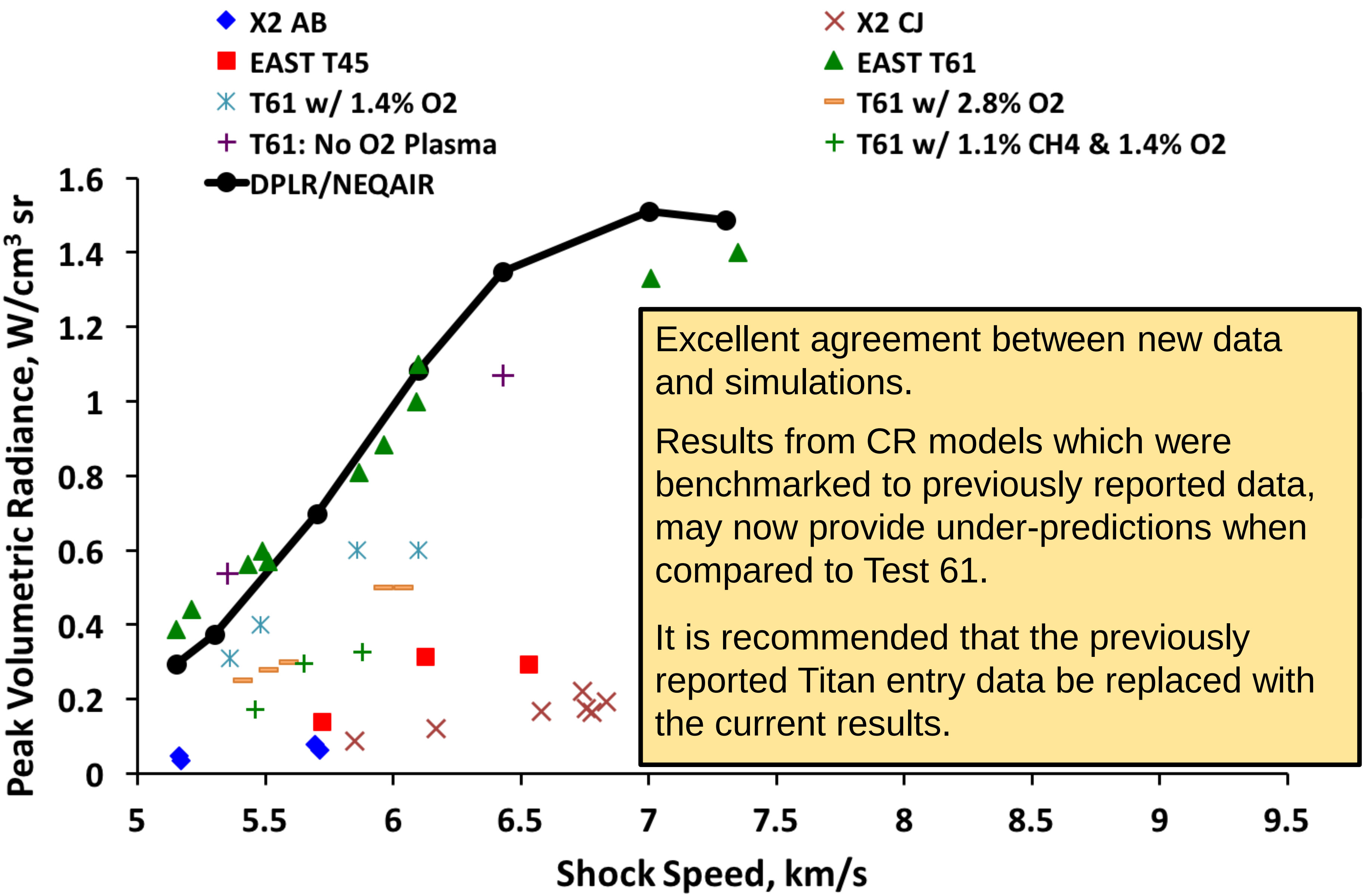
Previous Titan Radiation Studies

5.15 km/s, 98% N_2 : 2% CH_4, 0.1 Torr, 400 – 430nm. EAST T43-25



- Test 43 & 45 from EAST (2003 to 2005)
- Boltzmann predictions shown to substantially over-predict
- CR models deemed to adequately match peak (within a factor of ~2)
- Simulations showed slower decay rate than experiment

Understanding The New EAST T61 Data



Excellent agreement between new data and simulations.

Results from CR models which were benchmarked to previously reported data, may now provide under-predictions when compared to Test 61.

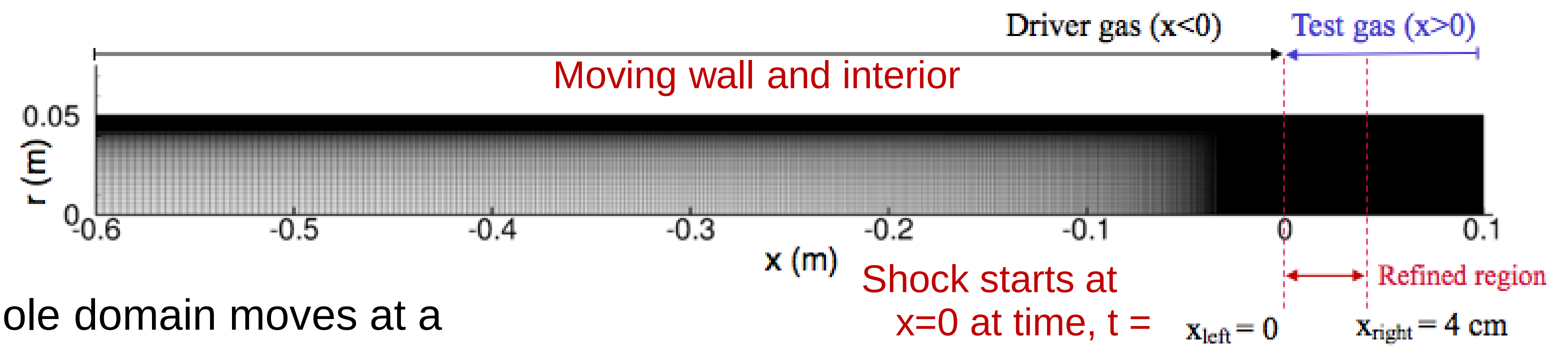
It is recommended that the previously reported Titan entry data be replaced with the current results.

CFD SIMULATIONS OF EAST

EAST Simulations

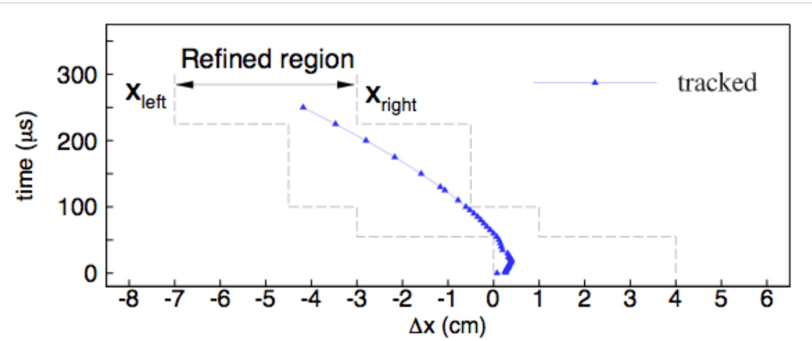
- One of the main uses of EAST data is to extract or infer reaction rates
- This is a difficult task, as many inter-connected reactions occur simultaneously.
- However, in order to better understand the extraction of rates, there are two main avenues we are taking:
  - Doing simplified chemistry tests in EAST, e.g. Pure CO, CO_2, N_2
  - Understanding the influence the shock tube has on the state of the shocked test gas
- We need to disconnect the influence of shock tube effects on the test gas non-equilibrium excitation and relaxation from the actual kinetics
- Furthermore, in order to probe and analyze the results from the upcoming expansion testing in EAST, we NEED a facility model.
  - There are no analogous CFD tricks to play for expansion (ie blunt body simulations for compression)

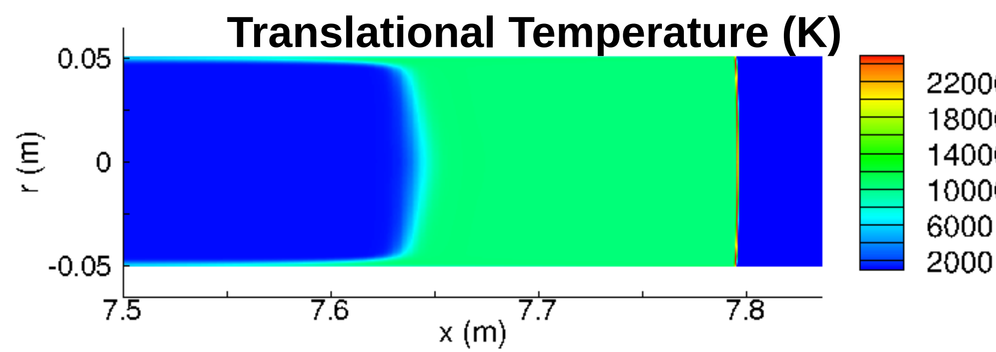
US3D Simulations of EAST at UMN



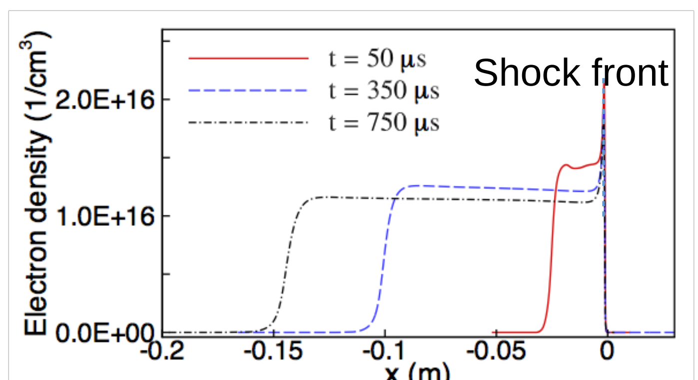
Shock starts at x=0 at time, t = 0

- The whole domain moves at a constant speed close to shock-speed
- Shock tracking is used to ensure a well-resolved calculation at all times





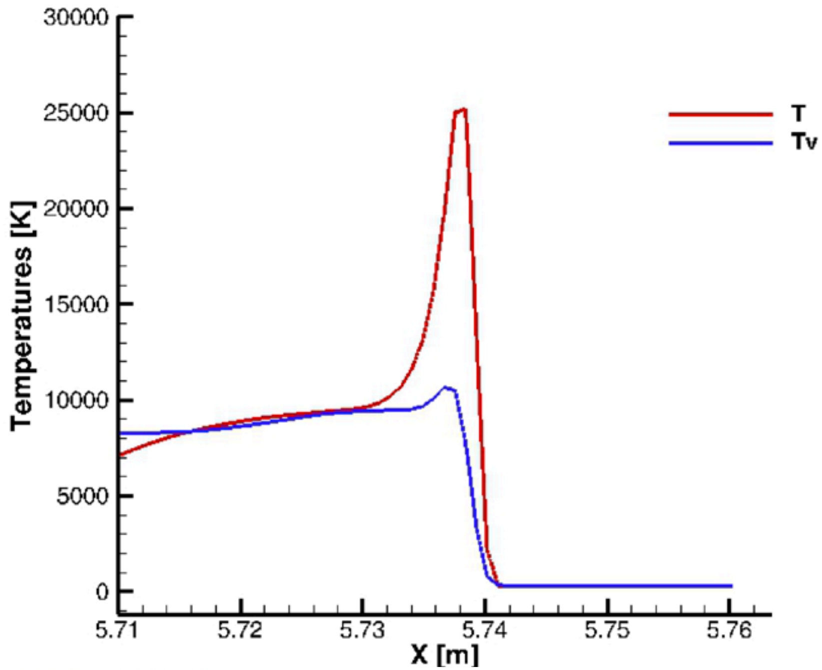
- Shock starts at 26.3 km/s (goes to 10.5 km/s within 5 μs)
- After t = 50 μs (10.4 km/s to 10.1 km/s over a period of 350 μs)

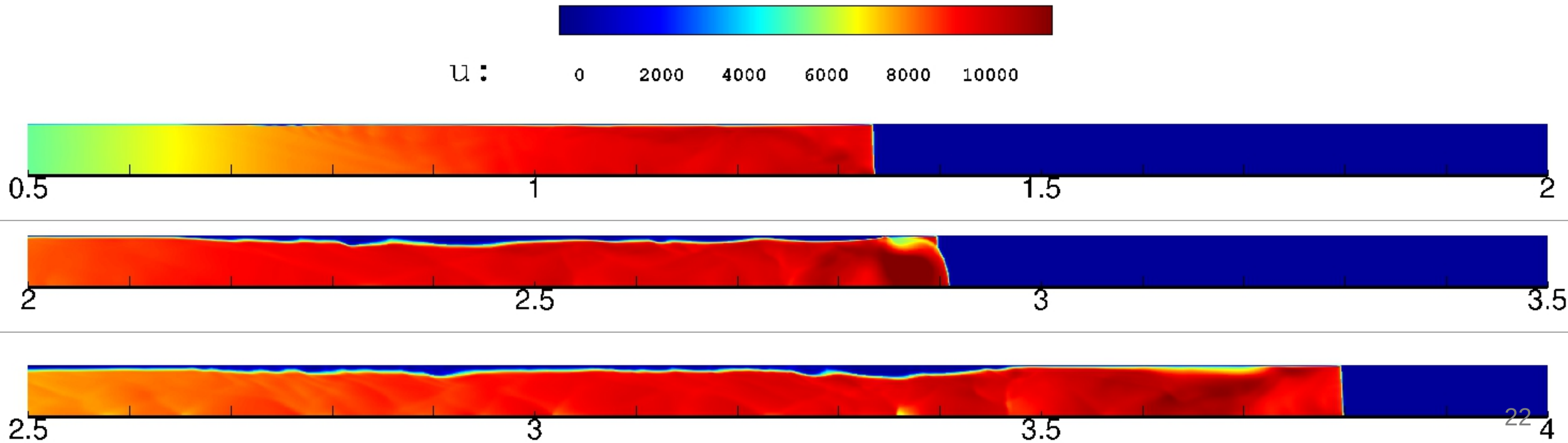


u_s = 10.00 km/s Electron density increasing behind shock, as is seen in EAST

COOLFluiD Simulations of EAST (Khalil Bensassi)

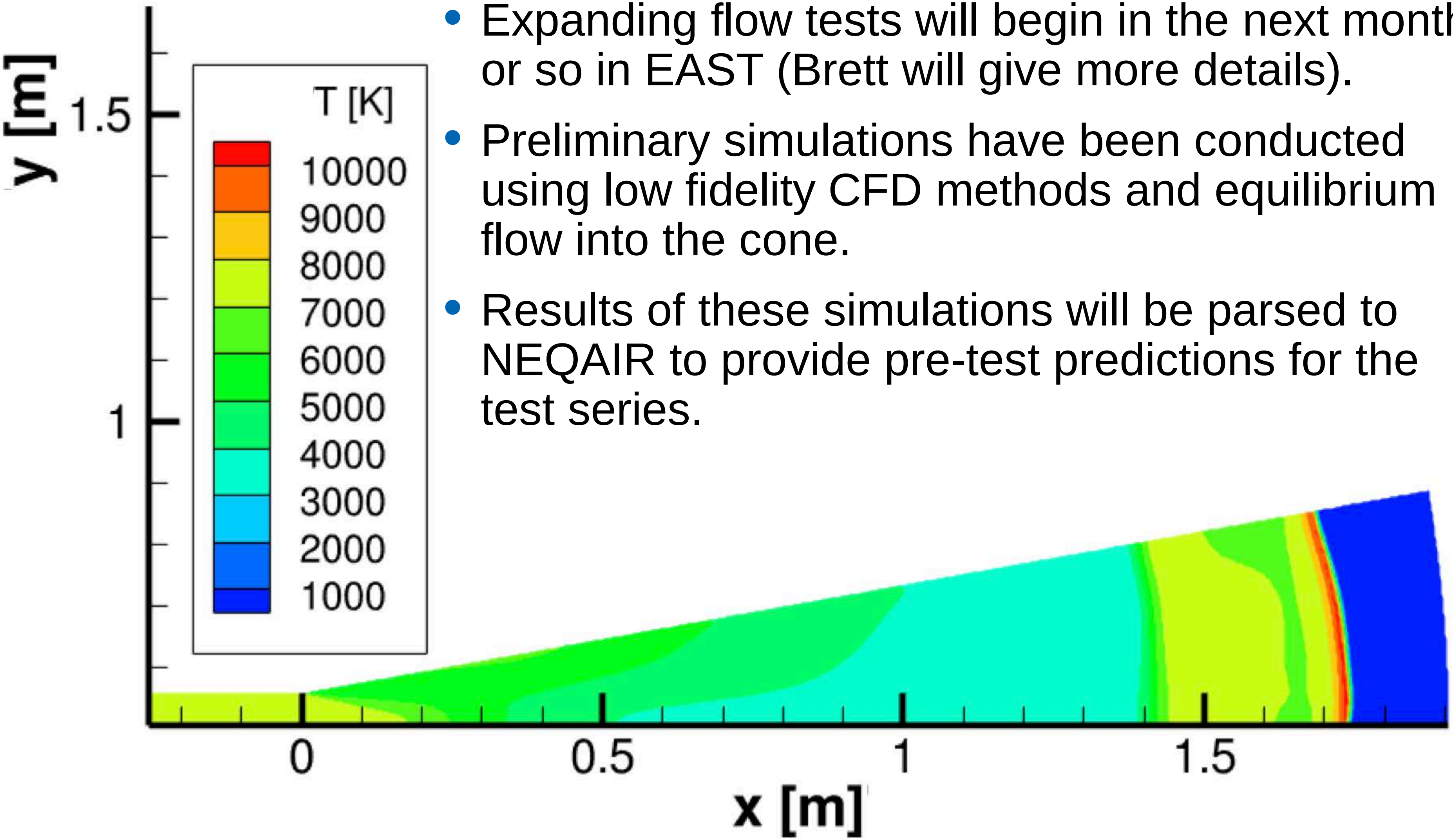
- 2-D axisymmetric finite volume solver, second order in space and time.
  - The US3D simulation was first order in time
- Modeling the entire length of EAST, as opposed to the moving grid method used by US3D





First Steps to Aftbody Validation Data

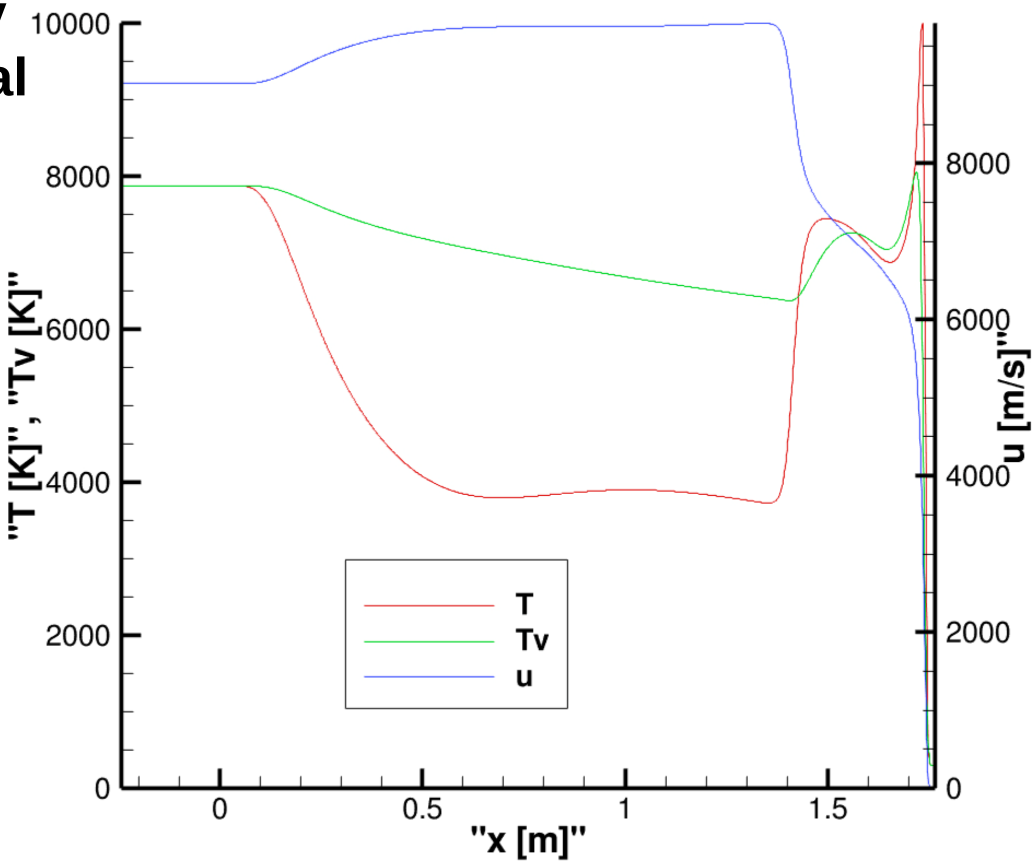
First Steps to Aftbody Validation Data



- Expanding flow tests will begin in the next month or so in EAST (Brett will give more details).
- Preliminary simulations have been conducted using low fidelity CFD methods and equilibrium flow into the cone.
- Results of these simulations will be parsed to NEQAIR to provide pre-test predictions for the test series.

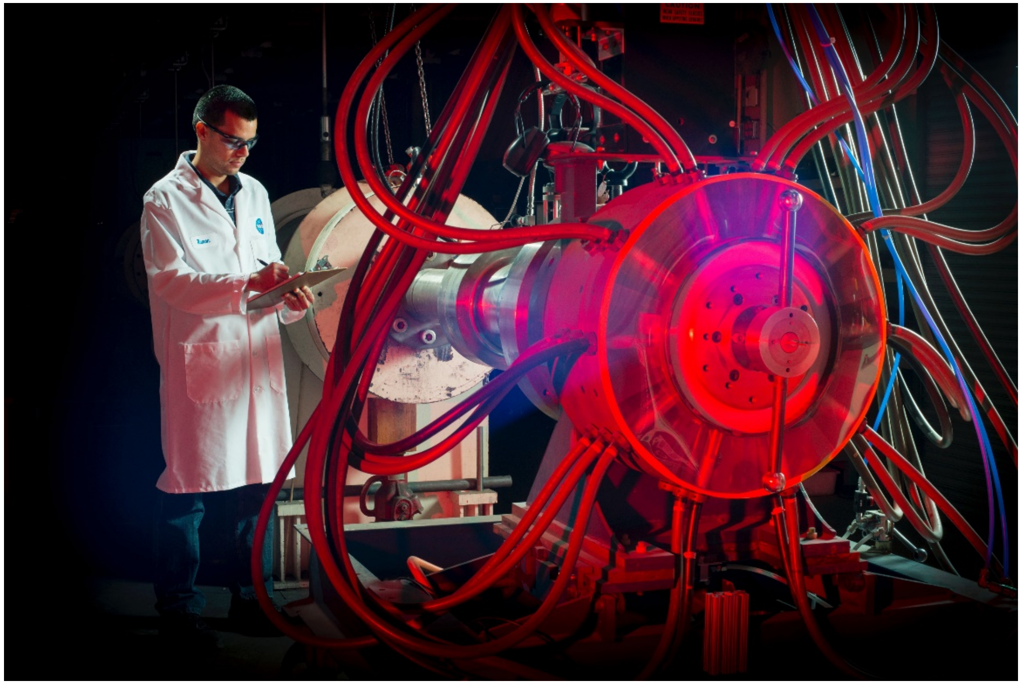
First Steps to Aftbody Validation Data

- Symmetry line plot of velocity and translation and vibrational temperature.
- Simulations show a compressive region just behind the shock front.
- Large expanding flow region identified beginning 0.6m behind the shock.



Future EAST Plans

- What's in the pipeline for future EAST testing?
  - Using carbon/hydrogen based test gases (e.g. acetylene, C_2H_2) to mimic ablation species
  - At present, outer planets testing has been performed with just H/He, when in reality there is also some CH_4
    - This could drastically effect the formation of ions/electrons
  - More tests in the 24" tube facility with an aim to improve lower speed Earth and Mars tests
    - Focus on lower density regimes.



Acknowledgements

- EAST Facility Operations
  - Mark McGlaughlin, facility manager
  - Ramon Martinez
  - Rick Ryzinga
- NASA Radiation Group
  - Brett Cruden
  - Chris Johnston
- Project Management
  - Michael Wright/Michael Barnhardt, Entry Systems Modeling

Conclusions

- EAST Facility is a nation-unique facility capable of achieving flight-similar conditions for entry vehicles

- Analysis with NEQAIR and DPLR, combined with the data from EAST have been used to quantify the nature and magnitude of radiative heating for re-entry problems
  - Multi-purpose crewed vehicle/Orion, MSL, Mars 2020, New Frontiers proposals
  - Informs accuracy of predictive models
  - Allowed reduction of aerothermal margin for radiative heating

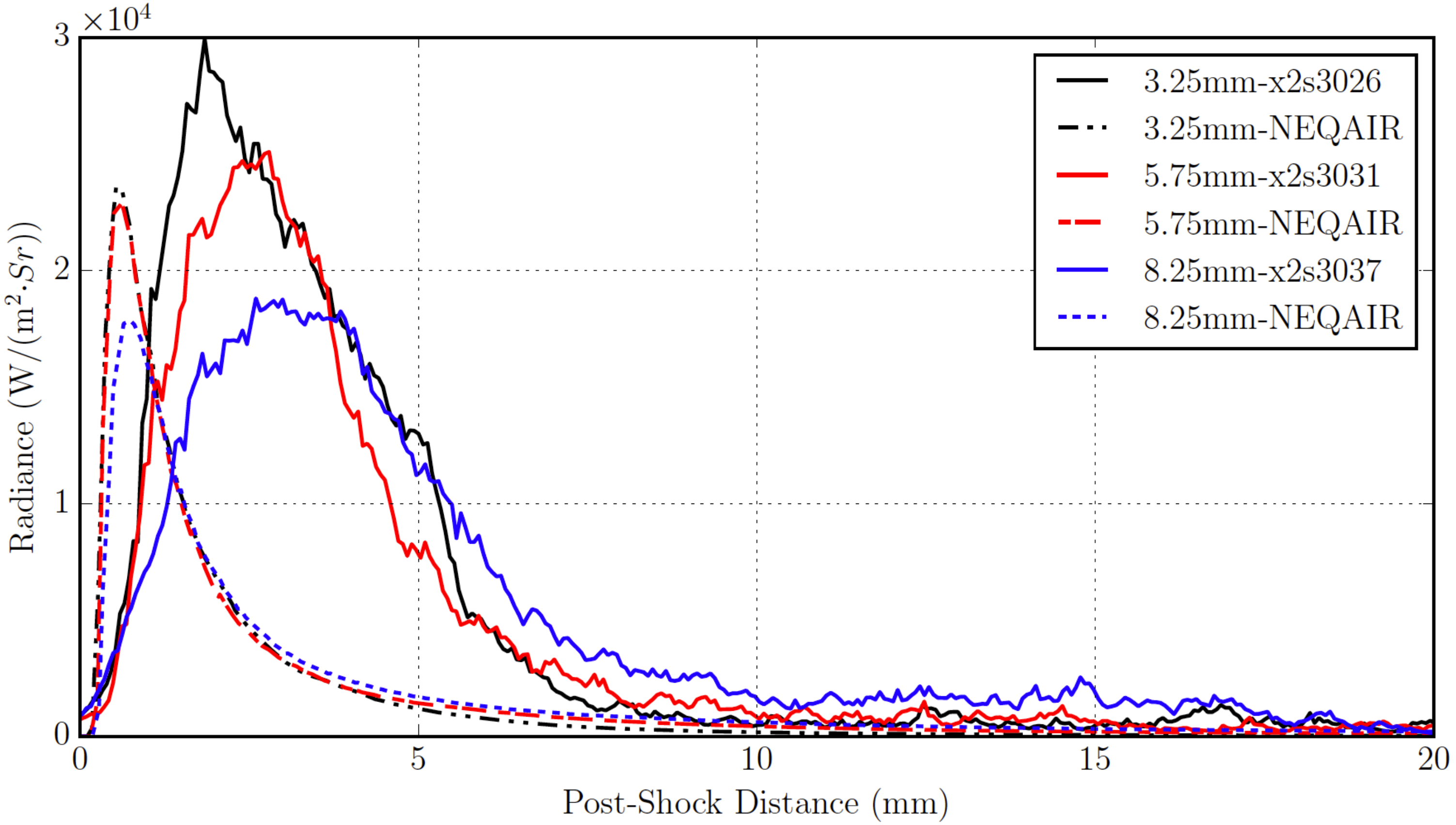
- Benchmark datasets from recent EAST Earth re-entry test campaigns have been identified.
  - Data can be found at:
    - https://data.nasa.gov/docs/datasets/aerothermodynamics/EAST/index.html

National Aeronautics and
Space Administration

Ames Research Center
Entry Systems and Technology Division

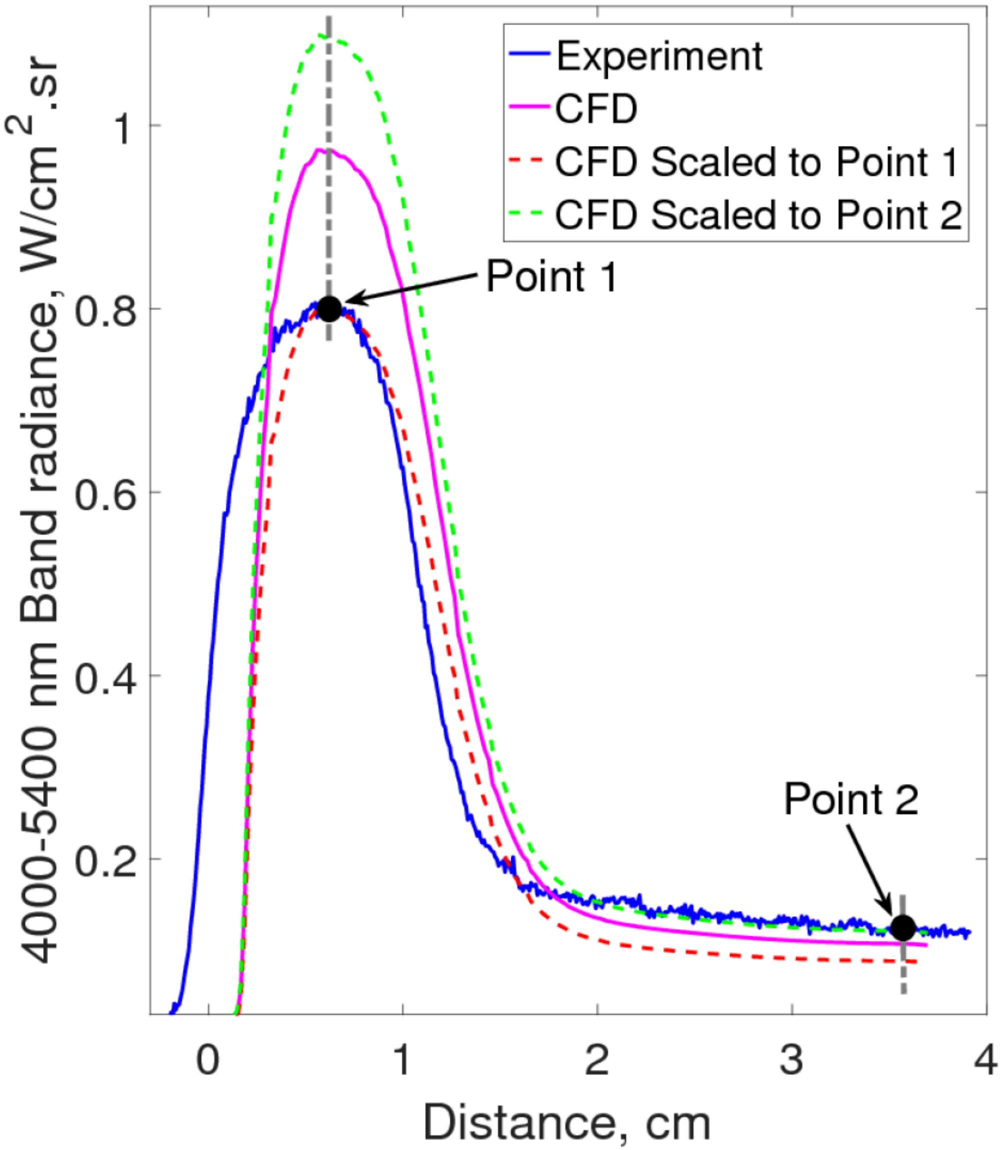
First Steps to Aftbody Validation Data (Han Wei)

- Tests over a wedge model have been conducted in the X2 facility at the University of Queensland for both Air and CO_2.
- Plot below shows comparison of simulations with X2 data for an expanding Air flow integrated over the 149 nm N line



First Steps to Aftbody Validation Data (Sangdi Gu)

- Plot to the right shows a comparison of simulations with X2 for MWIR CO_2.
- The scale factors required across conditions tested vary between approximately 0.8 and 3.
- Questions remain with regards to the accuracy of the quoted freestream conditions.
  - The test gas goes through an unsteady expansion then through a nozzle before arriving at the wedge.

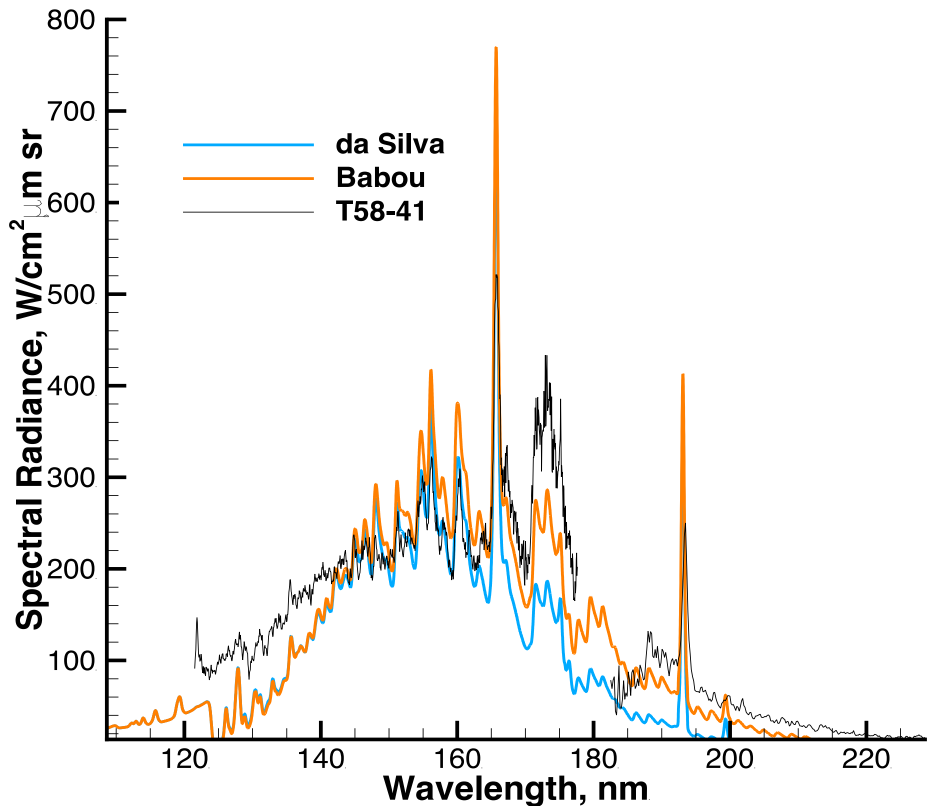


Benchmark EAST Earth Data

- Large number of EAST experiments
  - Great for statistical analysis, but problematic for identifying representative shots for detailed analysis
  - Provide more accessible data for future code validations and facility-to-facility comparisons
- Benchmark experiments are the ones in closest agreement to line of best fit and with the best experimental characteristics
- Data is reported in different formats for analysis, and all the information needed to simulate EAST is provided
- Data can be found at:
  - https://data.nasa.gov/docs/datasets/aerothermodynamics/EAST/index.html

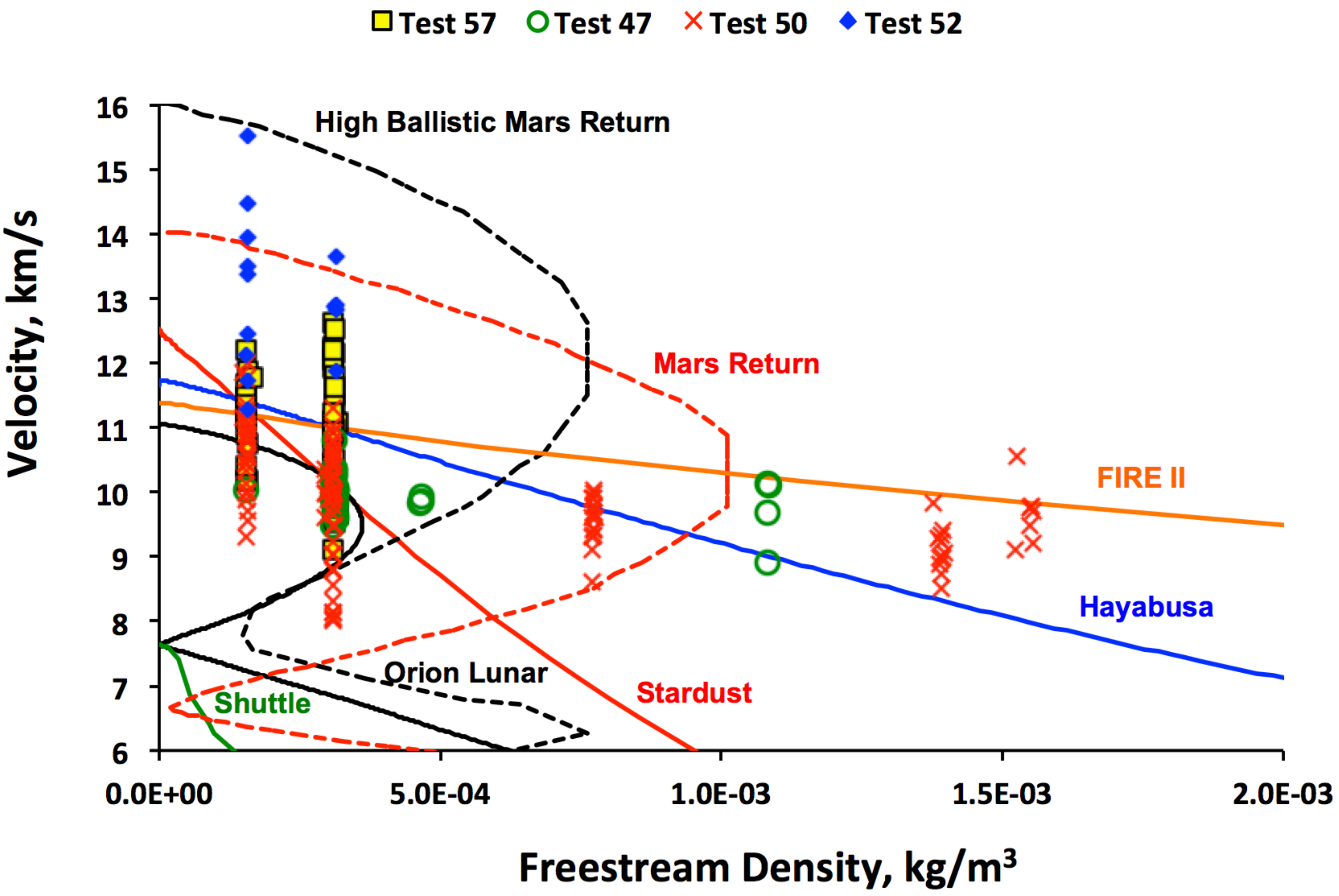
Recent Testing – CO_2/Ar

- Particular interest for Mars and Venus entries
- Several EAST tests have helped develop/confirm equilibrium radiation models and CO_2 reaction kinetics.
- However, results remain somewhat ambiguous
  - e.g. HARA and NEQAIR use two distinct CO 4th Positive models are used
  - Under different conditions or assumption one is observed to agree better than the other
  - The choice of spectroscopic database influences inferring reaction rates from EAST data



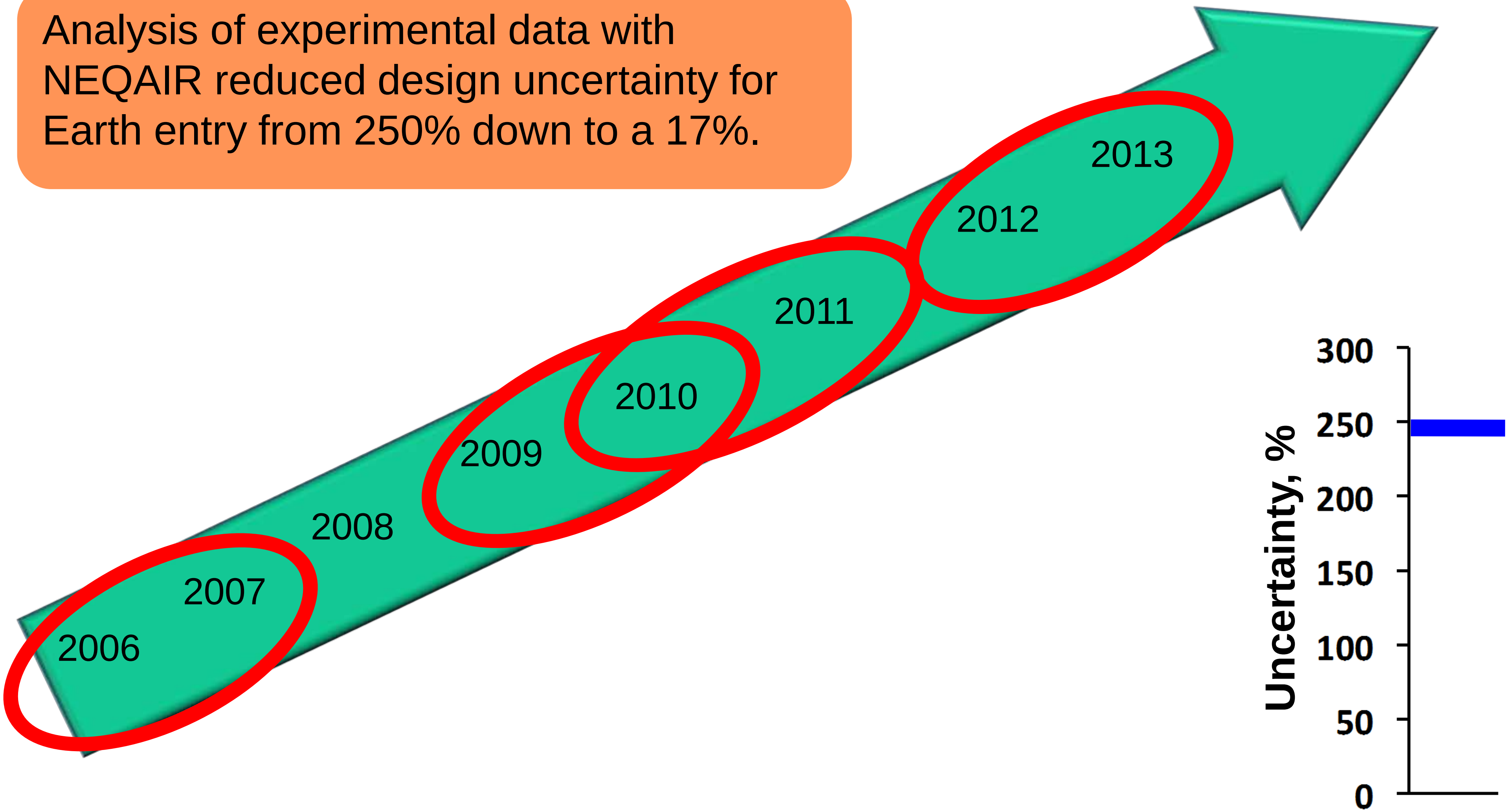
- Hybrid spectral database might provide better solution
- Possible test series to repeat with TDLAS and/or with 24” tube

Recent EAST Earth Testing Conditions

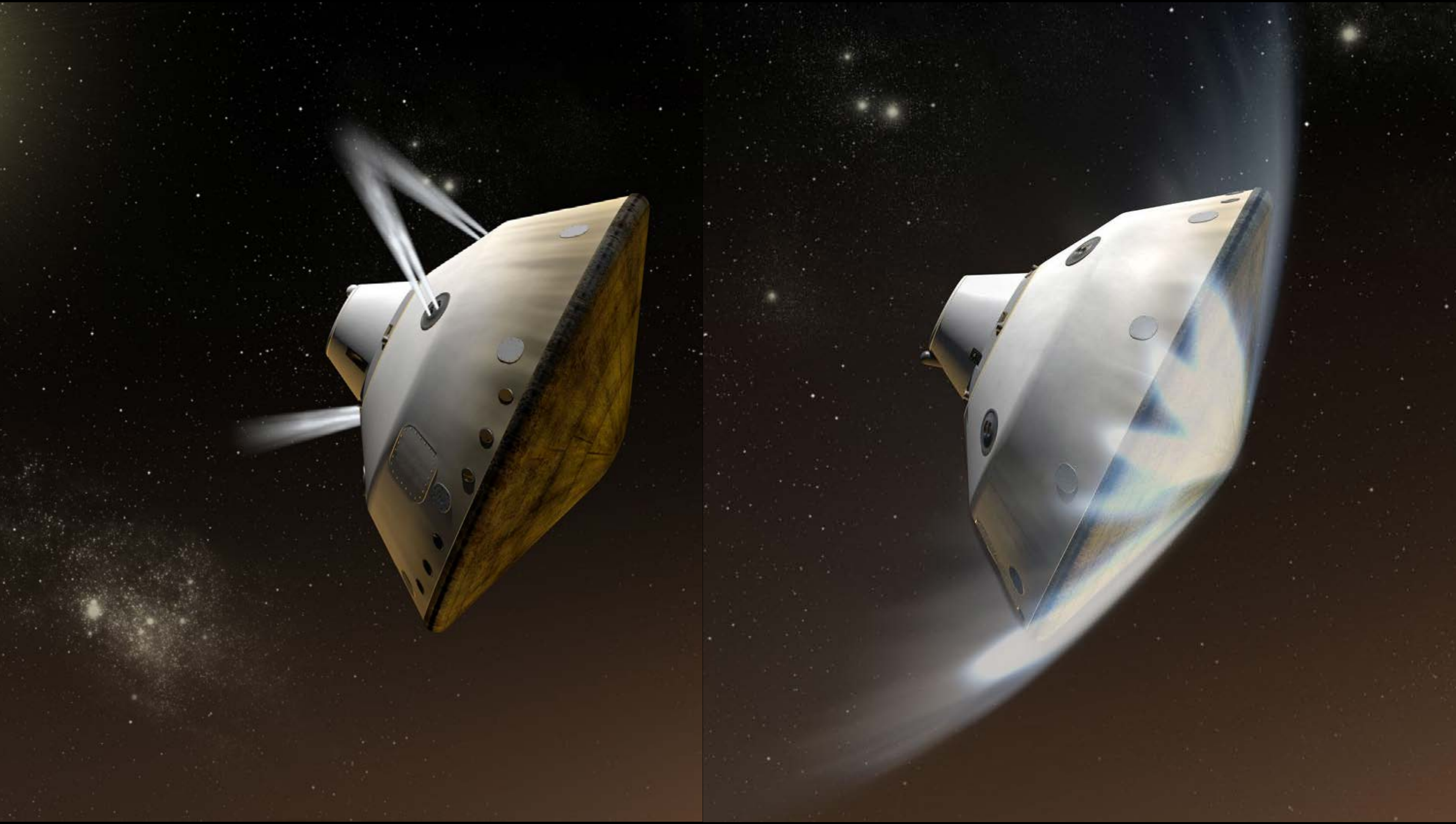


Improvement of Uncertainty for Earth Equilibrium Radiation

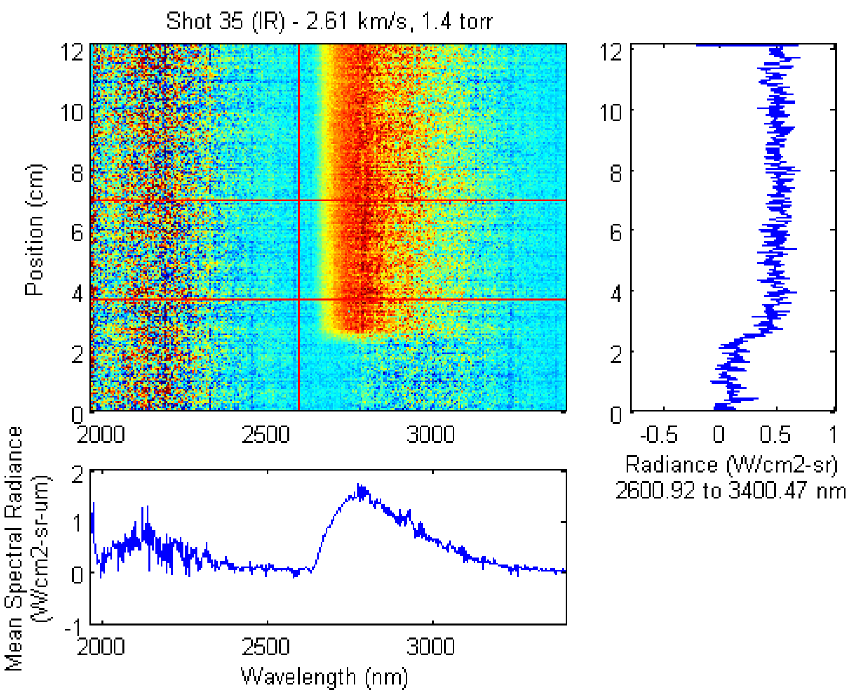
Analysis of experimental data with NEQAIR reduced design uncertainty for Earth entry from 250% down to a 17%.

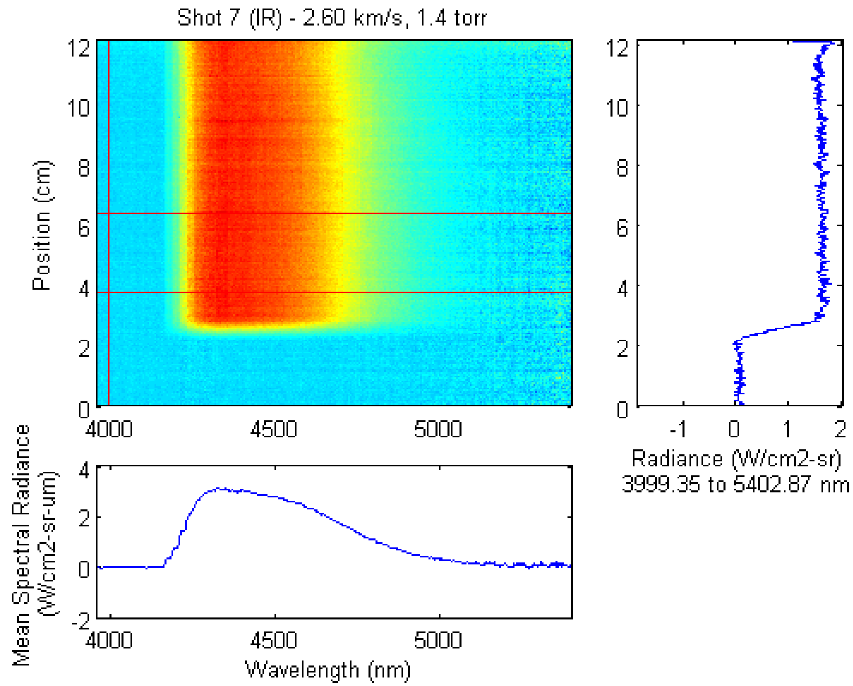


Radiative Heating for Mars Exploration



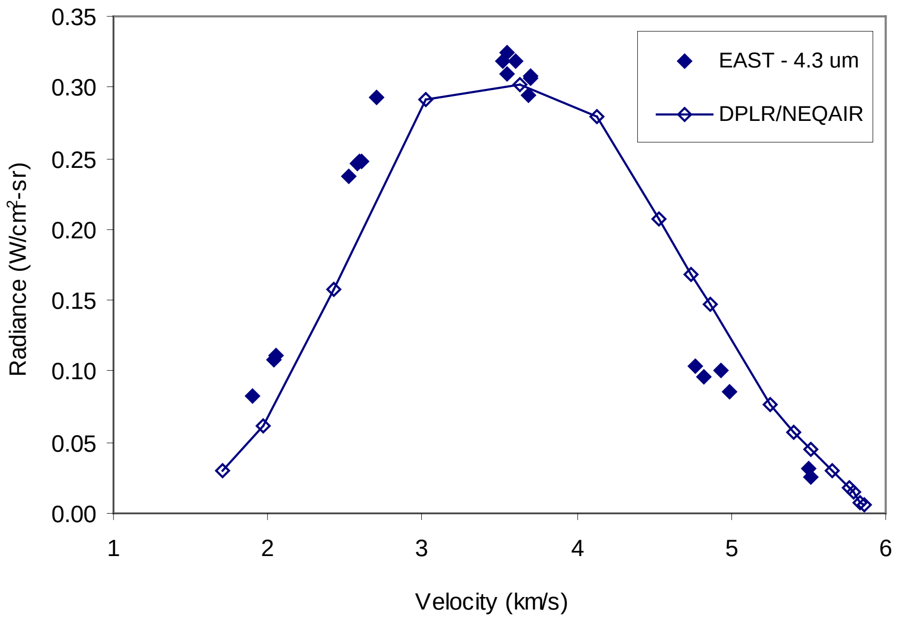
EAST Experiments – Later Trajectory

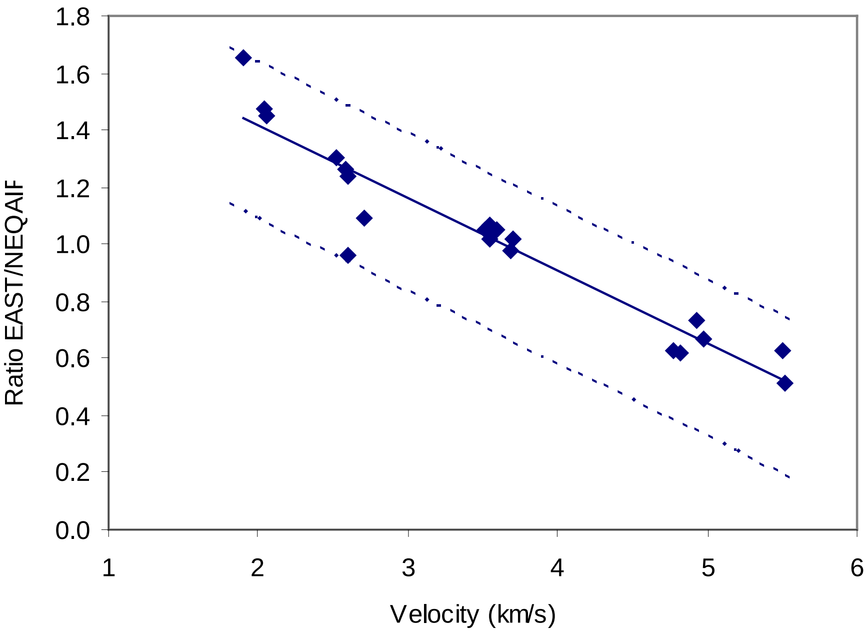




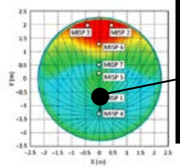
- Condition of 2.6 km/s and 1.4 Torr corresponds to t = 95.2s point of MSL Entry
- In this condition
  - No non-equilibrium zone observed
  - No radiation observed in UV/VUV. Visible is weak
  - Both 2.7 μm and 4.7 μm bands of CO_2 are observed

Validation – 4.3 μm

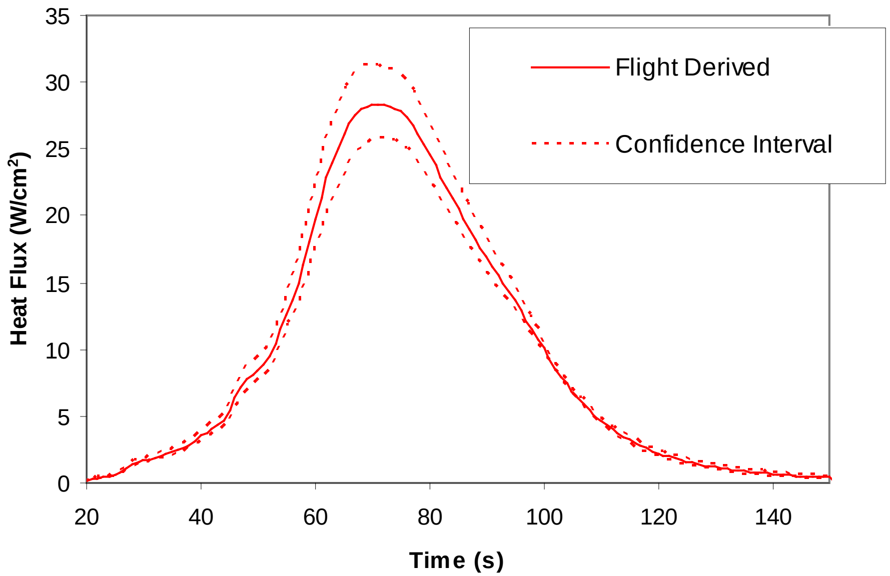


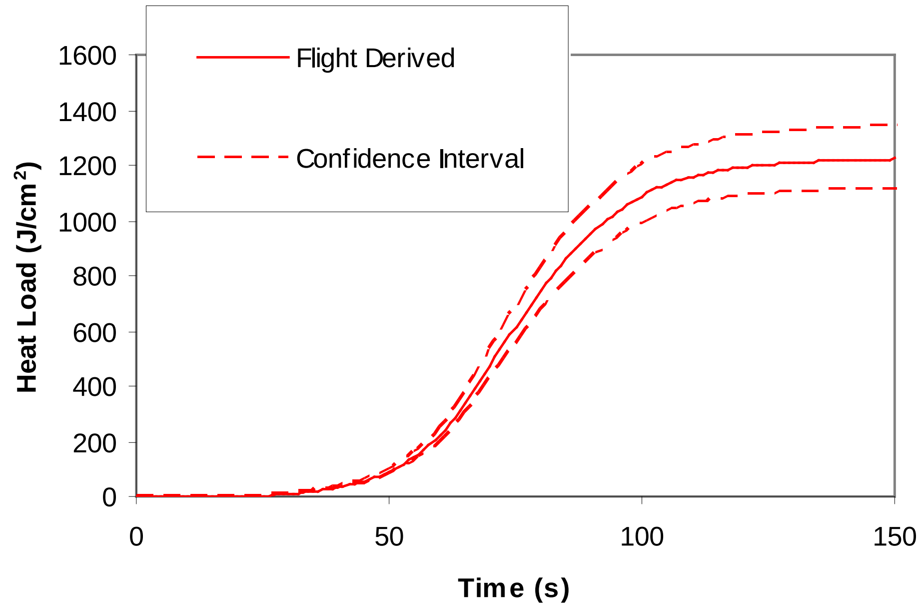


- The 4.3 μm band is matched, but appears shifted by ~0.2 km/s
  - This shift is larger than facility velocity uncertainties
  - We speculate that it may be related to uncertainties in the chemical kinetic model
- Corresponding mean uncertainty:
  - +50% at low velocity, -50% at high velocity
  - Almost zero at peak radiation



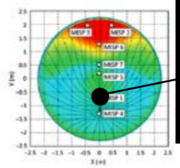
Flight Derived Heating

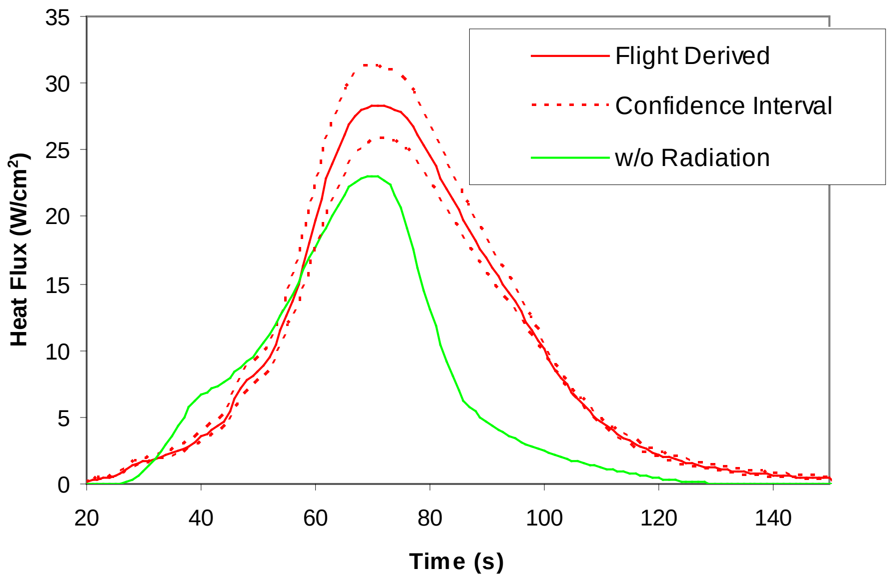


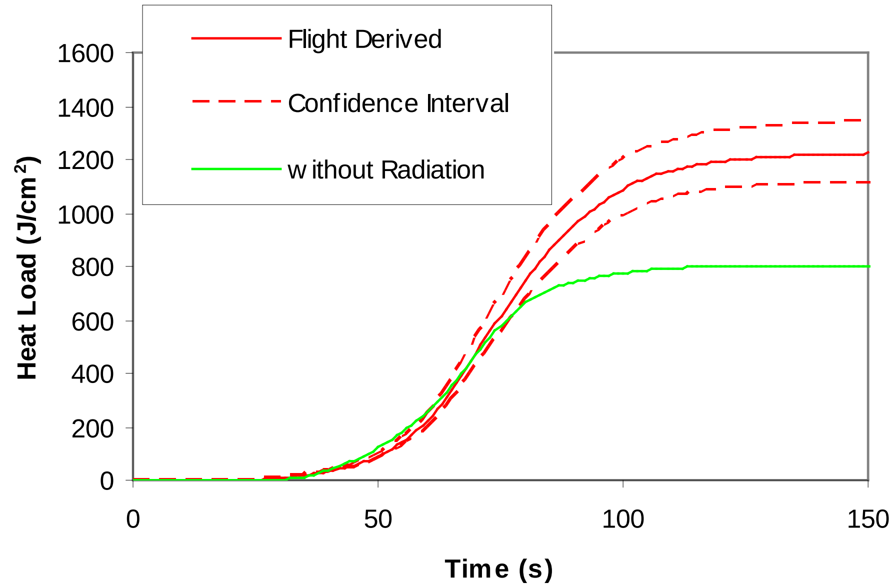


- Confidence intervals are based on using a Monte Carlo analysis
- Heat load can be more relevant for heat shield sizing

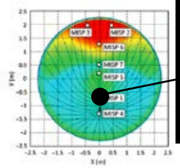
Comparison to Flight Data



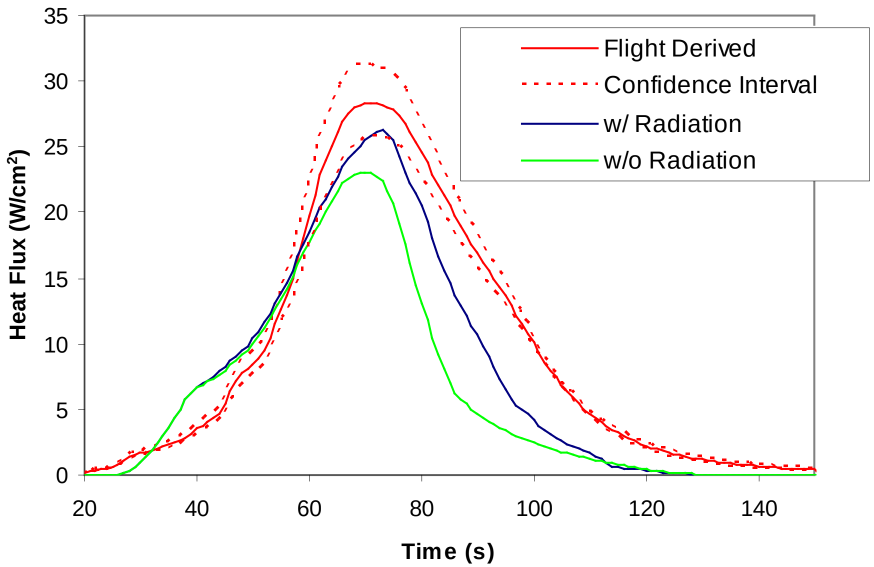


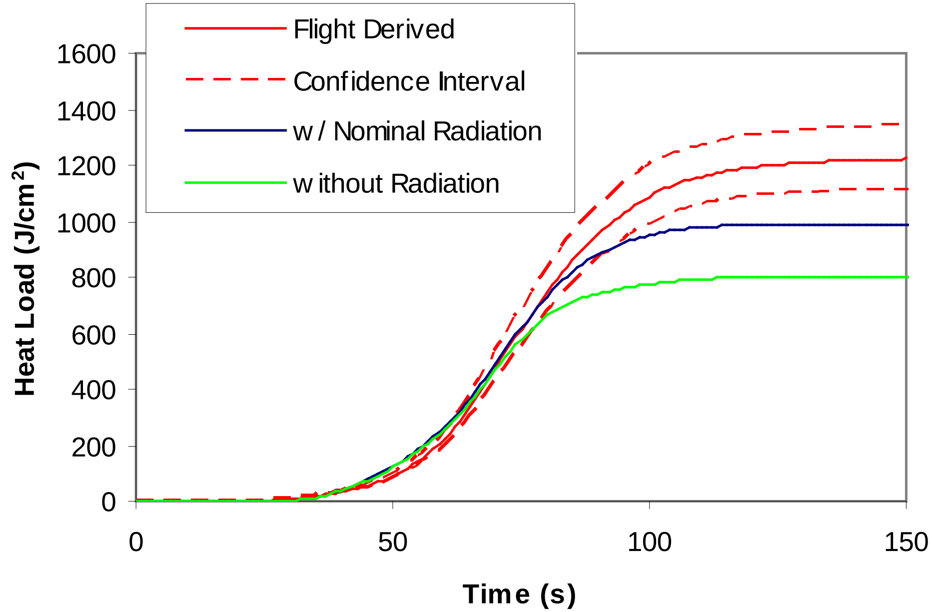


- Confidence intervals are based on using a Monte Carlo analysis
- Heat load can be more relevant for heat shield sizing
- Using convection only, the heat flux is under-predicted significantly
- Heat load is under-predicted by 400 J/cm^2, or 33%



Impact of Radiation

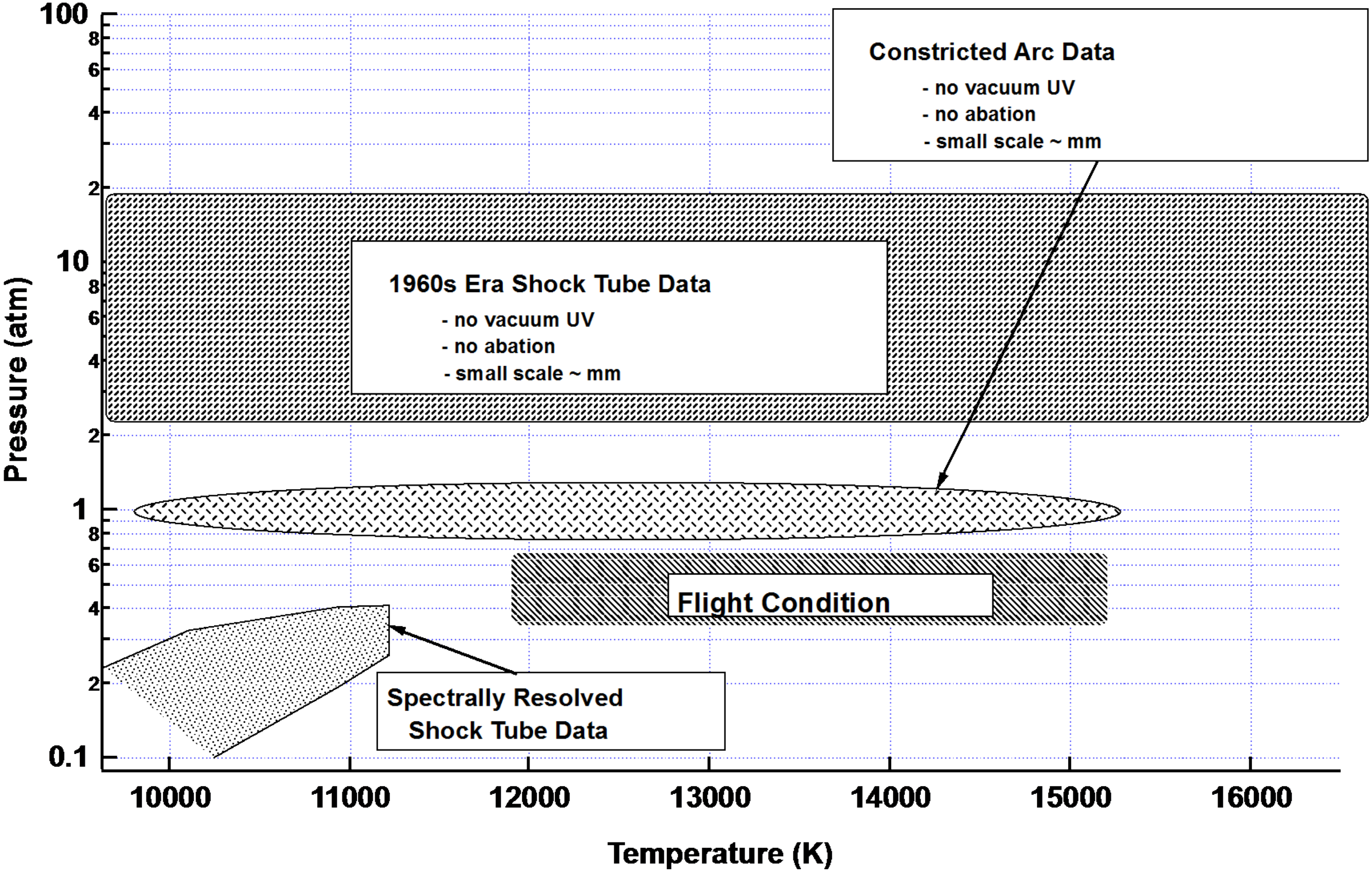




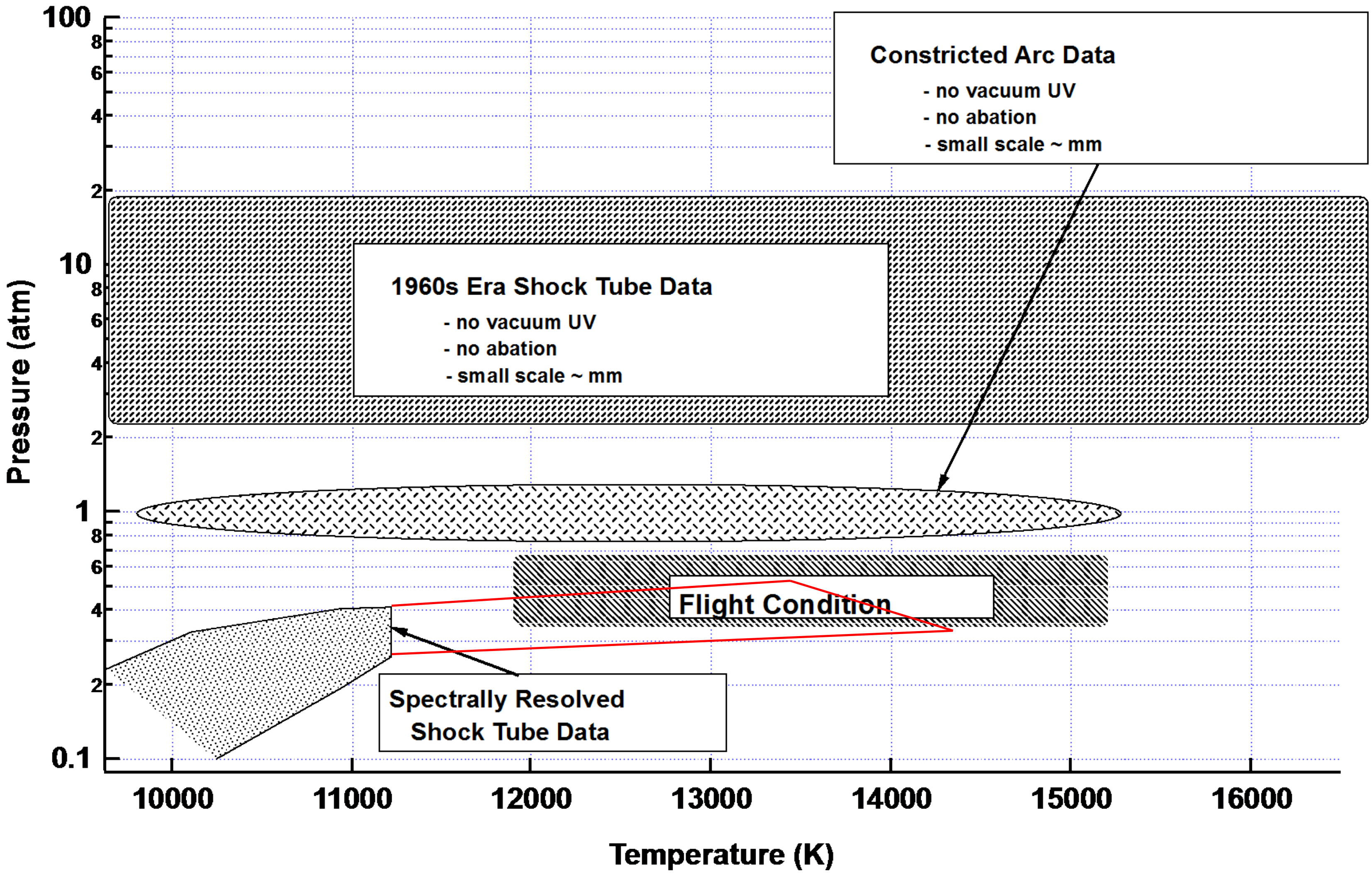
- Including radiation calculated by NEQAIR reduces heat flux discrepancy by approximately half
  - Heat load under-prediction reduced to 19%
- Peak heat flux is just within confidence interval at peak heating

High Speed Earth Return

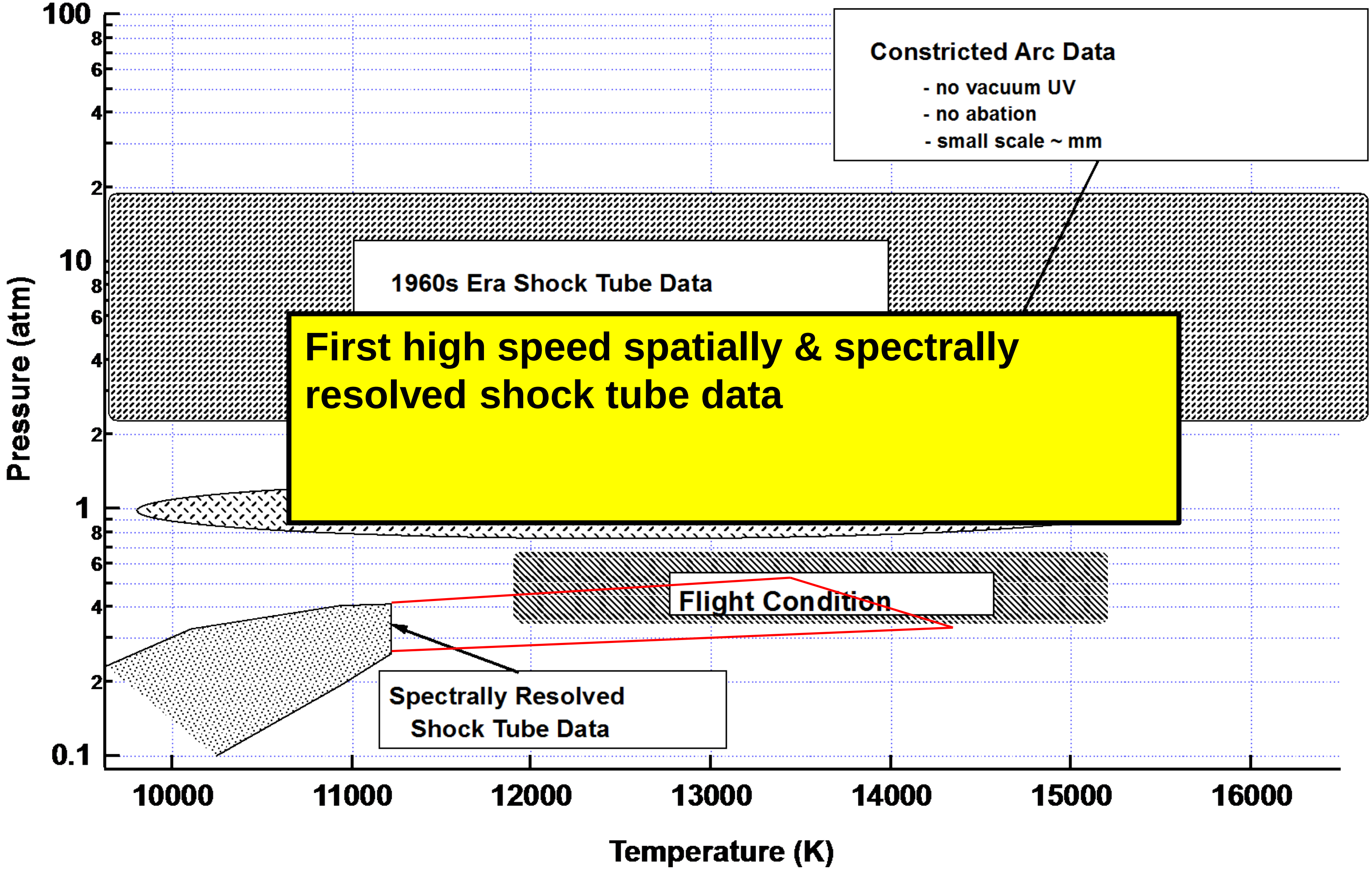
High Speed Earth Entry Data



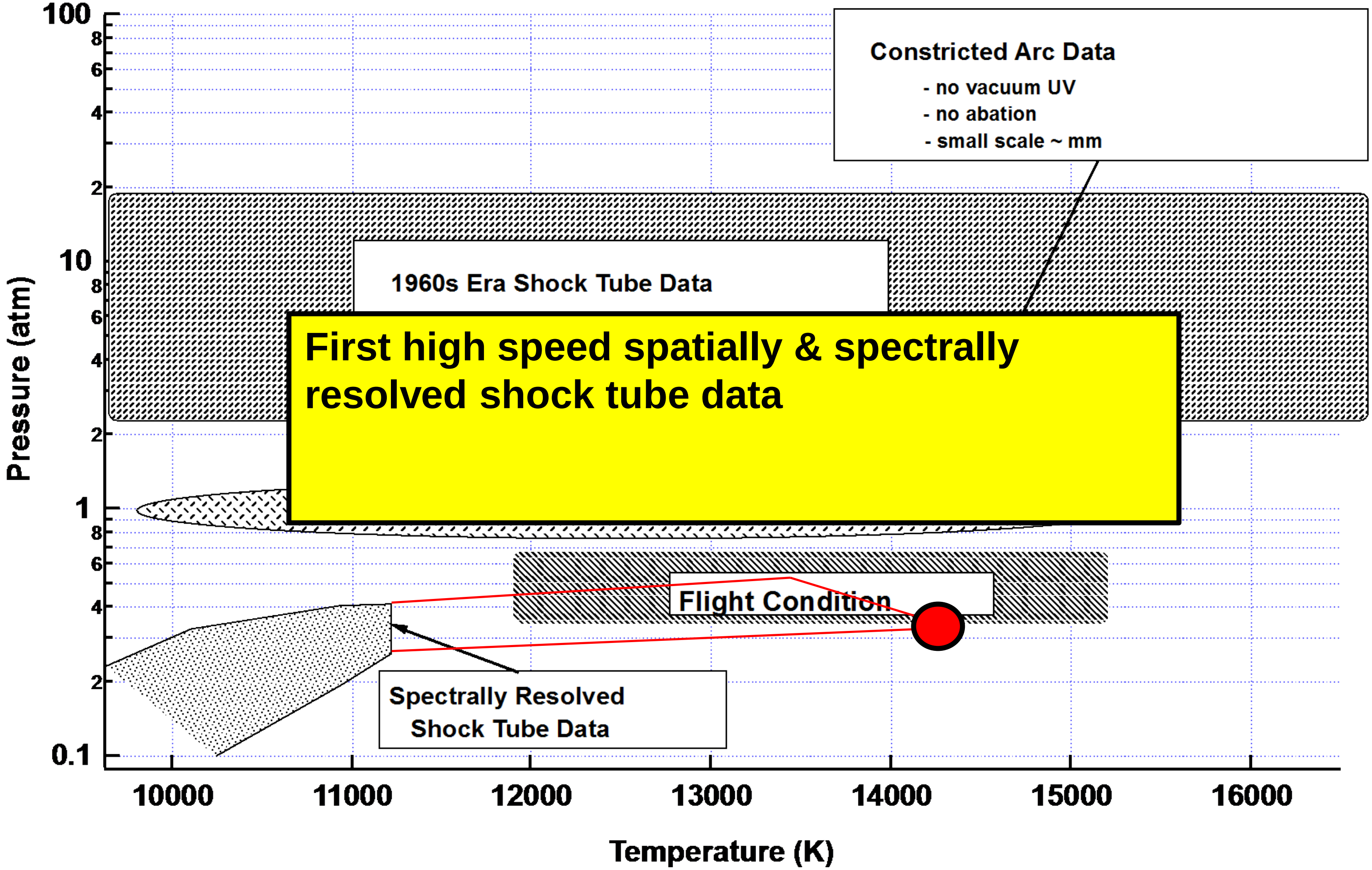
High Speed Earth Entry Data



High Speed Earth Entry Data

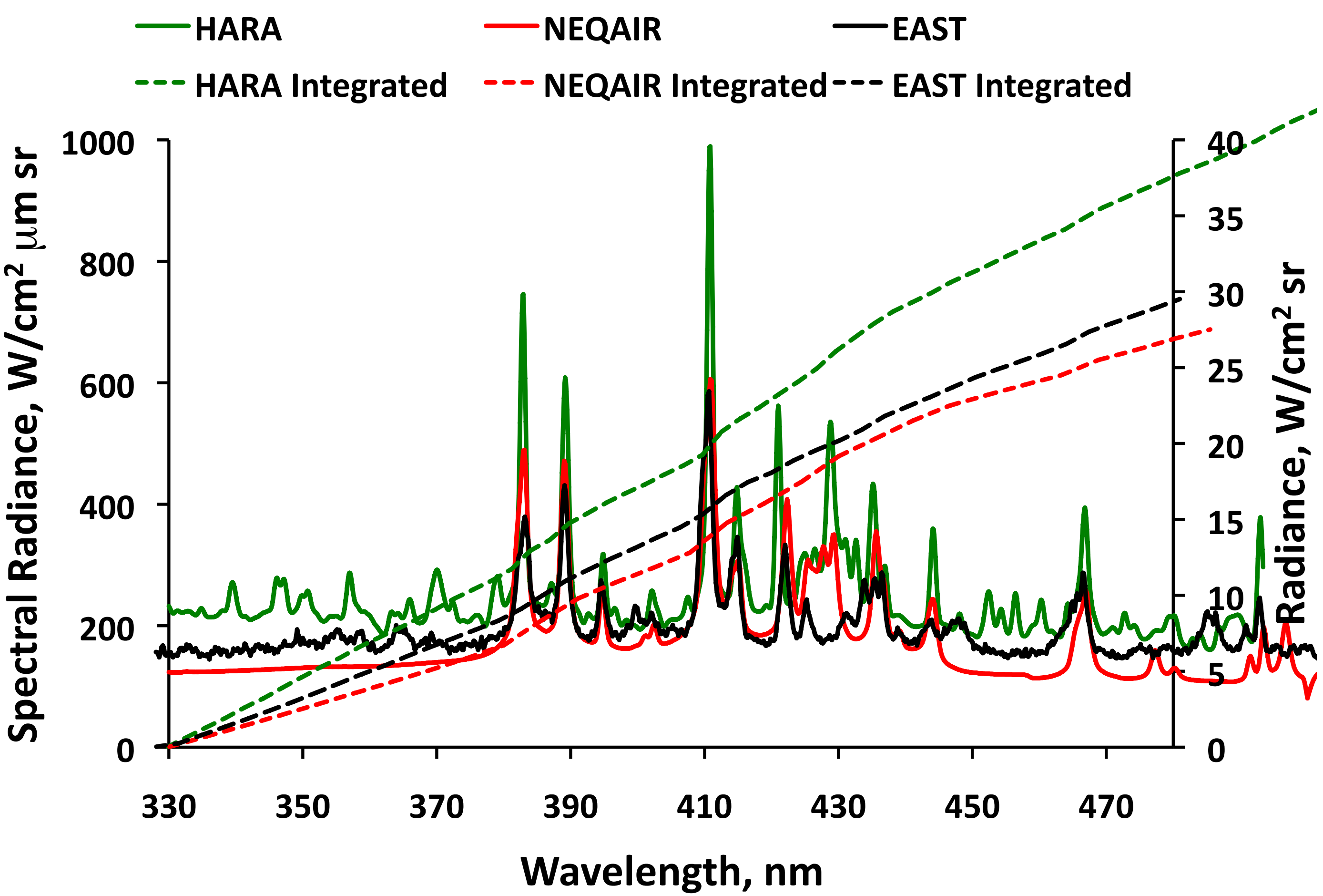


High Speed Earth Entry Data



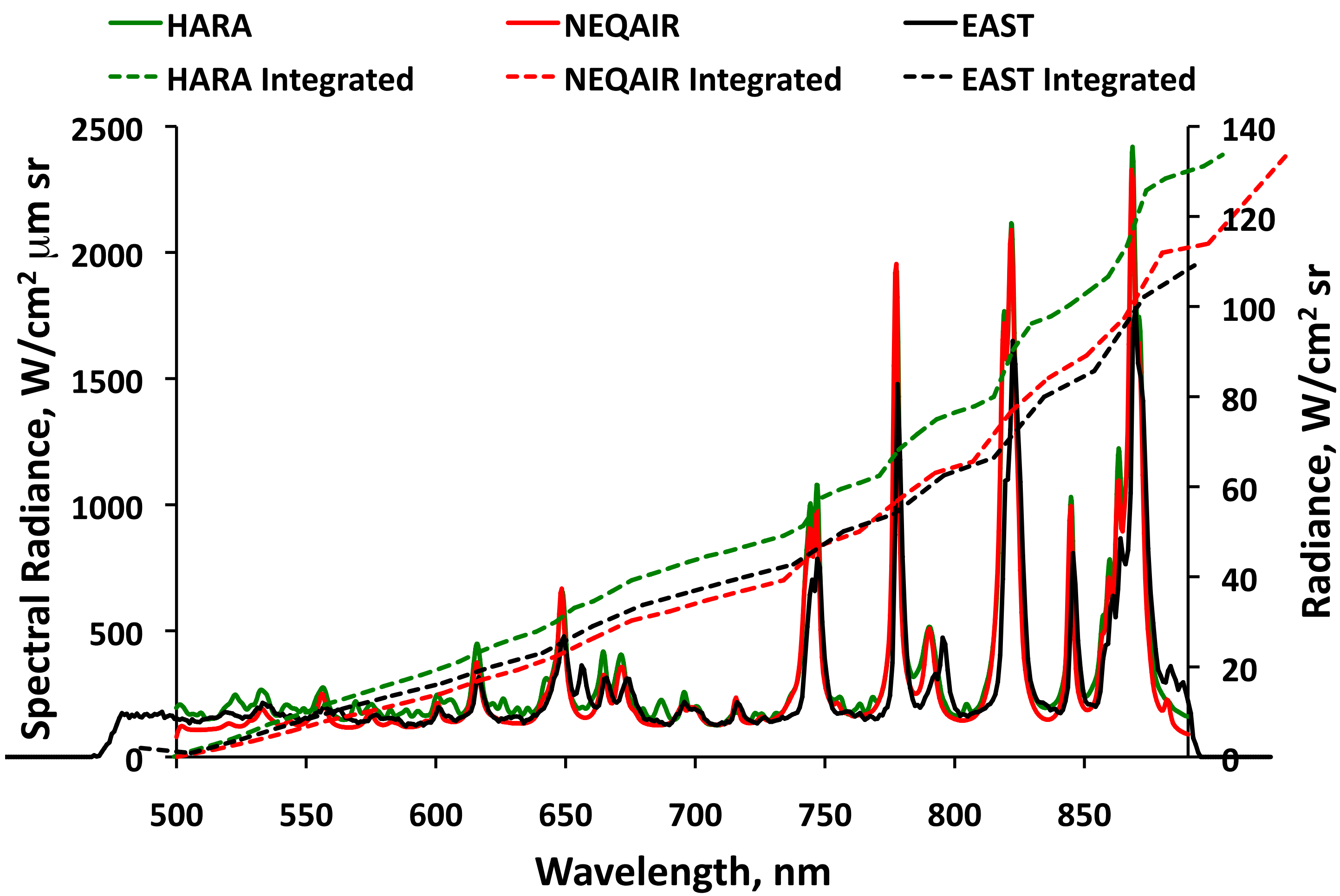
Spectral Comparison 15.5 km/s: UV/Vis

Good agreement for both codes in UV/Vis within 30%

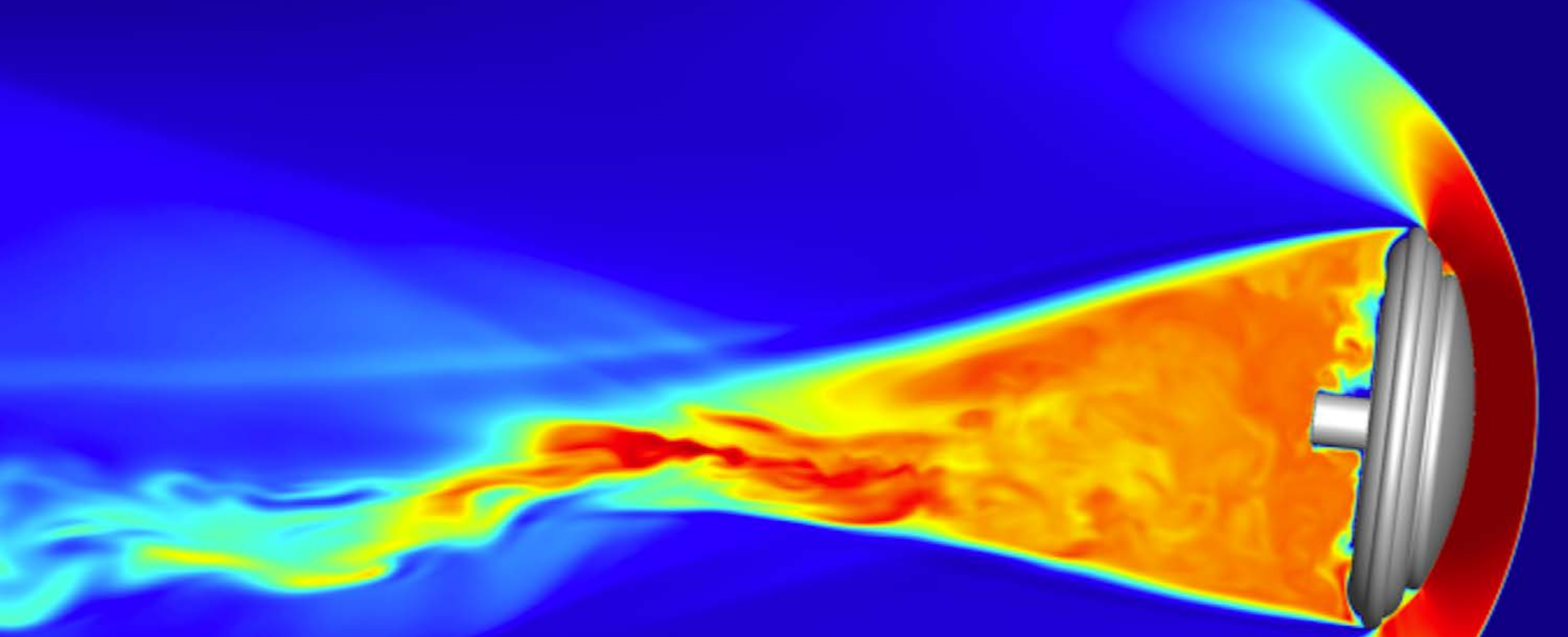


Spectral Comparison 15.5 km/s: Vis/NIR

Excellent agreement for both codes in Vis/NIR within 20%



What are DPLR and US3D?



DPLR and US3D are suites of CFD tools for the computation of supersonic and hypersonic flows in chemical and thermal non-equilibrium.

What is NEQAIR?

NEQAIR was NASA's first radiative heating code and has been the go-to-tool for 30 years

NEQAIR computes spectra and radiative heating based on a given flow-field