Investigation of Non-Equilibrium Radiation for Earth Entry

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Overview

- Provide motivation and introduce EAST and Computational Tools
  - EAST shock tube facility
  - LAURA and DPLR for flowfield calculations
  - HARA and NEQAIR for radiation calculations
- Methodology

This presentation should convey 3 main points:

1) Non-equilibrium radiance compared between EAST and NASA's CFD & radiation simulations tools
2) Significant relative discrepancies are observed and there are compensating errors
3) The absolute level of error due to non-equilibrium is often small

  - Depending on shock speed, simulations under-predict EAST by up to 50% or over-predict up to 20%
  - At 0.2 Torr, below 9 km/s error in radiative heat flux due to non-equilibrium < 1 W/cm^2, and < 20 W/cm^2 at 11 km/s

Introduction

- Re-entry missions involving larger vehicles and higher entry velocities motivate improved simulation of radiative heating and associated uncertainties, e.g. EM-1

Brief Overview of Missions

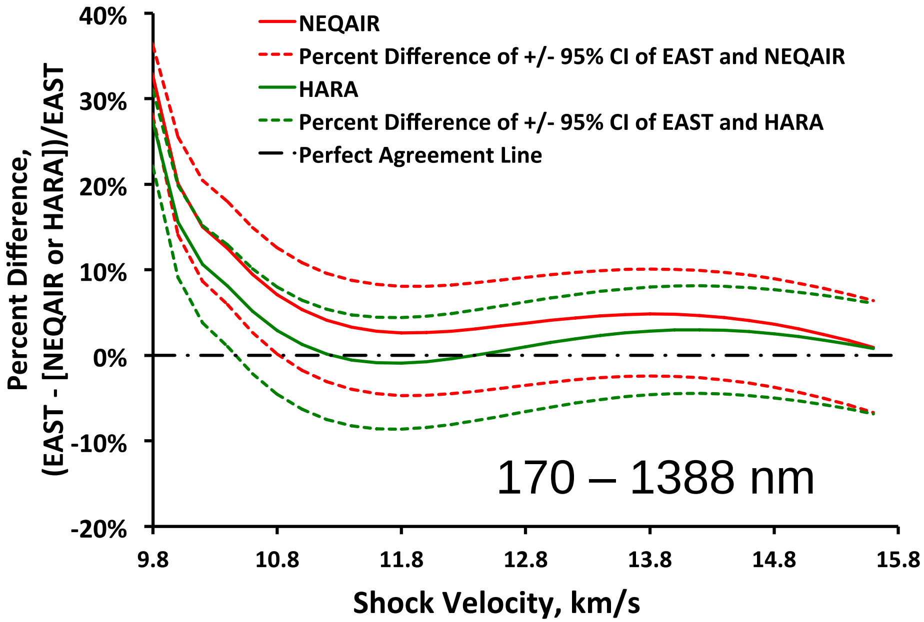
EFT-1: First Orion flight test; entered Earth's atmosphere from a highly elliptical orbit in December of 2014

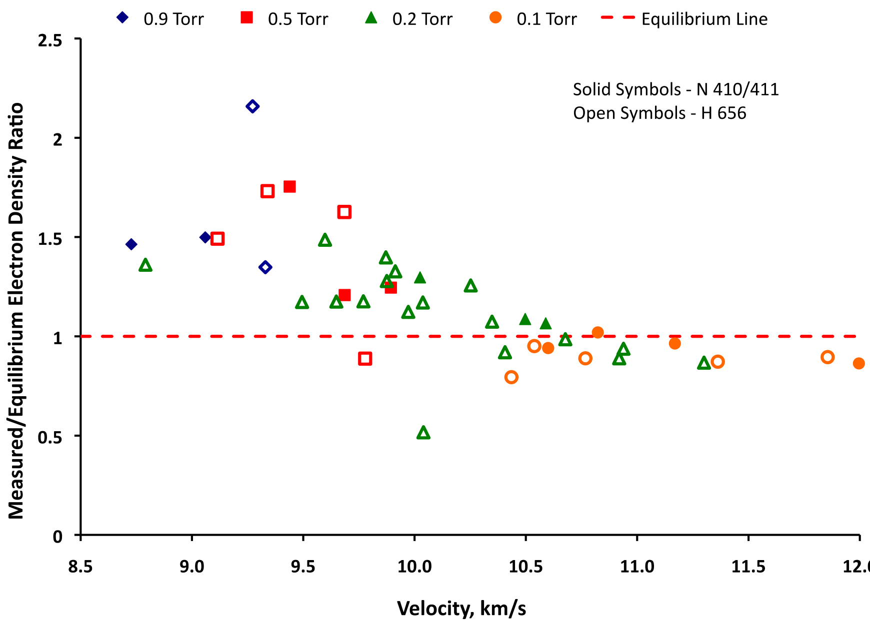
EM-1: the next Orion flight will undertake a lunar return trajectory (radiation will be significant)

- Using shock tube data to validate non-equilibrium should only be attempted if equilibrium is well understood
- Previous analyses have conducted extensive comparisons between EAST and radiation calculations at equilibrium

Equilibrium Summary

- Uncertainty for model predictions of EAST was shown 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%].

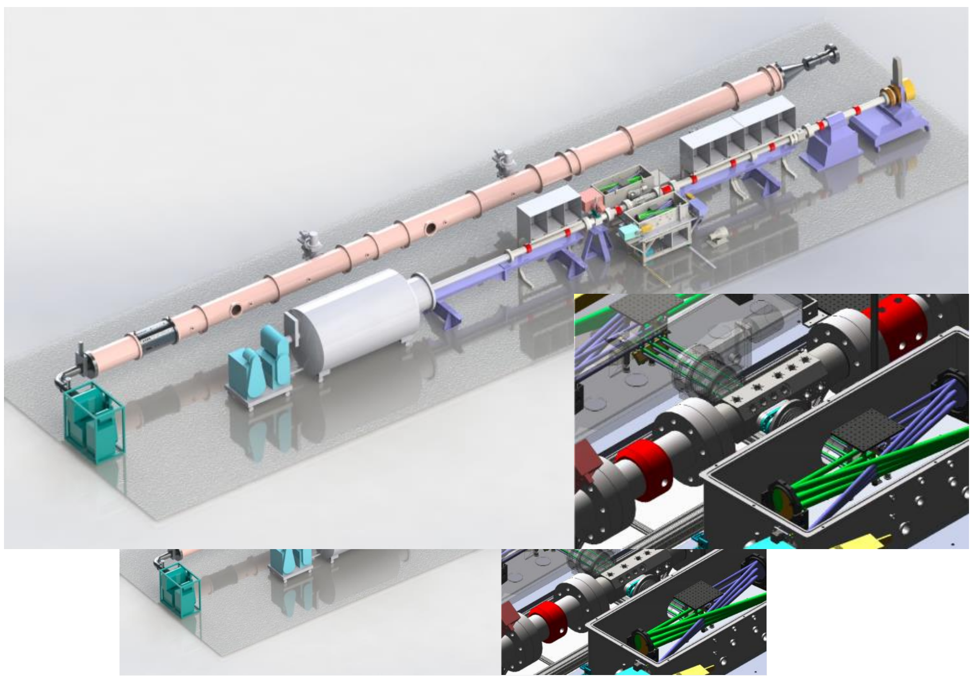


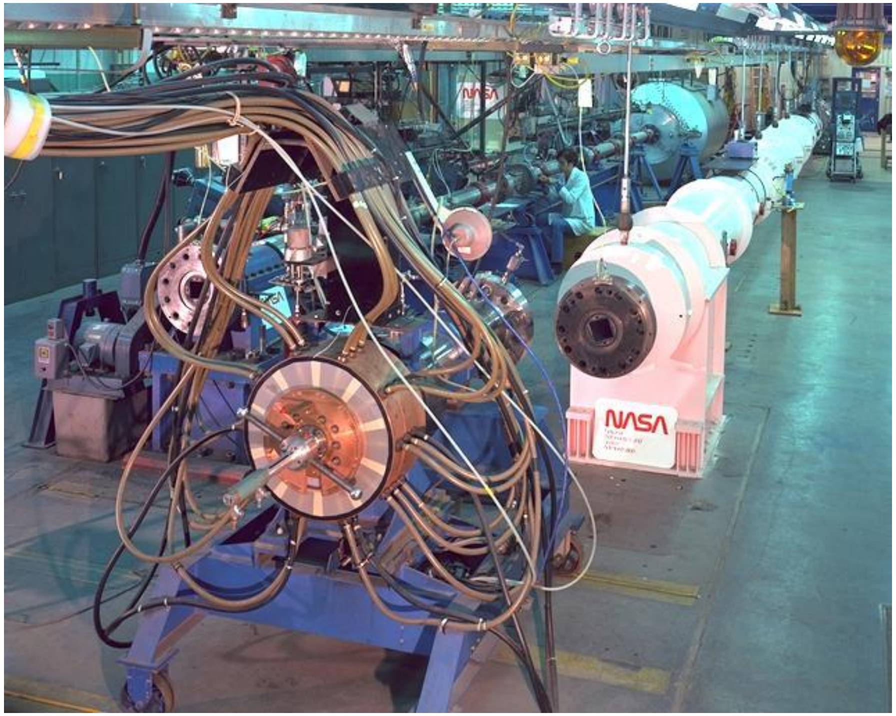


Methodology

EAST Facility

- EAST: Electric Arc Shock Tube, located at NASA Ames Research Center
- Shock is driven by an electric arc discharge.
- 10.16 cm in diameter at the test section.
- 4 spectrometers analyzing different spectral ranges in each shot. These ranges are typically:





Simulation Tools

- Two sets of simulation tools are used in the analysis:
  - NEQAIR radiation calculations based on DPLR flowfields.
  - HARA radiation calculations based on LAURA flowfields.
  - Additional calculations also performed with NEQAIR and LAURA.
- Different combinations of simulations used to determine if discrepancies are due to modeling issues of the flowfield, physics or radiation.
- The latest release of DPLR has fixed the ability to run $T_e = T_v$
- NEQAIR v15.0 is used (what will become the next release)
  - The non-Boltzmann model needed to be modified for some transitions of N_2 and IR atomic lines
  - Previous versions of NEQAIR would have set the populations to Boltzmann
- An updated NO non-Boltzmann model has been implemented in HARA, but is not included in this presentation
- The electron impact excitation rates of Park and Huo have been also compared using NEQAIR

Computational Methodology

- DPLR used a 3m sphere with 803 grid points along the stag-line, while LAURA used a 2.5m sphere with 256 points.
- 11 species gas model, with ionization species. No ablation products.
- Two temperature model used for thermo non-equilibrium:
  - $T_{trans} = T_{rot}$
  - $T_{vib} = T_{electronic} = T_{electron}$

Spectral Range	EAST Camera	Dominant Radiators
117 – 153 nm for $V \geq 9$ km/s	VUV	N, O
123 – 153 nm for $V < 9$ km/s	VUV	N, O
170 – 178 nm	VUV	N
178 – 210 nm	VUV/UV	NO
210 – 328 nm	UV	N_2, N_2^+, N
328 – 496 nm	UV	N_2^+, N, N_2
496 – 888 nm	Vis/NIR	N, O, N_2
888 – 1445 nm	IR	N, O

Differences Between Reaction Sets

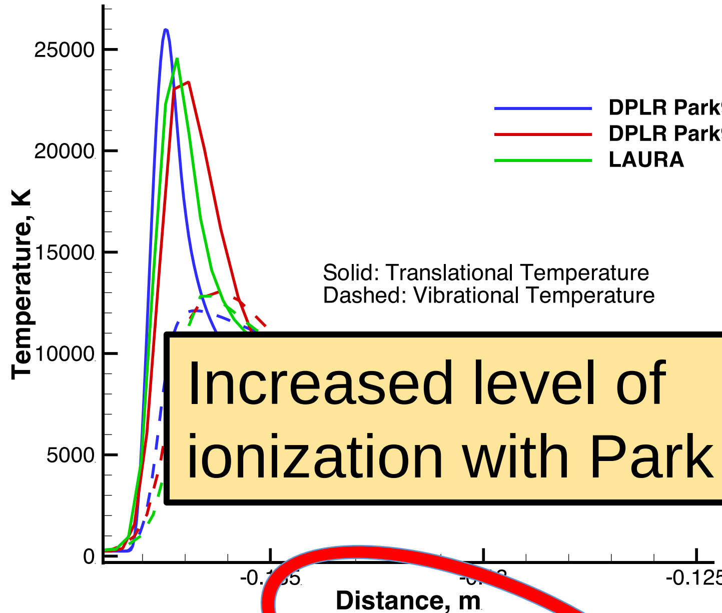
- The main difference between Park 90 and Park 93 chemistry is that Park 90 does not contain the nitrogen electron exchange reaction:
  - $N^+ + N_2 \longleftrightarrow N_2^+ + N$

Reason for increased level of ionization with Park 90

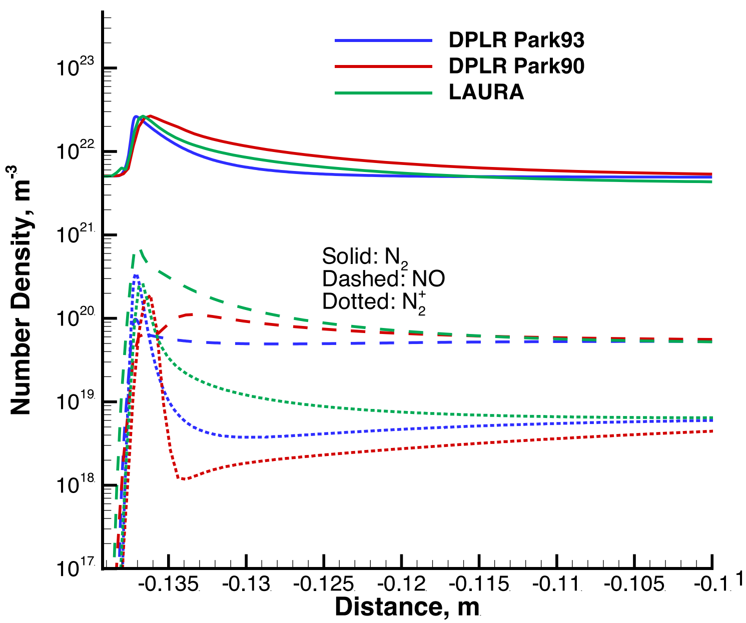
- LAURA chemistry uses a combination of newer rates from various sources, rates tuned to match EAST and some of the heritage rates from Park 90 and Park 93

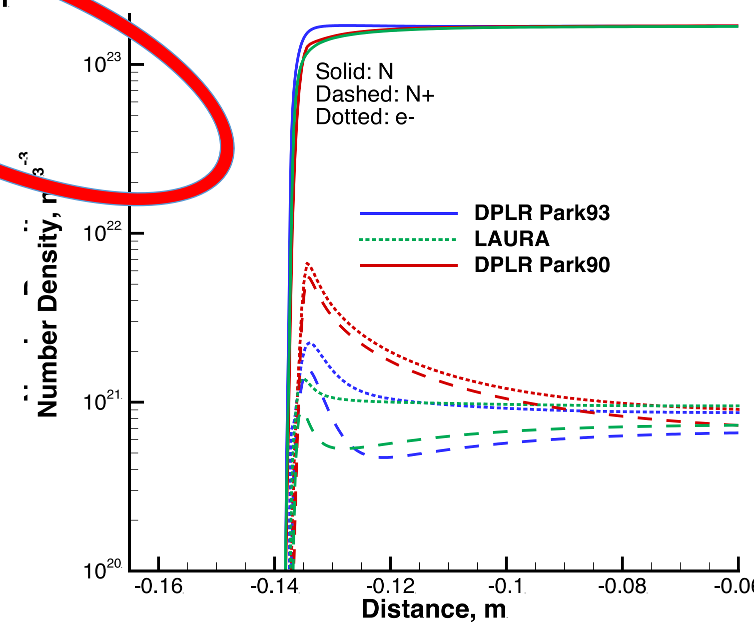
Rate	Comment	Reference
$NO + M \longleftrightarrow N + O + M$	Adjusted by Johnston to match EAST CO_2/N_2 data	Johnston el al.
$N_2 + e \longleftrightarrow N + N + e$	Updated rate for electron dissociated impact	Bourdon et al.
$O_2 + e \longleftrightarrow O_2^+ + e + e$	Updated rate	Teulet et al.
$N_2 + O \longleftrightarrow NO + N$	Updated rate	Fujita et al.
$O_2 + N \longleftrightarrow NO + O$	Updated rate	Bose and Candler

Influence of Reaction Rates at 9km/s & 0.2Torr



Increased level of ionization with Park 90



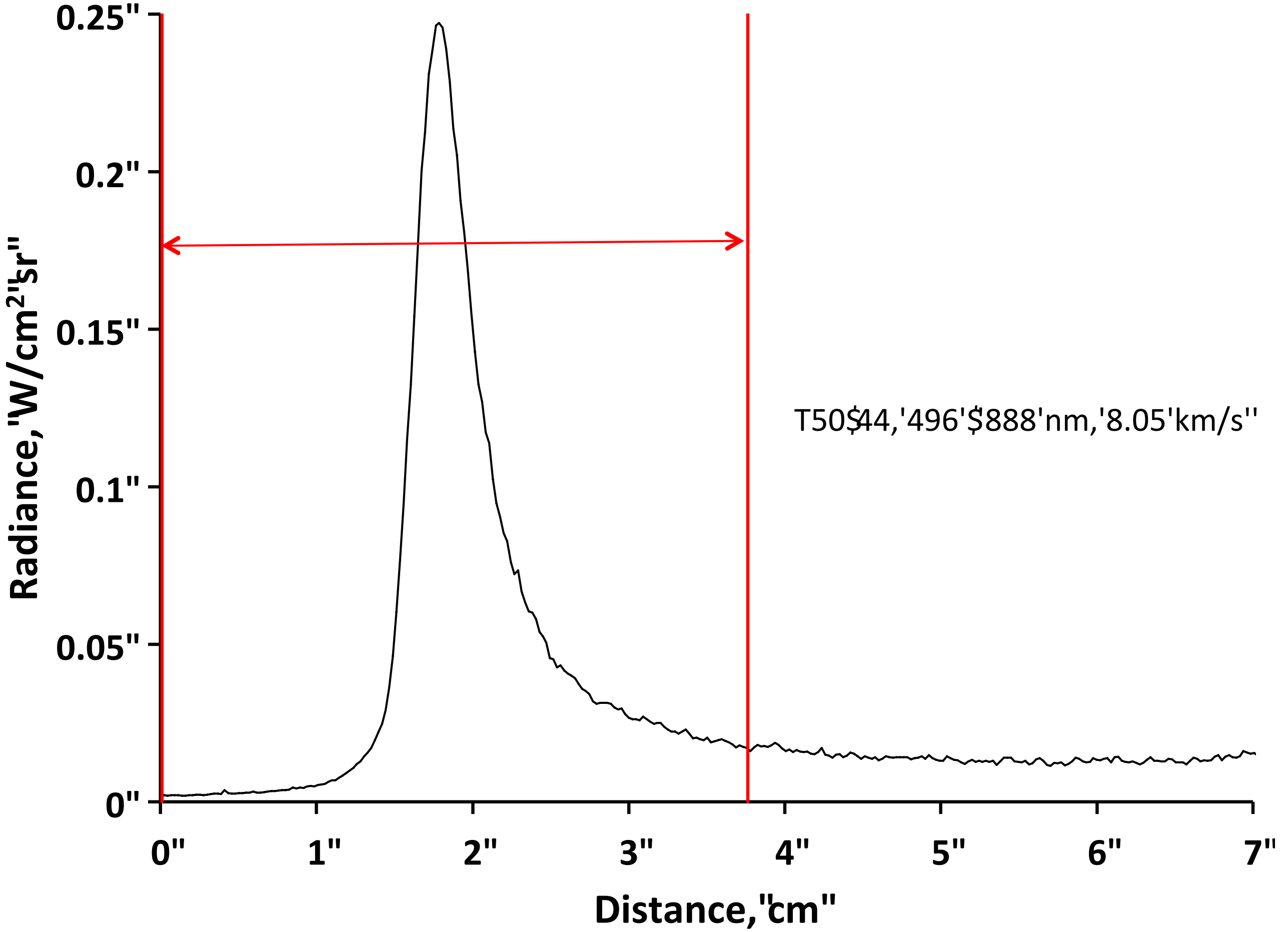


Development of Non-equilibrium Metric

- Many insights gained by comparing equilibrium radiance vs velocity trends between simulations and experiments.
- For non-equilibrium, it is not clear that 1 metric can represent all aspects of the flow. Ideally, the metric would be:
  - Independent of experimental parameters (such as gate width and spatial resolution).
  - Applicable to a wide range of conditions.
  - Easily comparable to simulation results.
  - Consistent with limitations of test time in the facility.
  - Accommodate a shot dominated by equilibrium.

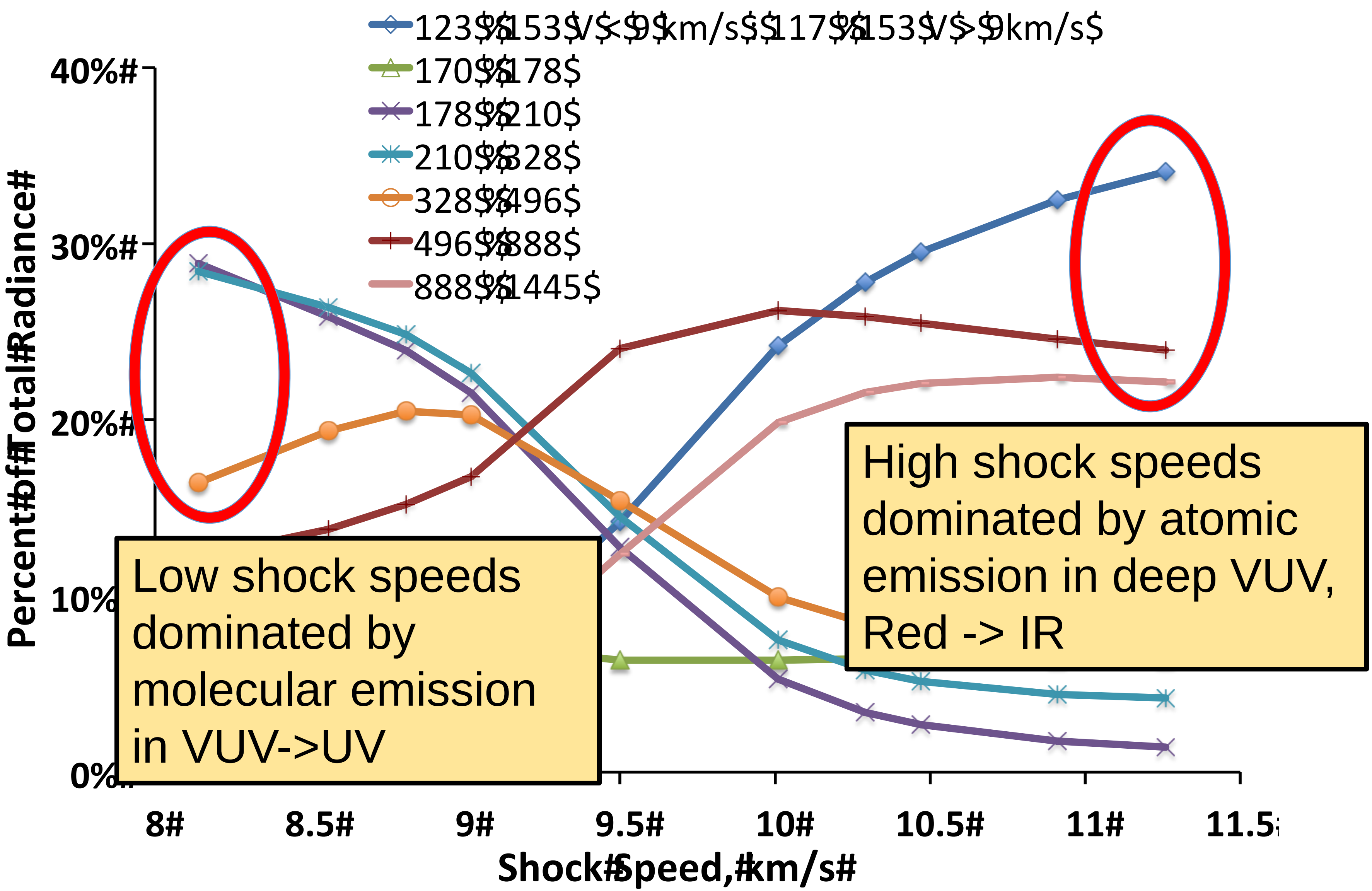
Non-equilibrium Metric

Absolute Non-Equilibrium Radiance



Integrated +/- 2cm either side of shock front.
Normalized by shock tube diameter

Radiation Emitted From Different Wavelengths



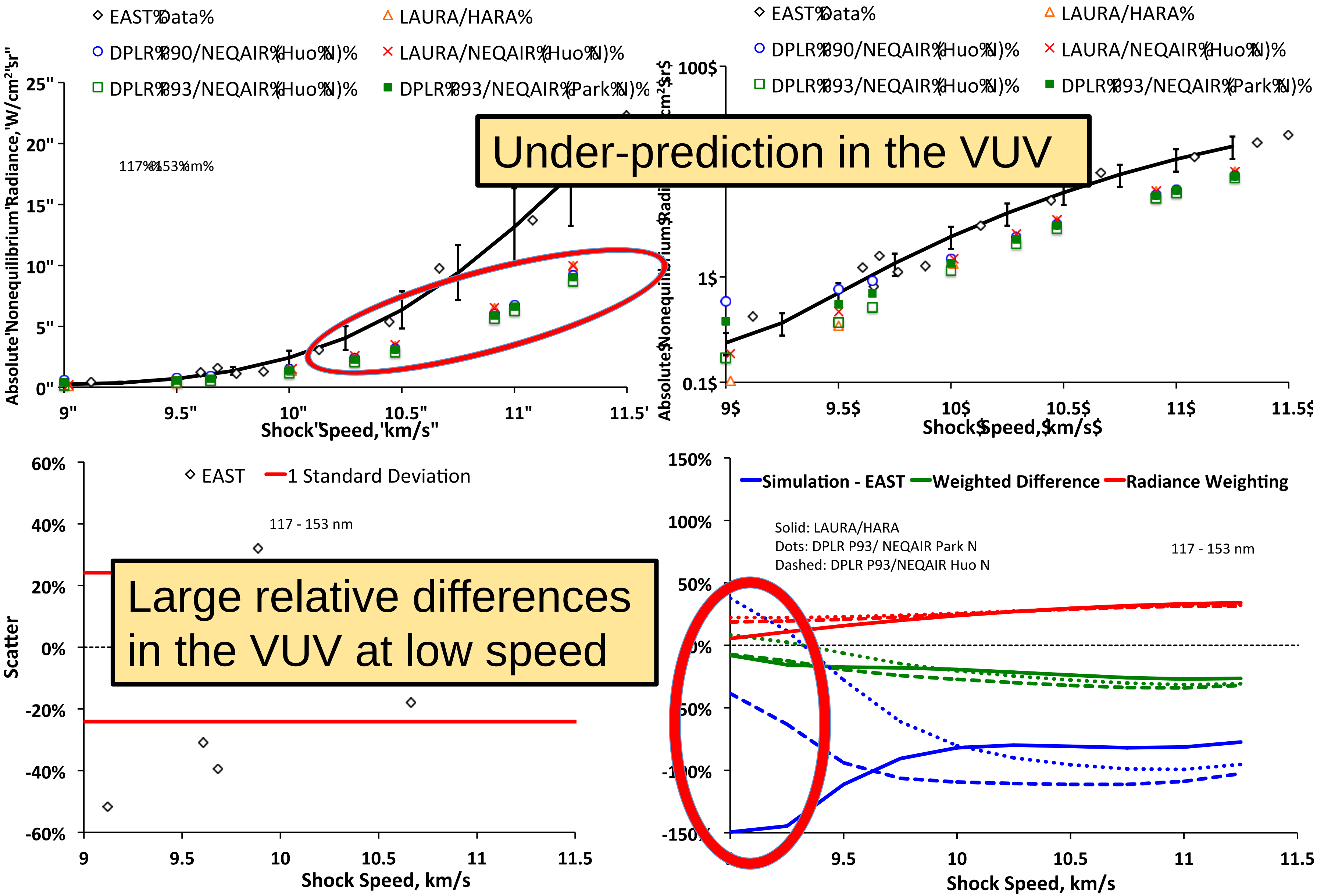
Results

Simulations vs EAST

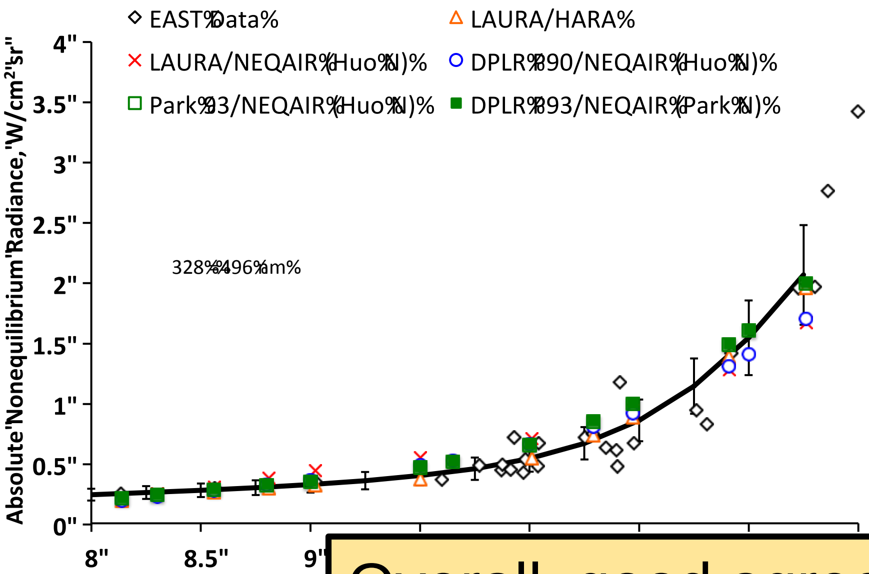
Simulations vs EAST

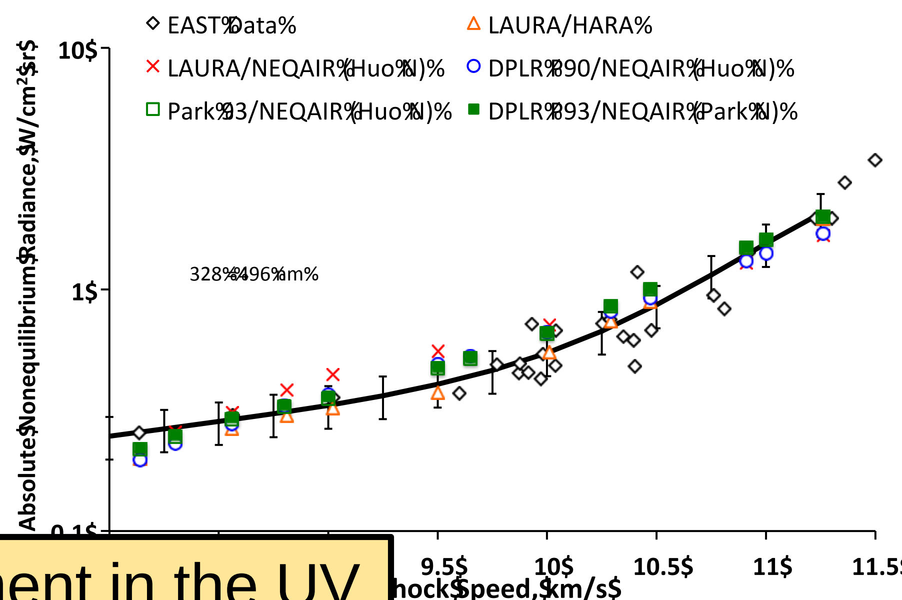
- Simulations vs EAST are shown for 4 spectral regions:
  - VUV, UV, Vis/NIR and IR
  - Constant free-stream pressure: 0.2 Torr
- Each slide will show 4 plots:
  - Comparison between EAST and simulations on a linear and log scale
  - The scatter of the EAST data around the line of best fit
  - The weighted difference between the simulations and EAST
- A prominent conclusion (or 2) will be highlighted for each spectral region.

Simulations vs EAST: VUV

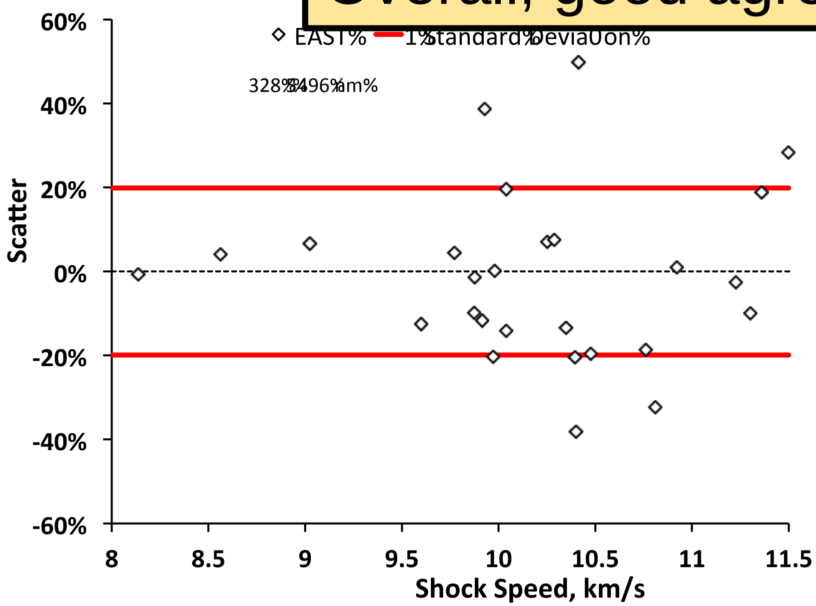


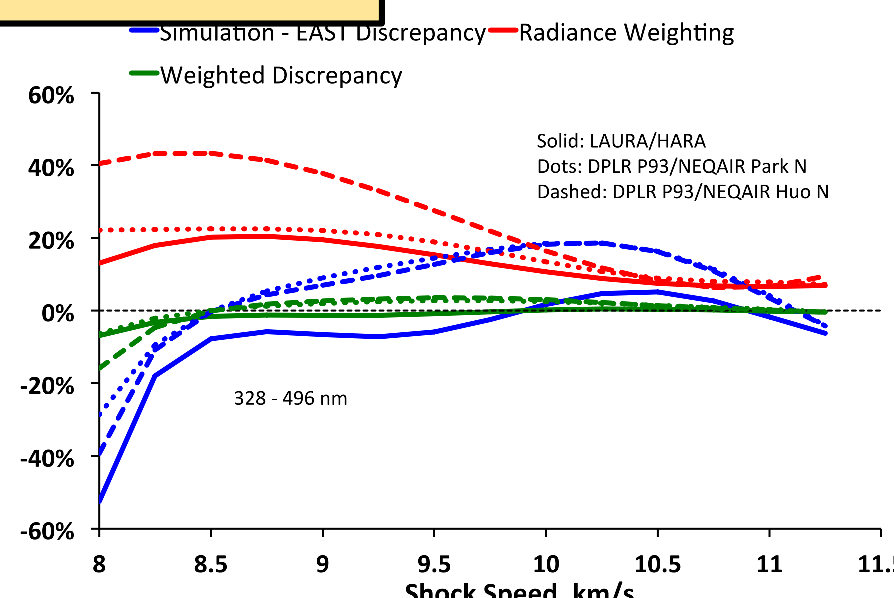
Simulations vs EAST: UV



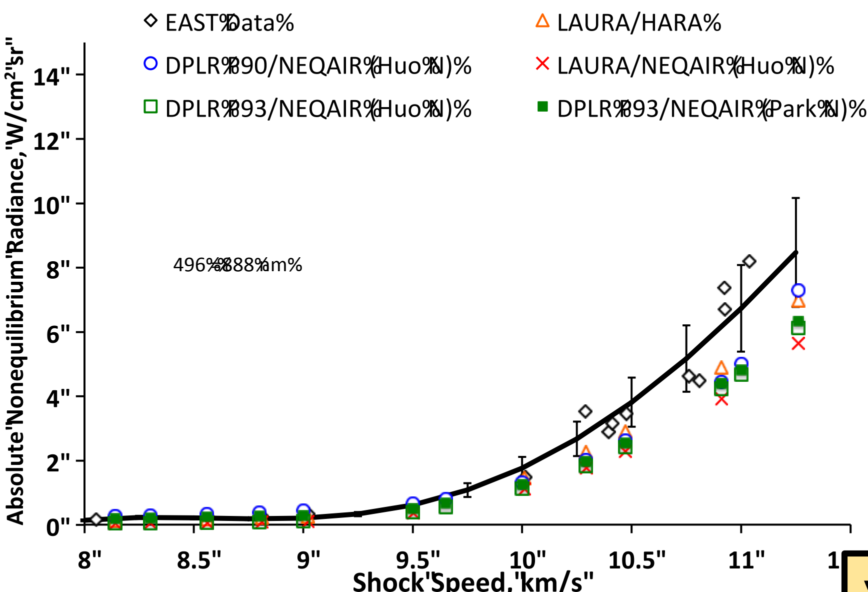


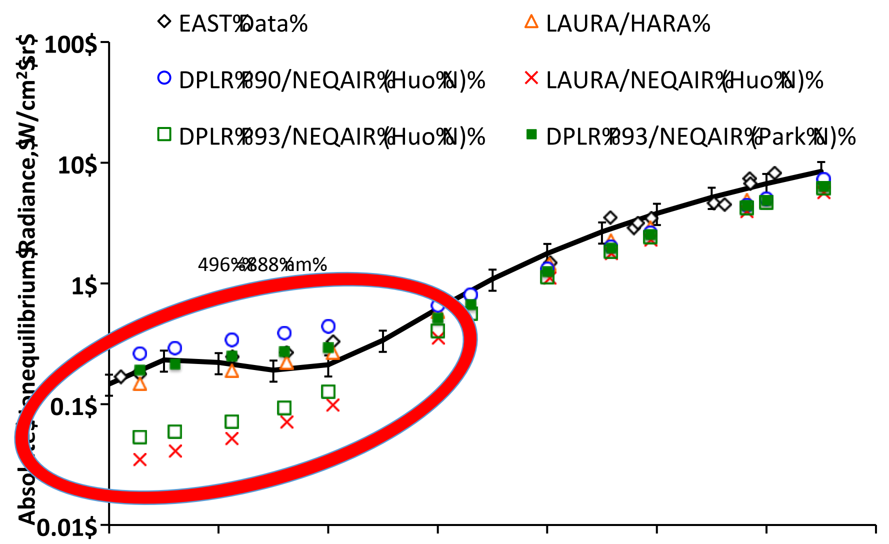
Overall, good agreement in the UV



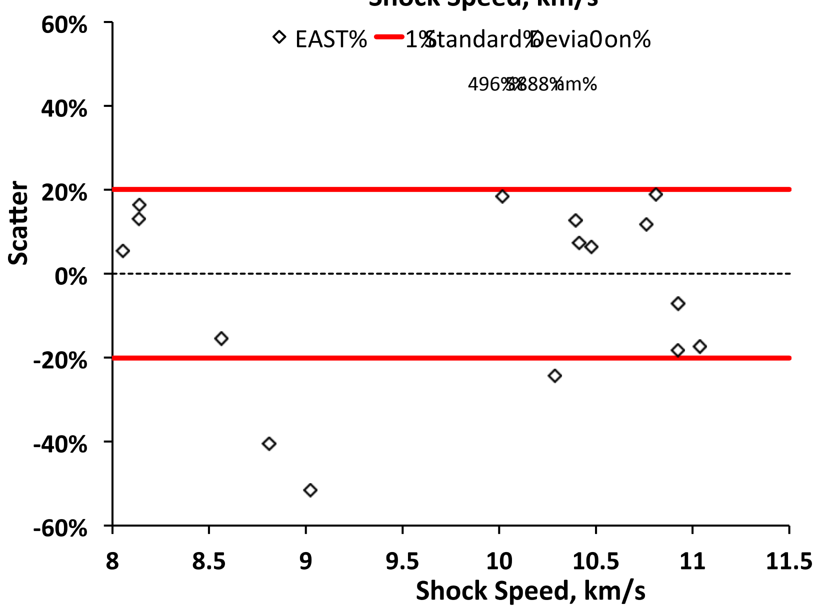


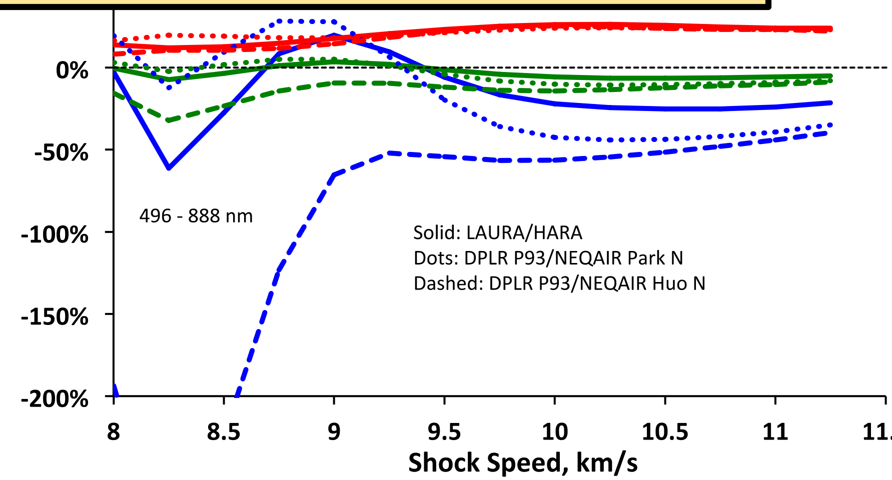
Simulations vs EAST: Vis/NIR



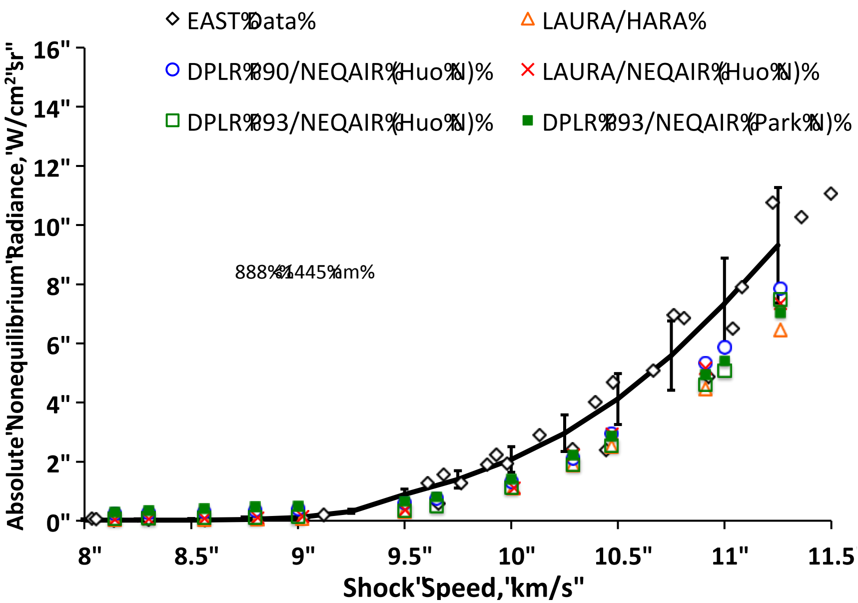


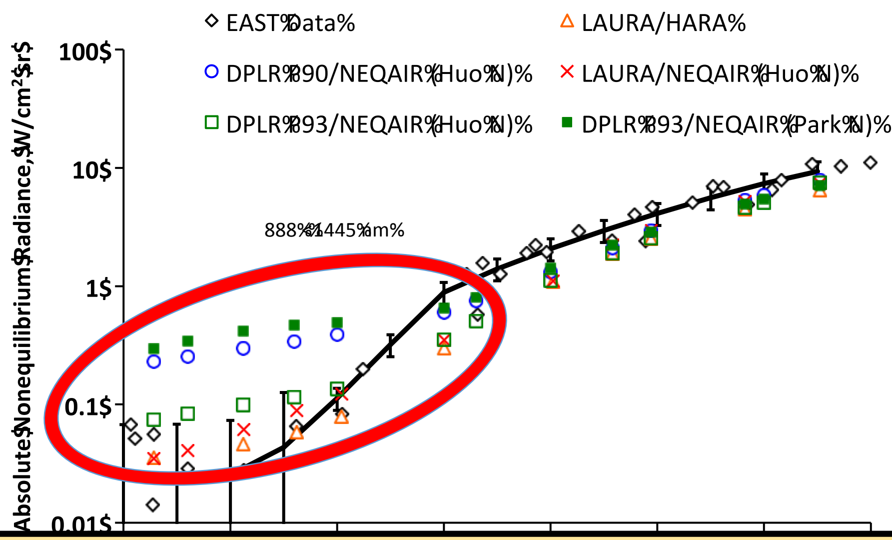
Very large relative differences in the Vis/NIR at low speed

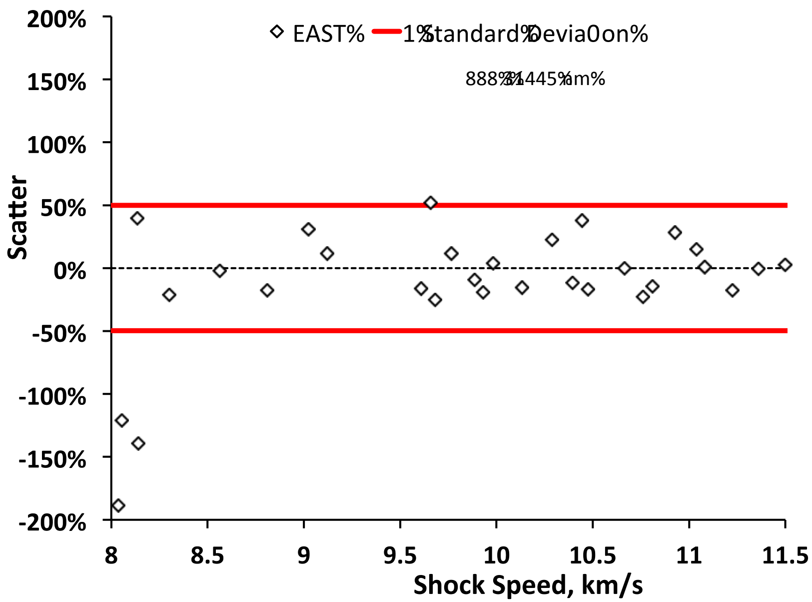




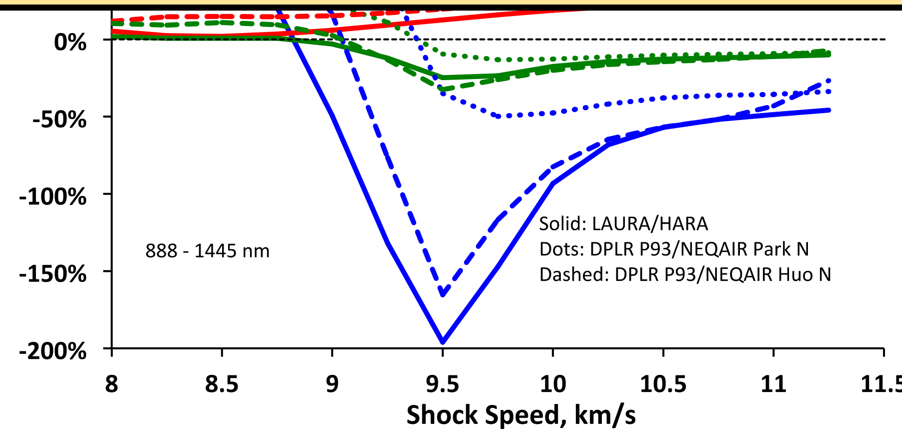
Simulations vs EAST: IR





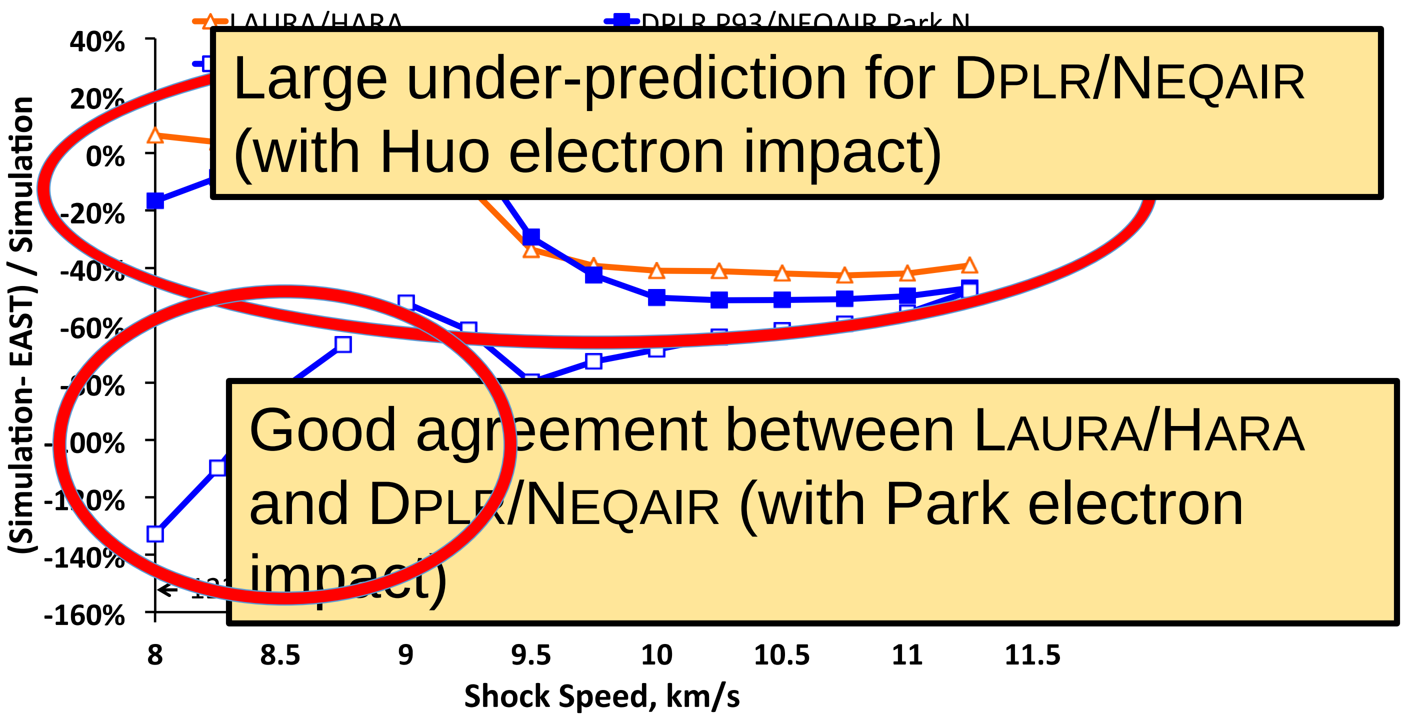


Certain modeling choices can create a significant over-prediction in the IR at low speed



Overall Summation

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

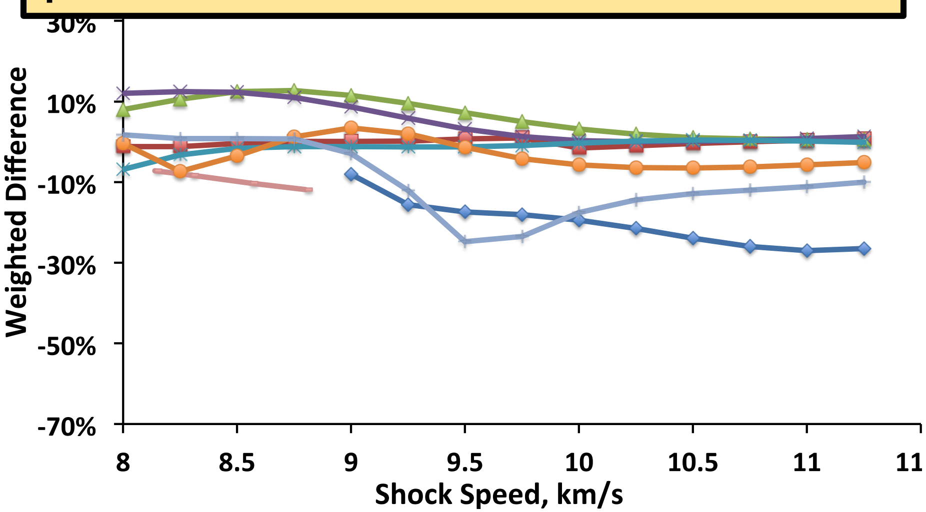


- Lower speeds, where non-equilibrium is more significant, there are large differences.
- Improving agreement between the codes as shock speed is increased.

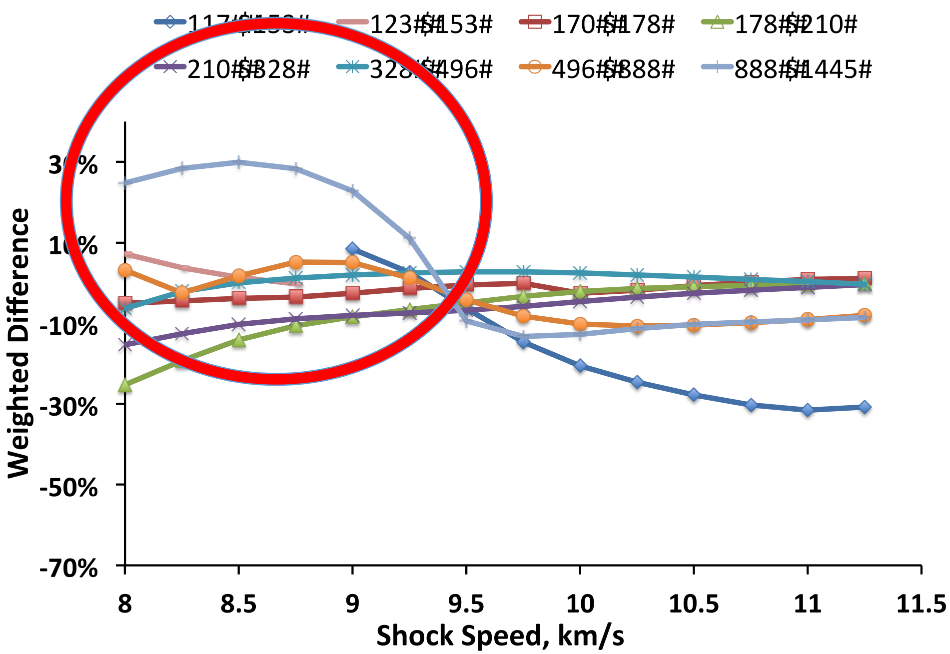
Overall Summation

- Even though the differences between 2 simulations and EAST might be similar, it can be due to compensating errors.
- Both plots below sum to similar values, but show different characteristics.

The over-prediction in the IR is counter acted by the under-predictions of the VUV/UV



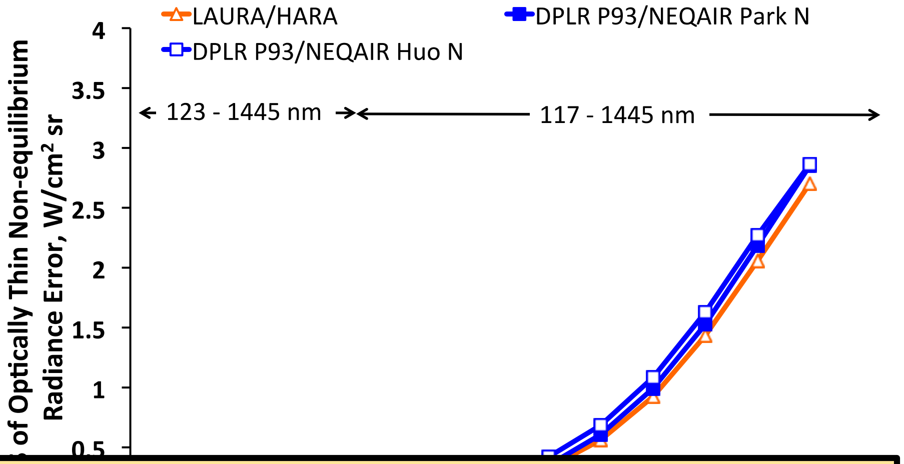
LAURA/HARA dd

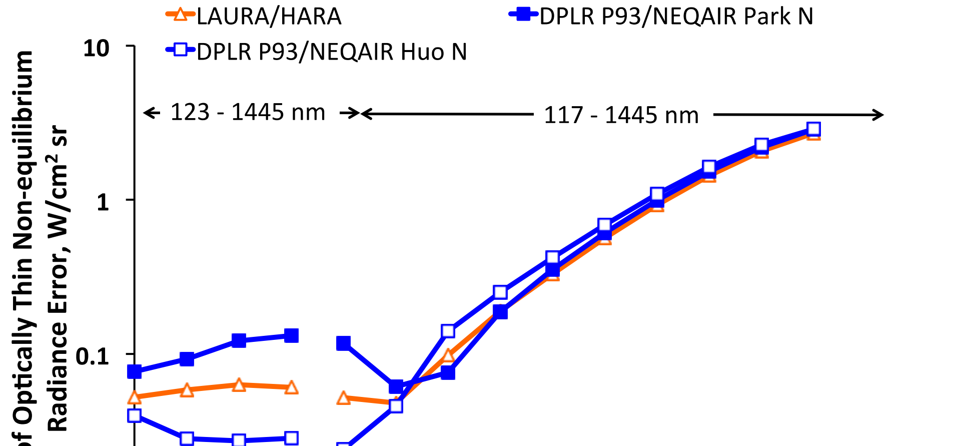


DPLR/NEQAIR (Park N)

Overall Summation

- Even though the relative differences can be high, the absolute differences tend to be small





For ρ = 3e-4 kg/m³, R_n = 5m, V = 9 km/s:
Qconv ≈ 111 W/cm², Qrad ≈ 23 W/cm²

For ρ = 3e-4 kg/m³, R_n = 5m, V = 11 km/s:
Qconv ≈ 180 W/cm², Qrad ≈ 725 W/cm²

For ρ= 3e-4 kg/m³, R_n = 0.5m, V = 9 km/s:
Qconv ≈ 355 W/cm², Qrad ≈ 8 W/cm²

For ρ=3e-4 kg/m³, R_n = 0.5m, V = 11 km/s:
Qconv ≈ 610 W/cm², Qrad ≈ 255 W/cm²

radiative head flux of a 2cm optically thin shock layer

- < 9 km/s, the difference is less than 1 W/cm², ~ 11 km/s, less than 20 W/cm²

Summary

- A metric has been used to compare non-equilibrium radiation measurements and NASA's simulation tools.
- The scatter of the EAST experiments was calculated to have a 1 standard deviation of 31%.
- Depending on the shock speed, simulations were shown to under-predict by up to 50% or over-predict by up to 20%.
- The level of ionization calculated using Park 90 chemistry is very high, and should not be used in simulations to predict radiative heating.
- LAURA/HARA and DPLR/NEQAIR (using excitation rates from Park) agree well

Summary

- Using the excitation rates from Huo in NEQAIR results in an under-prediction
  - For a back shell case, this would become an over-prediction (as its expanding flow)
- Future work should focus on N_2, N_2^+, NO and under-prediction of VUV
- Even with significant relative differences, the absolute magnitude of the error for non-equilibrium is fairly small
  - N.B. At much lower pressures, non-equilibrium will become more significant and the uncertainty will likely be much higher
- Framework for running radiation calculations for flight cases should be re-visited.

Questions?

National Aeronautics and
Space Administration

Ames Research Center
Entry Systems and Technology Division