Destructive Re-entry Modelling: SAM Development and Approach

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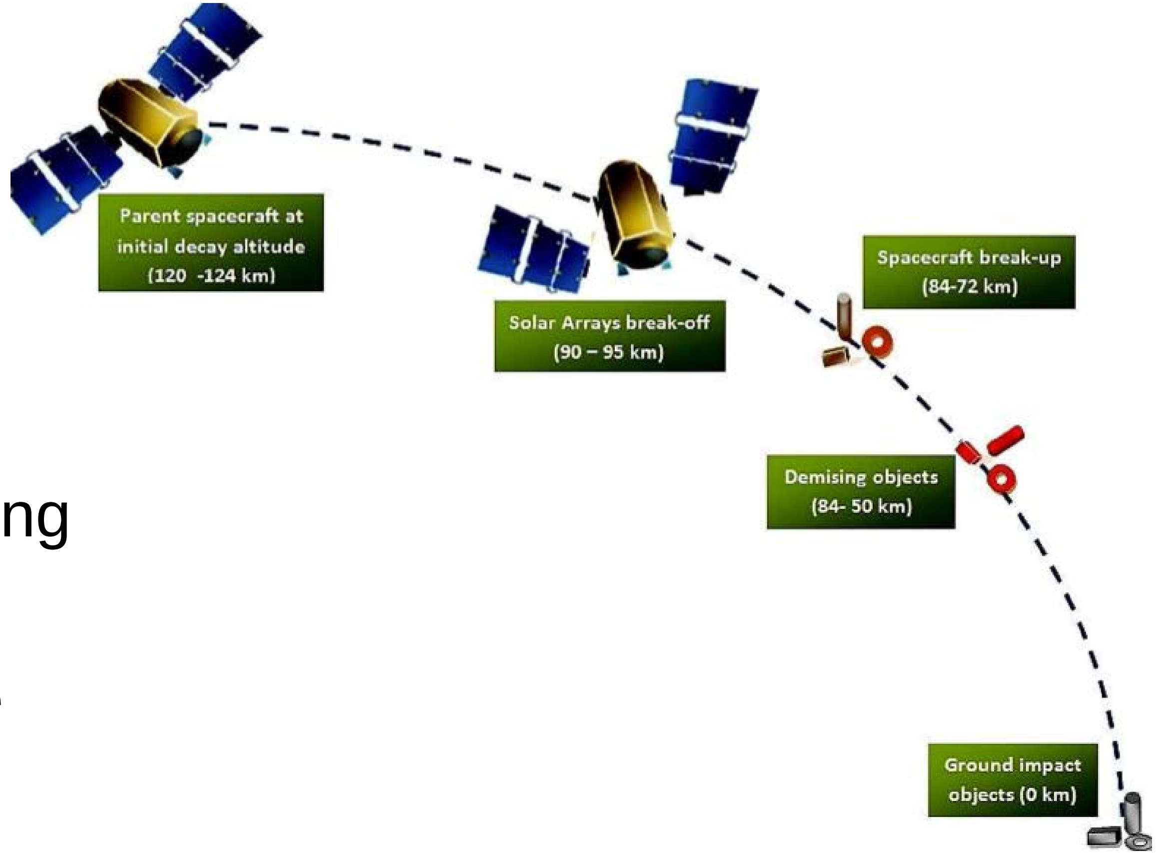
Destructive Re-entry Processes

- Initial entry
- Fragmentation
- Aerothermal heating
- Material response
- Uncertainty



Validating Models

- How do we know that our model is representative?
  - Very easy to get *an answer* : Very hard to get *a good answer*
- Validation Data: top-down
  - Flight data would be ideal; limited observations
    - Currently available data is macro-scale
    - Only really suitable for tuning very basic models
- Validation Data: bottom-up
  - Each submodel can be verified against existing/new data
    - Experimental testing (where available)
    - Higher fidelity modelling (CFD, FEA, Ablation codes, …)
  - This provides a grounding for the basic models
    - If the model can't do this… then is your answer good?

General Modelling Approaches

- Object Oriented
  - Single breakup; Simple child objects; 3 DOF analysis
- Spacecraft Oriented
  - Complete panel representation of spacecraft; 6 DOF analysis
  - Predictive fragmentation model
- Validation
  - Majority is code-to-code, some macro-level tuning comparisons
  - Some material phenomenology tests (quantitative modelling?)
  - No aerothermal heating comparisons (up to SCDW)
  - No fragmentation experiments (up to CleanSat BBs)

Spacecraft Aerothermal Model (SAM)

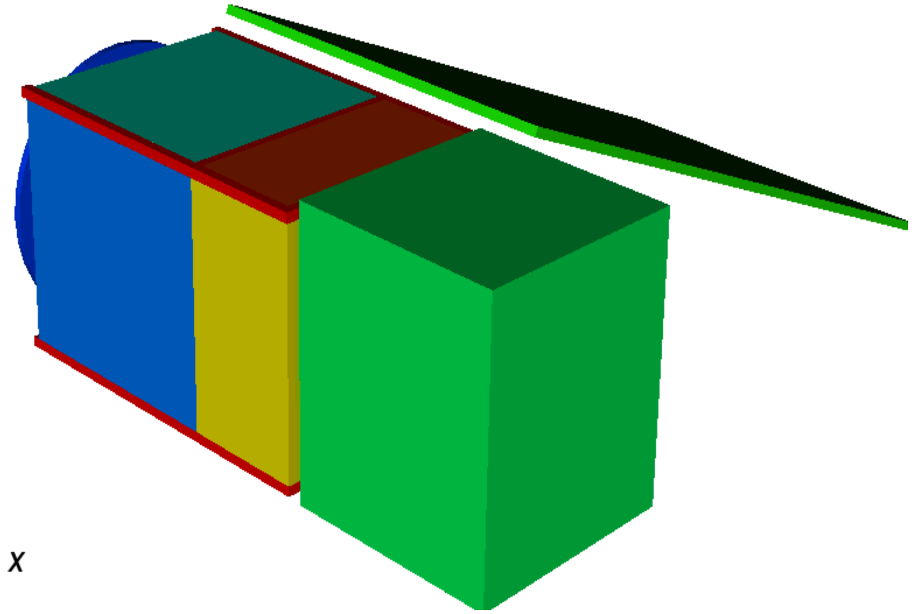
- Basic Philosophy
  - Physical Understanding
    - Capture important phenomenological effects in model
    - Account for uncertainties in models/physical processes
  - Provide Confidence in Modelling
    - Bottom-up validation of models
    - Testing (preferred); CFD; Literature data
- Modelling Approach
  - Determine the important physics
  - Capture the important physics and uncertainties
  - Verify the modelling against available data (or generate data!)

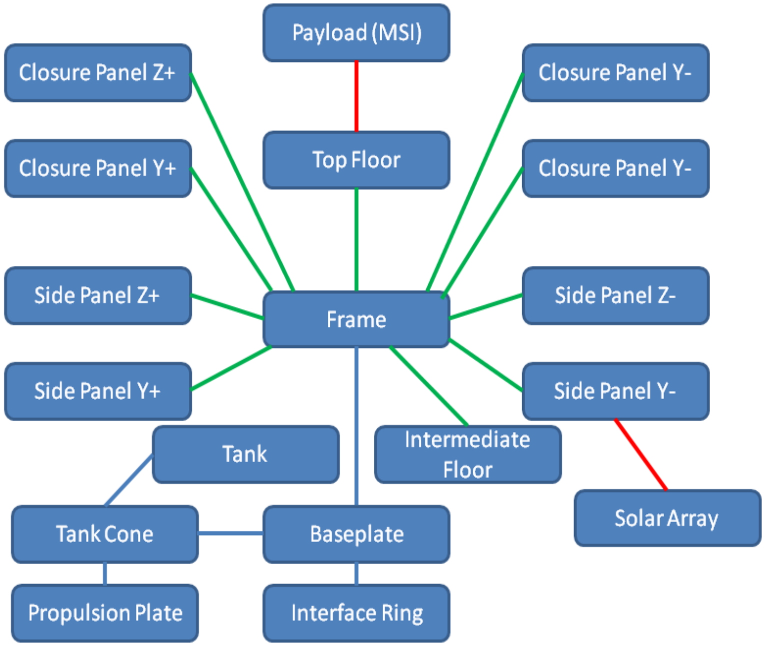
Driving Phenomena

- 6DOF aerodynamics
- Aerothermodynamic heating
  - Large impact
  - Extremely difficult to get good answer on arbitrary shapes
- Materials and material response
  - Generally poorly represented; equivalent metal insufficient
- Fragmentation processes
  - Least well understood – very high uncertainty
  - Main driver of risk
- Uncertainty
  - Mandatory as standard. *Accuracy* and *Precision* analyses

SAM Spacecraft Model

- Set of Components connected by Joints
  - Full geometry, primitive representation
    - Aerodynamics and heating generated for each configuration
  - Fragmentation by joint failure or component failure





Aerothermodynamic Heating

- Generally used models
  - Correlation based; ORSAT numbers most common (from SAE)
  - Sphere heating, box heating about 20% high in general
  - Cylinder heating from Klett is good
  - Average heating better than specific location heating
- SAM uses streamlength-dependent models
  - Basic shapes
  - Higher fidelity than shape correlations or inclination methods
  - Verification of flux profiles; literature tests and CFD (SCDW)
  - Can construct average heating
    - Demonstrates errors in “standard” correlations
    - Demonstrates errors in inclination methods

Aerothermodynamic Heating

- Complex Shapes
  - Inclination models used – robust, but inaccurate
  - Planned tests at Oxford University on compound shapes
  - Will provide first data for improved modelling of complex shapes
- Uncertainties on heating are high
  - At least 10% at stagnation point
  - At least 20% at a point on a primitive object
  - Much higher on an arbitrary object
    - *Inclination model is >40% in error on long cylinder*
    - *There is no good heating model for concave shapes (cavities / open spacecraft)*
    - *There is no good heating model for multiple length scales*
  - Inclusion of uncertainties is vital

Material Response

- Generally used models
  - Many codes use an ‘equivalent metal’ approach
  - Inadequate representation of ablative materials
  - Materials such as glasses fail before melt
- Non-metallic materials becoming more common
  - CFRP structures
  - SiC mirrors, optical glass lenses, high performance materials
- SAM uses appropriate material models
  - Bulk heating for high conductivity
  - Heat balance integral for low conductivity
  - Equivalent diffusivity heat balance integral with outgassing / blowing / de-densification for ablators
  - Model for glasses in development (ESA TRP)

Material Response

- Improved Validation Data
  - Oxidation of material increases surface emissivity
  - Testing suggests this is likely material state; not generally used
  - Partial catalycity to recombination at surface reduces heating
  - Testing suggests important (~20%); only used in SAM code
  - Required correct material data *and* correct phenomenology
- Final Demise
  - What does the final collapse of a material look like?
    - How does the area/ballistic coefficient change as it fails?
    - All current models are essentially arbitrary with no validation
  - *No satisfactory model exists for "balloon problem"*

Fragmentation Modelling

- Generally used Models
  - Catastrophic breakup; based on VAST/VASP tests
  - Spacecraft-oriented codes: Melt driven fragmentation
- SAM uses joint based fragmentation
  - Joints are weak points; mechanically, and often thermally
  - Intuitive expectation that fragmentation occurs at weak points
    - Basis of unique SAM fragmentation model
    - No (previous) data to support/deny this assertion
  - Joints can fail by a number of methods:
    - Melt
    - Force (function of temperature)
    - Thermal stress

Fragmentation: Missing Knowledge

- Fragmentation Model Phenomenology
  - Do we have the right phenomenologies?
  - How do we determine the correct mechanisms?
  - Can we construct a realistic model without understanding the correct phenomena?
- Data for Model Construction
  - Identify fragmentation mechanisms
    - Do different vehicles have different mechanisms?
    - How important are joints/fasteners?
  - Identify driving material properties
    - What are the key parameters determining the process?
    - How important is the correct material response?

Fragmentation: First Test Campaign

- CleanSat Building Block
  - Testing of sandwich panel adhesive; inserts
  - Testing of bolts/brackets with differential CTE
  - Failure temperatures well below structure melt
    - But heat soak and forces important
- Implications
  - Panel failure expected at panel level; not melt
    - No fragmentation by melt seen – even with no applied force
  - Below TBD (~78km?) Forces expected to Fail Joints
    - Melt model is not appropriate
    - Late item release below TBD (~70km?) questionable
    - Temperature / force balance to be established

Uncertainty Analysis

- SAM is sufficiently fast to run multiple cases
  - Uncertainties include both precision (orientation) and accuracy
  - Mandatory to include uncertainties for:
    - Aerothermodynamic heating
    - Material response
    - Fragmentation processes
- Practical Usage
  - SAM has a Monte Carlo capability
    - Towards 100,000 6dof runs performed using ATS6 module in GOCE uncertainty analysis
    - Planned 1000 runs per “spacecraft oriented” configuration in optics demise TRP

Important Gaps

- Aerothermodynamic Heating to Complex Shapes
- Final Demise
- (High Temperature / High Performance) Material Data
- Fragmentation Phenomenology
- Quantitative Fragmentation Data

- Uncertainties Currently Large
  - Must be accounted for within analysis
  - Can only be done properly using correct phenomenology

Conclusions

- Towards a truly representative destructive re-entry model
  - Phenomenologically based
    - Appropriate material modelling, including insulators/ablators
    - Joint-based fragmentation
  - Verified heating and material models
  - Testing gives improved material response; fragmentation
- Designed for Uncertainty Analysis as Standard
  - 6DOF Monte Carlo runs easily achievable
  - Large sensitivity studies can be run to inform design
  - Uncertainties can be included for wide range of effects