Appendix J

Thermal modelling of thruster nozzles and plumes for planetary landers

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Abstract

Future planetary landers will embark optical sensors (e.g. cameras and imaging LIDAR) which will feed data to navigation and hazard avoidance systems, to enable safe and precise landing. These sensors may be located in proximity to thruster nozzles which, during landing, may reach temperatures around 1000K. It is therefore important to model the radiative fluxes impingent on the cameras due to the thruster as well as the plume created. Geometrically modelling the plume was achieved by establishing a mathematical model of the setup, and the emissivities of a series of truncated cones of the plume were determined. The thruster and plume were then modelled in ESATAN-TMS and the thermal impact was studied during landing phase. A preliminary engineering design was considered for the LIDAR and camera, and an overall methodology for thermally modelling thrusters and their plumes was established.

Thermal Modelling of Thruster Nozzles & Plumes for Planetary Landers

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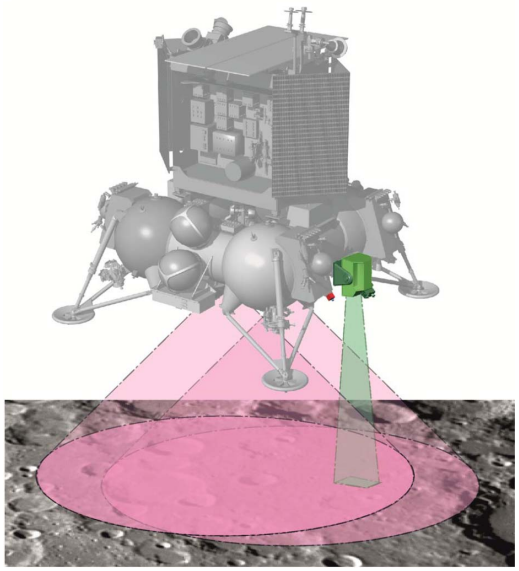
Objectives

- General method for radiatively modelling thruster plumes
- Case study – Luna Resource lander (HSO-IL, 2015)
- Nozzles around 1000K
- Radiation to nearby cameras & imaging LIDARs
- Propellant: UDMH



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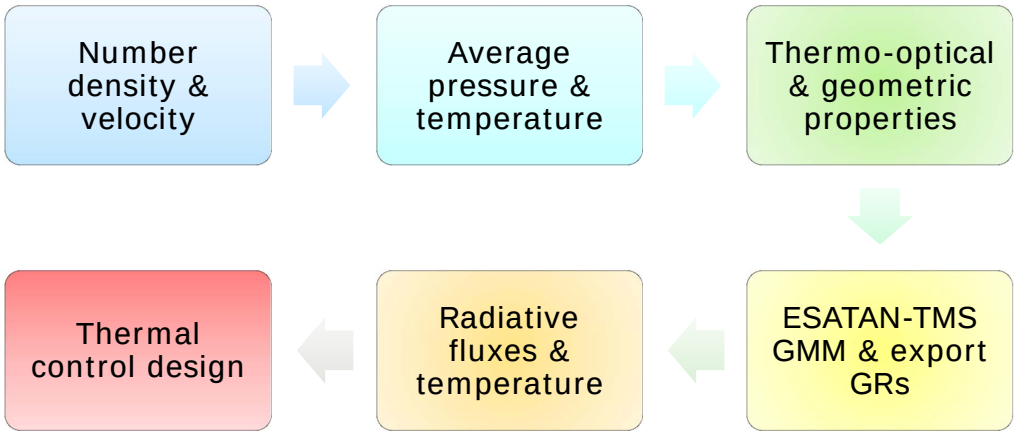
Modelling Process



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Analytical Plume Modelling

Collisionless effusion model

- Collisionless → molecules moving in straight line trajectory
- Gas expanding into a vacuum (Cai, C. & Boyd, I., 2007)
- Thermal velocity at exits expressed with Maxwellian distribution function characterized by number density and temperature
- Obtain plume field flow solutions for density & velocity at any point downstream of the nozzle exit, solved in MATLAB
- Plume temperature by polytropic expansion using *n*
- Boltzmann equation to obtain pressure

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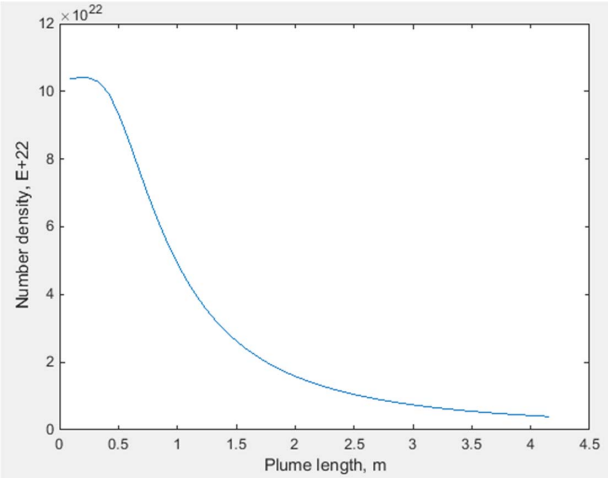
Analytical Plume Modelling

Inputs:

- Nozzle exit radius (m)
- Thrust (N)
- Exhaust velocity (m/s)
- Isentropic expansion coefficient
- Temperature of nozzle (K)
- Average atomic mass of flow (g/mol)

Number Density along Plume Length



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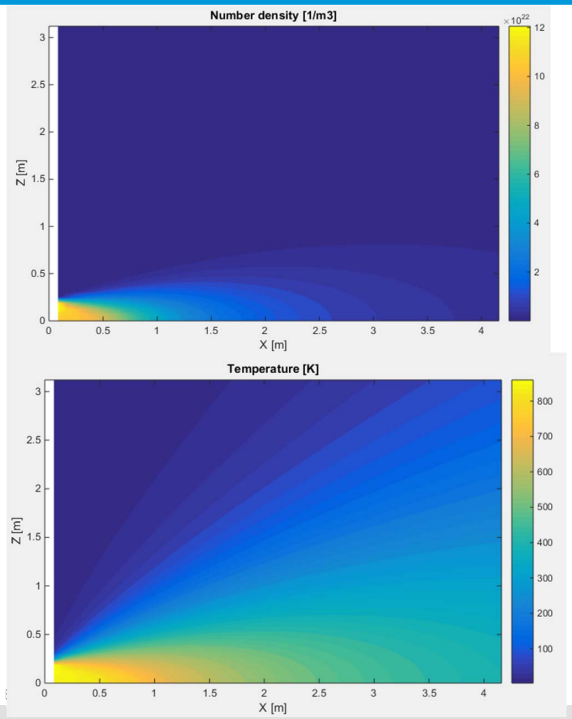
Analytical Plume Modelling



Parameter	Value
Nozzle temperature	840.5 K
Cone 1 temperature	605.1 K
Cone 2 temperature	394.5K
Average plume pressure	258.7 Pa

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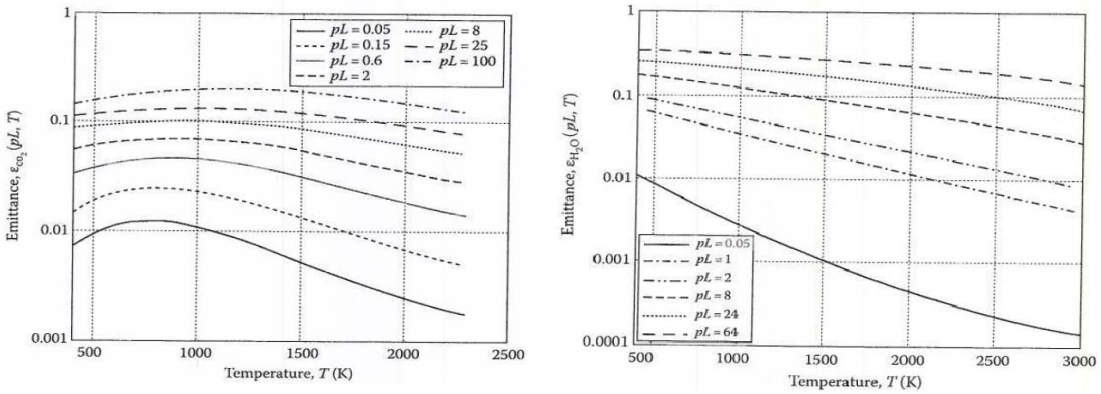
Analytical Plume Modelling

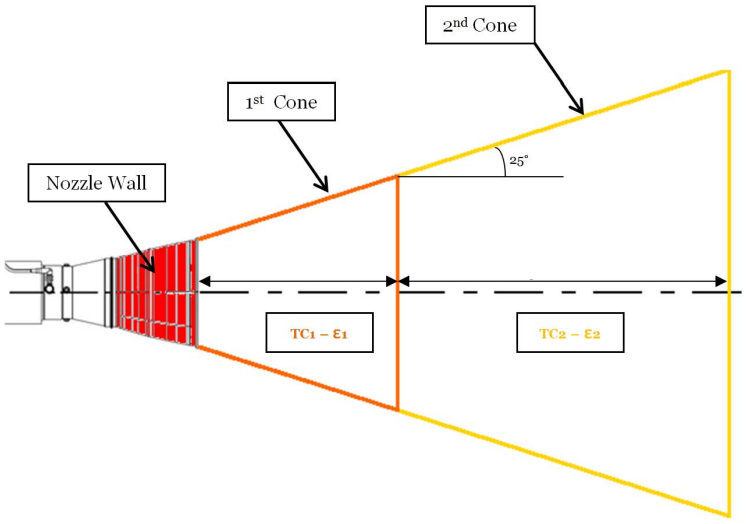
- **Gaseous emissivity-Temperature correlations**
- Charts established based on Leckner's correlations (Howell et al., 2016)
- Inputs required/assumptions:
  - Average pressure & temperature
  - Composition of combustion products
  - H_2O and CO_2 for IR emittance only



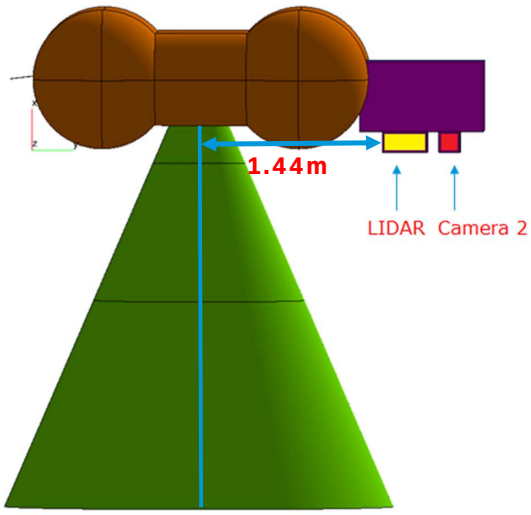
Analytical Plume Modelling

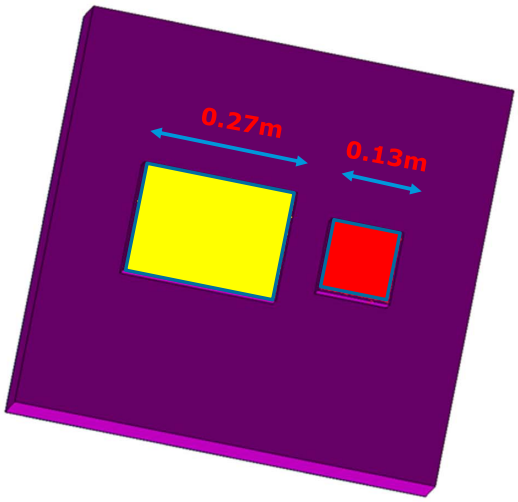
- The LIDAR and Camera 2 are modelled as black critical surfaces.

Nozzle	Value
Length	0.64m
Temperature	840.5K
Emissivity	0.6
Cone 1	**Value**
Length	0.83m
Temperature	605K
Emissivity	0.0181
Cone 2	**Value**
Length	1.25m
Temperature	395K
Emissivity	0.0041



GMM in ESATAN-TMS





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Impingent Fluxes

Nozzle		Nozzle	
Description	**Q (W/m2)**	**Description**	**Q (W/m2)**
Facing nozzle	**779**	Facing nozzle	0
Downwards-facing	29	Downwards-facing	18
Plume cone1		**Plume cone1**	
Description	**Q (W/m2)**	**Description**	**Q (W/m2)**
Facing plume	24	Facing plume	4
Downwards-facing	13	Downwards-facing	8
Plume cone2		**Plume cone2**	
Description	**Q (W/m2)**	**Description**	**Q (W/m2)**
Facing plume	0	Facing plume	0
Downwards-facing	1	Downwards-facing	1
Total			
Facing plume	**803**		

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Sensitivity Analysis

Key parameters impacting radiative fluxes in our case study:

- Distance between nozzle & instrument of interest
- Temperature of the nozzle & plume
- Propellant used

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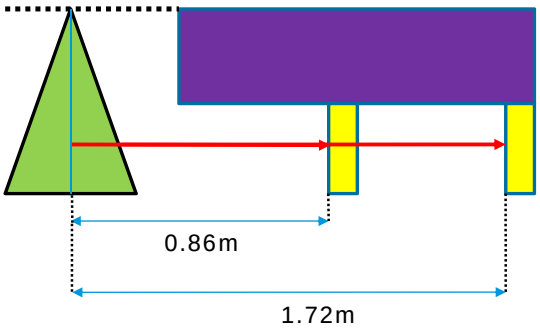
Nozzle-Instrument Distance

- Doubling distance decreases flux by an order of magnitude

	Distance (m)	Flux (W / m²)
LIDAR	0.86	779
Double distance	1.72	90



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Propellant Sensitivity

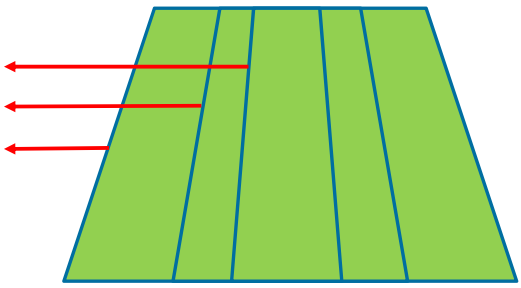
For Plume (Cone1)

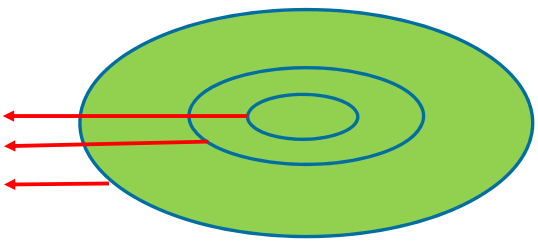
- Emissivity for UDMH: 0.018
- Emissivity for $H_2 O_{2\ (aq)}$: 0.215

Propellant	Emissivity	Flux on LIDAR (W/m^2)
UDMH	0.018	23.9
H2 O2	0.215	265.5

Model Limitations

- Collisionless
- Interaction with soil
- Volumetric ray tracing
- Truncating more cones





Concluding Remarks

- Objectives were met in creating methodology for thermally modelling thruster plumes.
- DSMC simulations can provide more detailed plume average temperature & pressure → accounting for collisions.
- Thermally most dominant entity is the thruster nozzle.
- Inputs heavily dependent on propellant, starting nozzle temperature & geometry.

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- Howell, J. R., Menguc, M. P., & Siegel, R. (2016). *Thermal radiation heat transfer.* Boca Raton, FL: Sixth Edition: CRC Press.
- HSO-IL. (2015). *Luna resource propulsion system data for the analyses of effects on PILOT units.* ESA-HSO-LEX-MEM-0013.

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