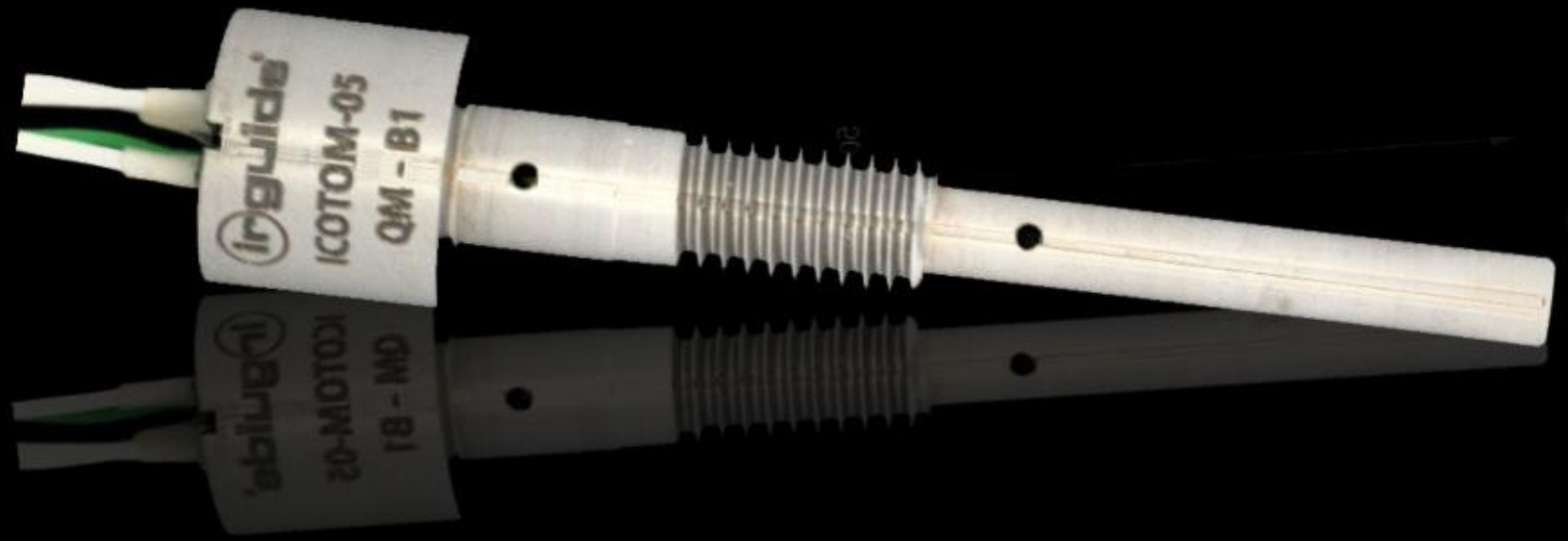
Exomars - ICOTOM

REBUILDING OF ICOTOM RADIOMETER DATA DURING SCHIAPARELLI MARTIAN ENTRY

J. Annaloro[(1)], P. Boubert[(2)], A. Bultel[(2)], M.C. Druguet[(3)], E. Duffour[(4)], P. Hébert[(1)], M. Jacquot[(2)], V. Lago[(5)], M. Lesage[(2)], S. Menecier[(4)], P. Omaly[(1)], F. Perisse[(4)], N. Rembaut[(5)], P. Rivière[(6)], A. Soufiani[(6)], M. Spel[(7)], D. Vacher[(4)], S. T. Surzhikov[(8)] , D. Yatsukhno[(8)]

[(1)] CNES [(2)] CORIA [(3)] IUSTI [(4)] Institut Pascal [(5)] ICARE [(6)] EM2C [(7)] R.Tech [(8)] IPM

ICOTOM : INFRARED RADIOMETER



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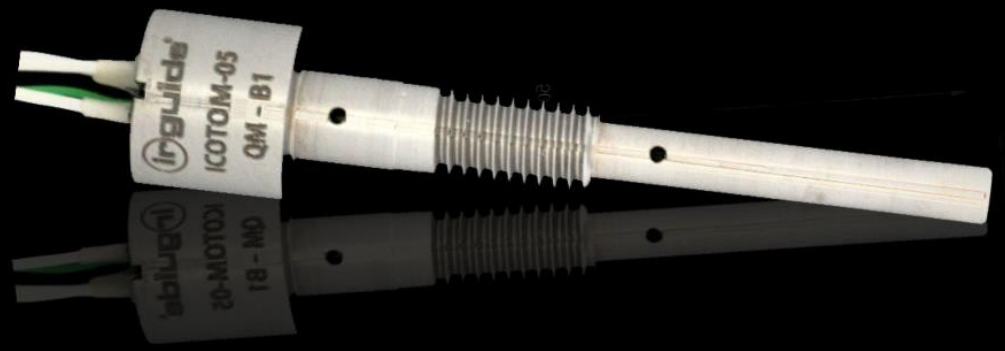

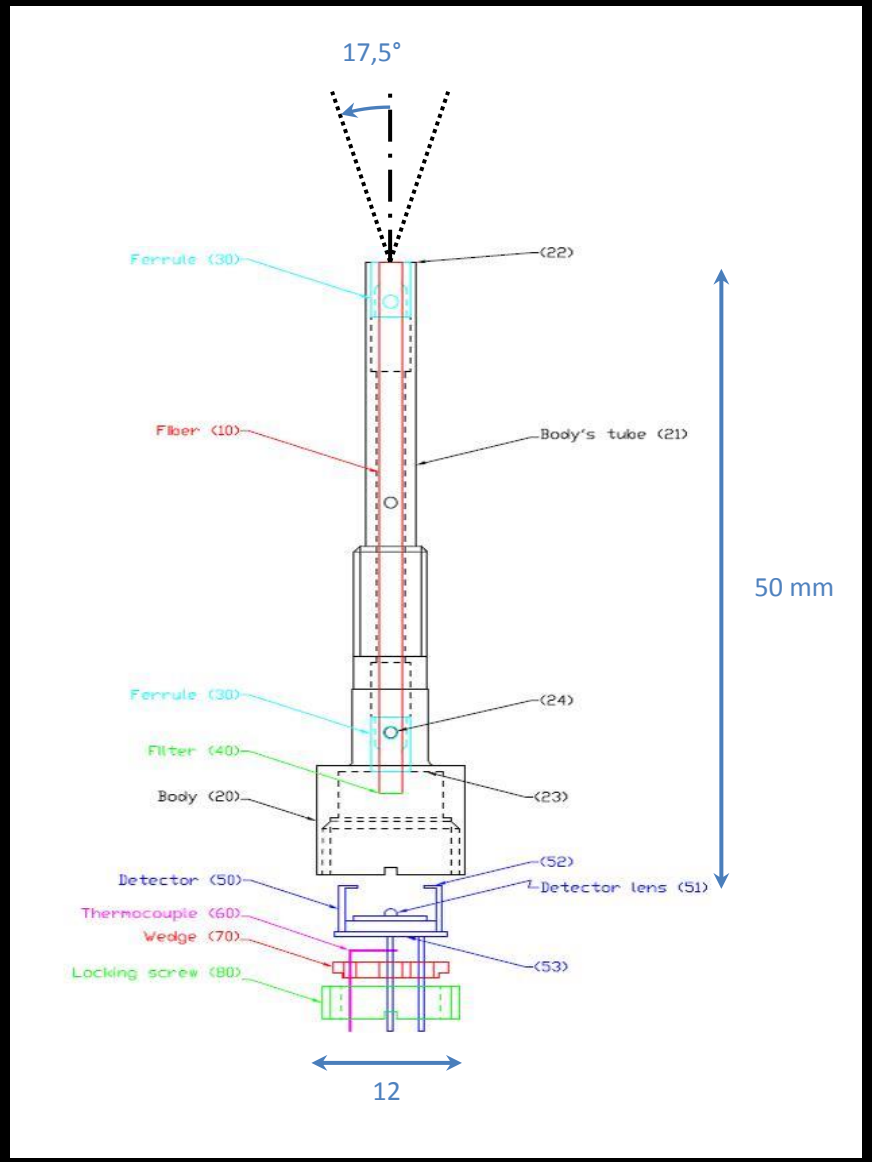

1. Objectives – Expected results

– Global objectives (CNES)

- TPS Design: IR radiative flux estimation during Schiaparelli entry
- Are TPS margins for the afterbody reasonable?

– Scientific objectives (Consortium)

- What is the meaning of ICOTOM data in terms of of radiative flux density?
- What was the chemical composition of the afterbody plasma?
- What was the thermodynamic (equilibrium-nonequilibrium) status of the plasma?
- Which molecular transitions contribute to the IR afterbody radiation?

OUTLINE

1. Objectives
2. ICOTOM calibration – Flight data analysis
3. Experimental studies
4. Chemical kinetics in Martian plasmas
5. Non equilibrium radiative transfer calculations
6. Flowfield
7. Summary, Conclusions and Outlooks

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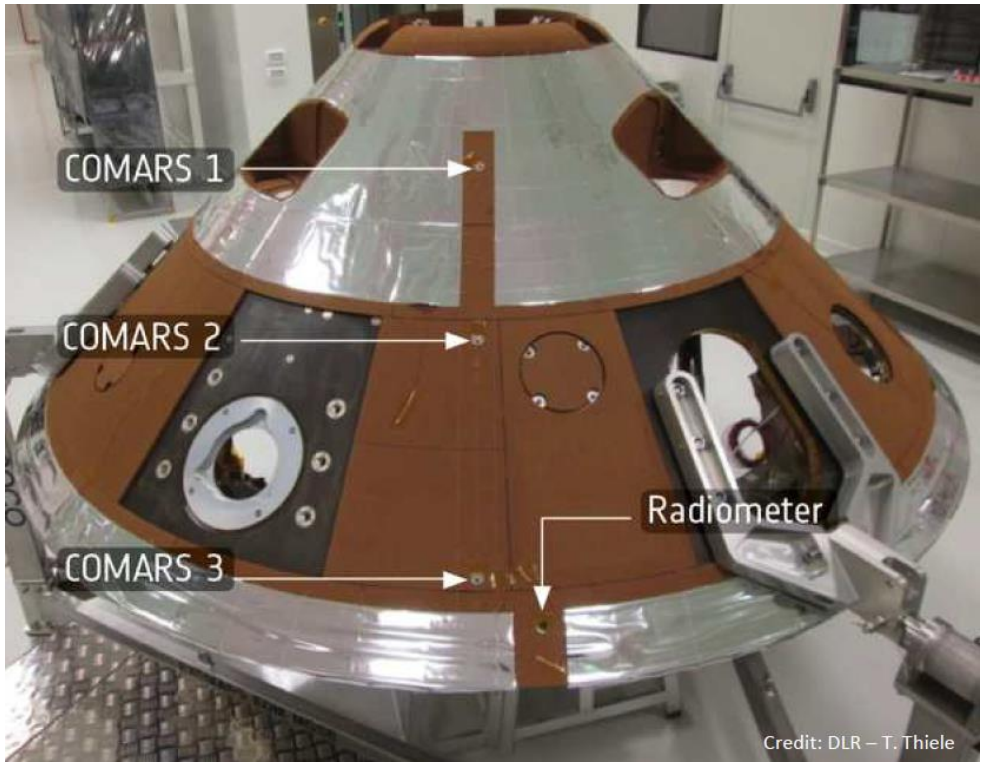
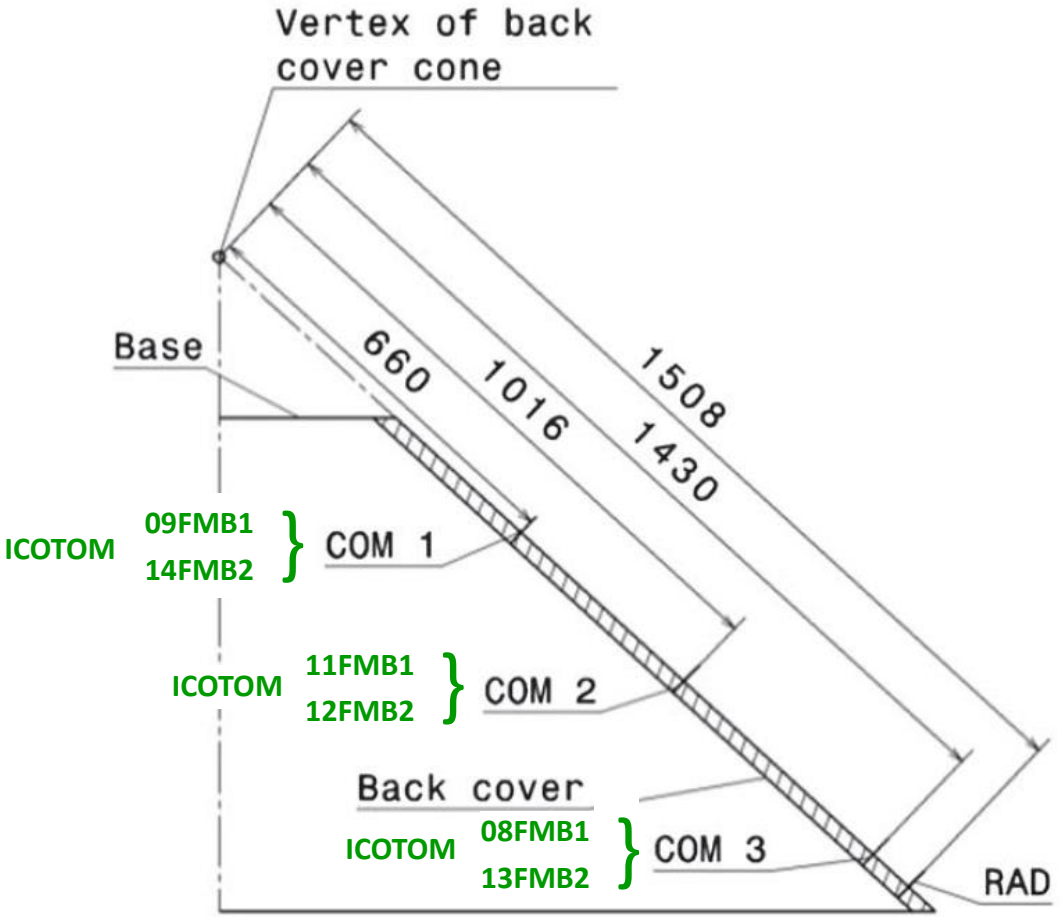
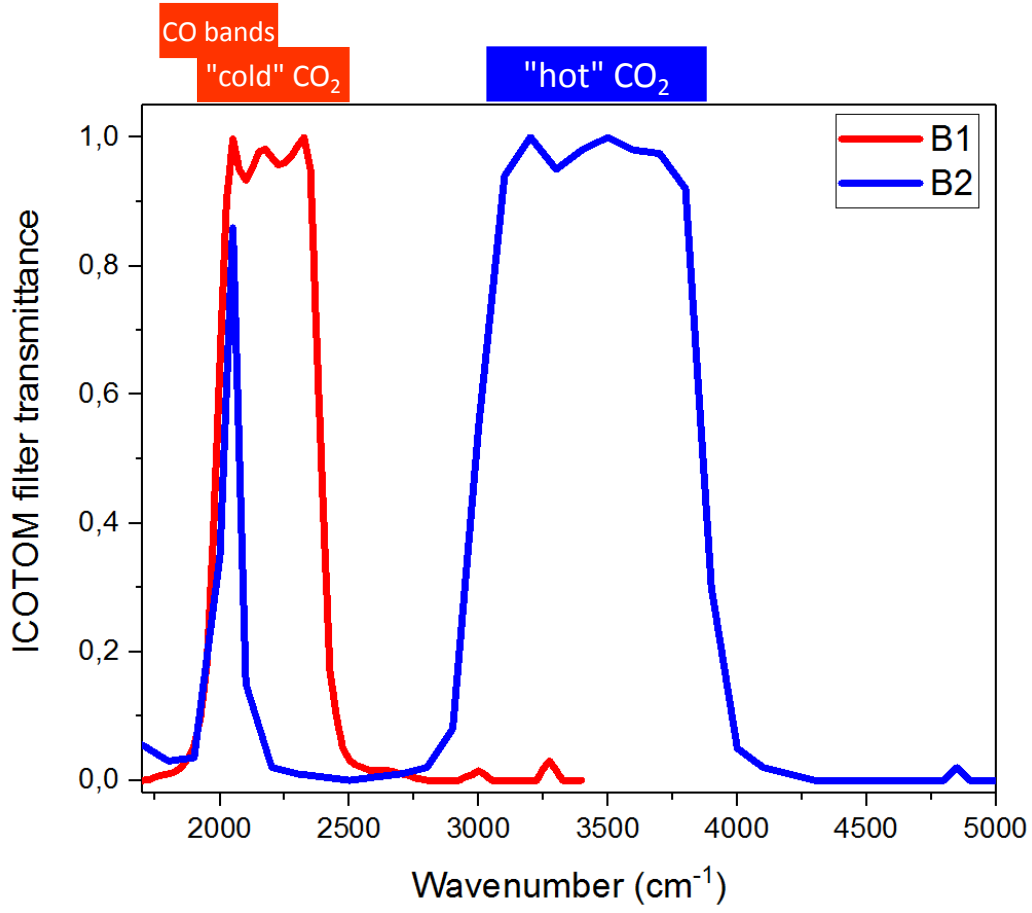
ICOTOM locations on Schiaparelli

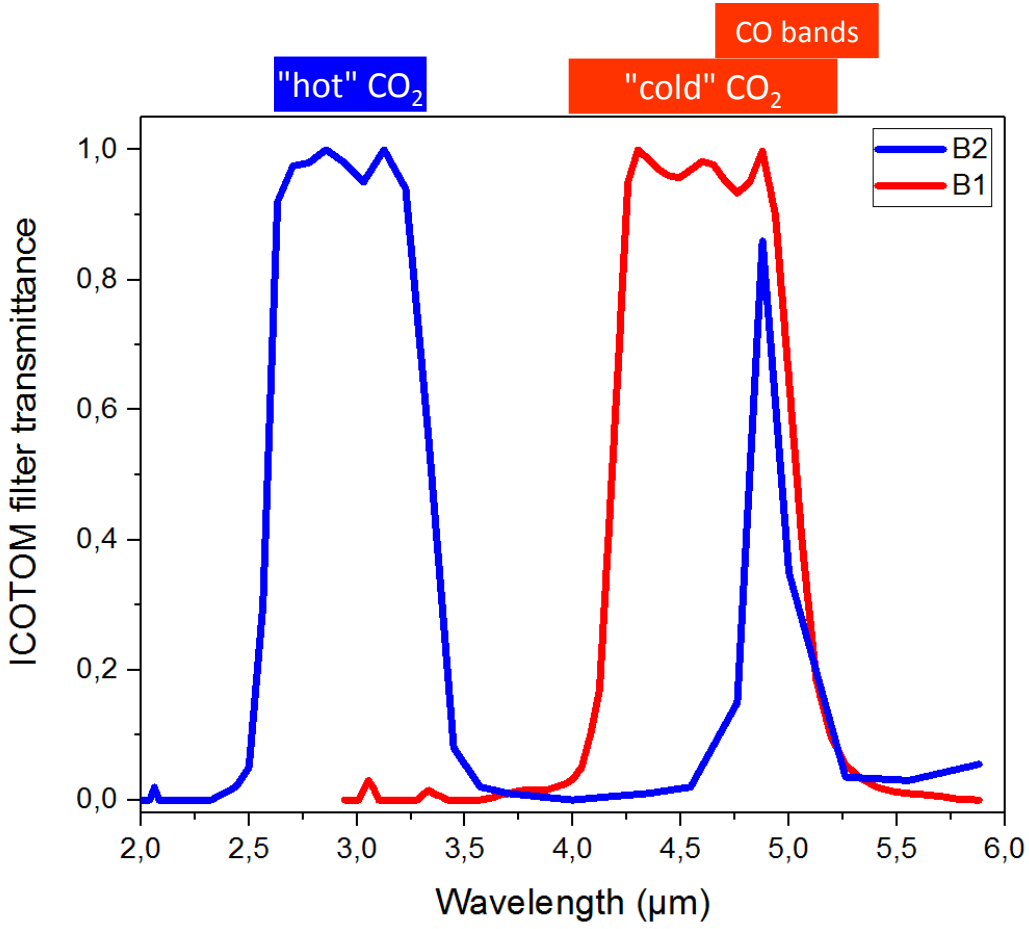




from Gülhan et al., JSR, 2018

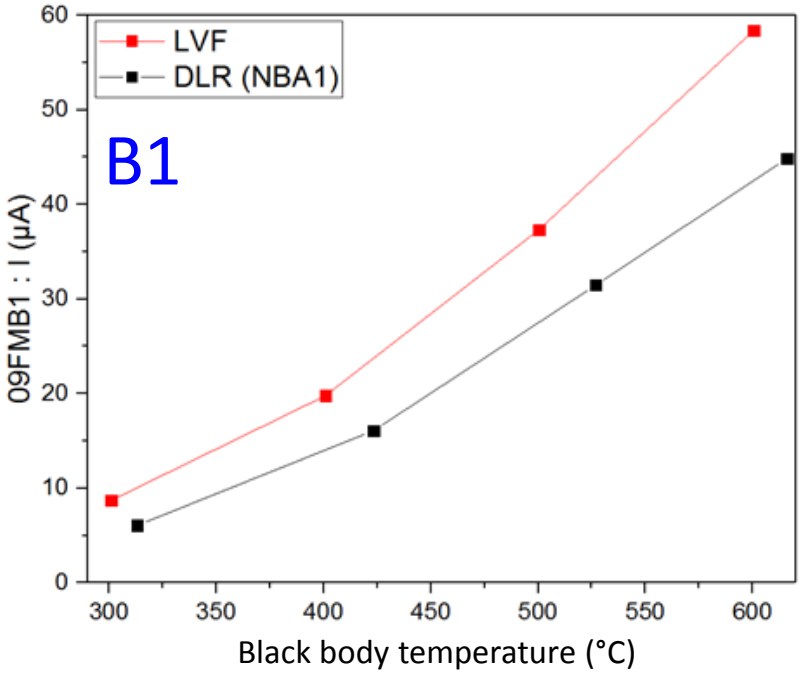
ICOTOM sensitivity ranges

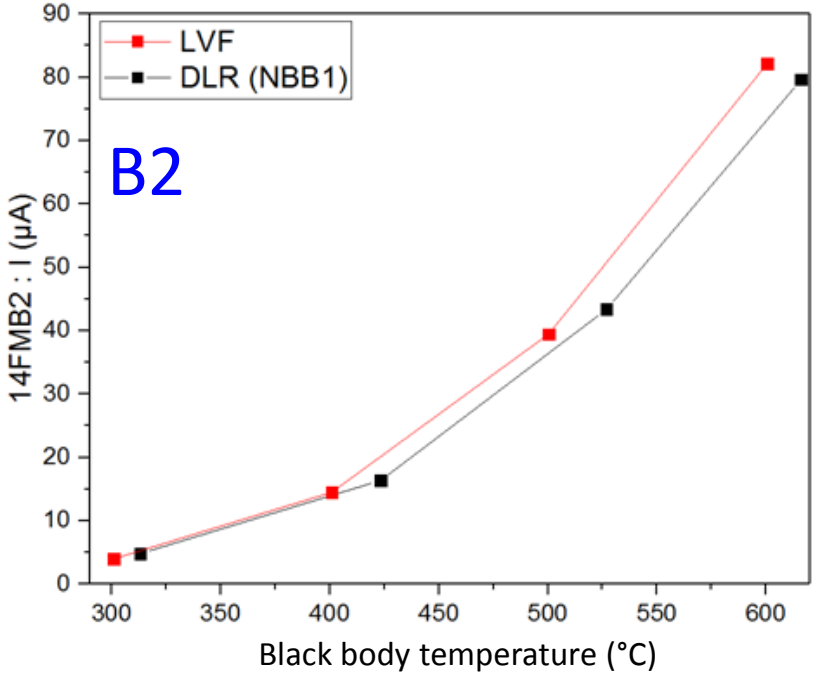




Calibration : Issues and Methodology

- **Two available pre-flight calibration by Le Verre Fluoré (LVF: ICOTOM manufacturer) and DLR (integration on COMARS)**





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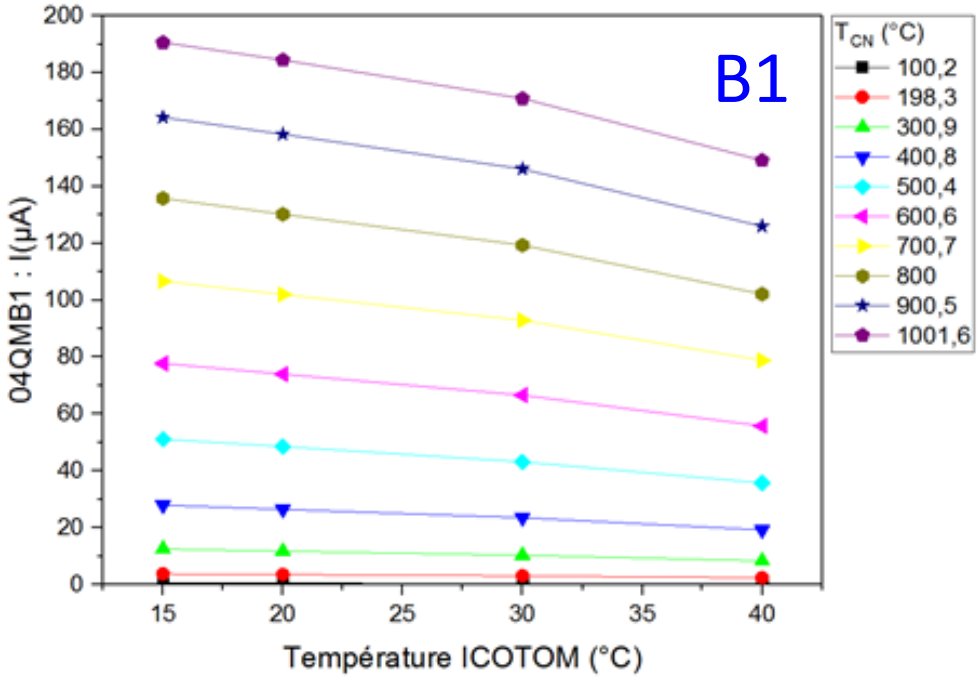

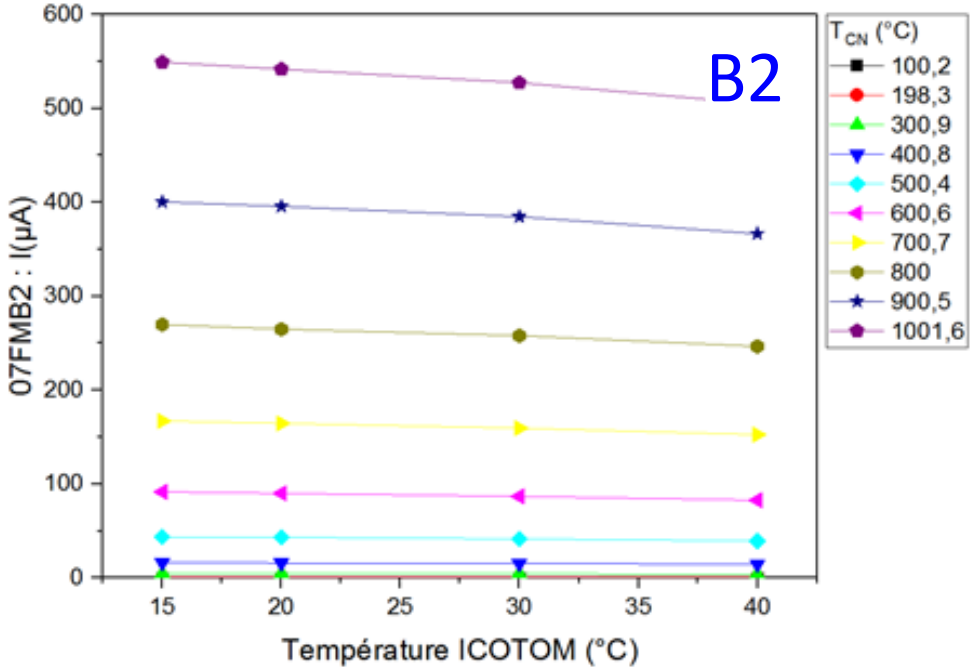

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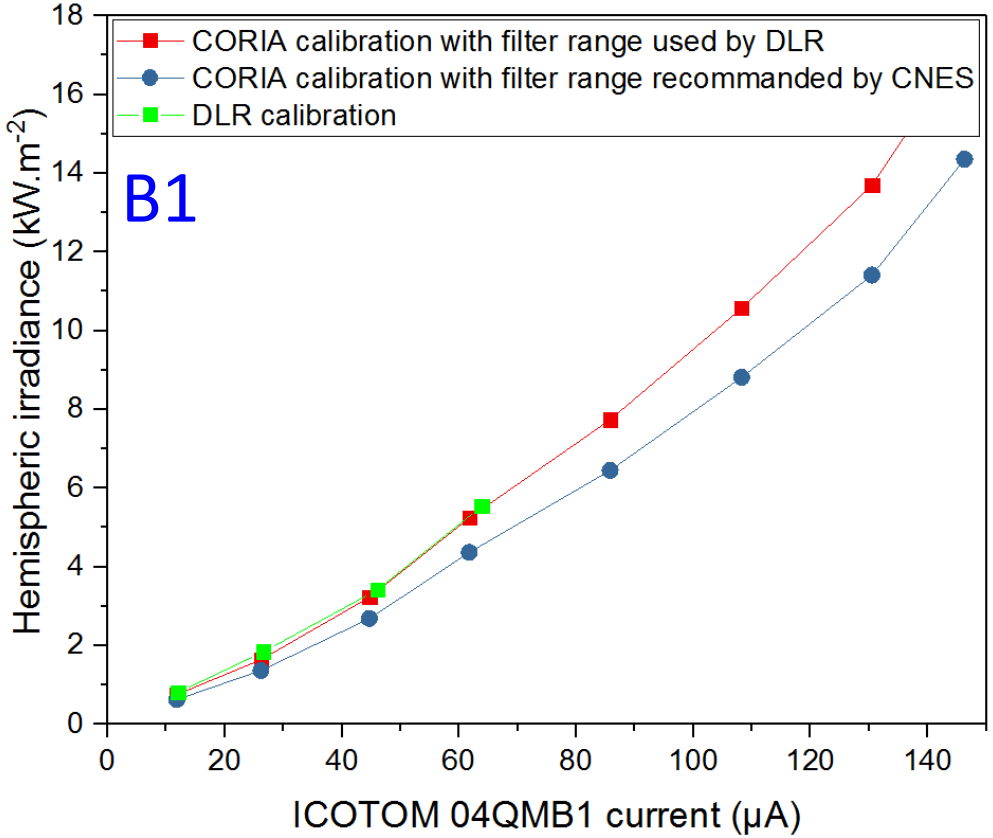

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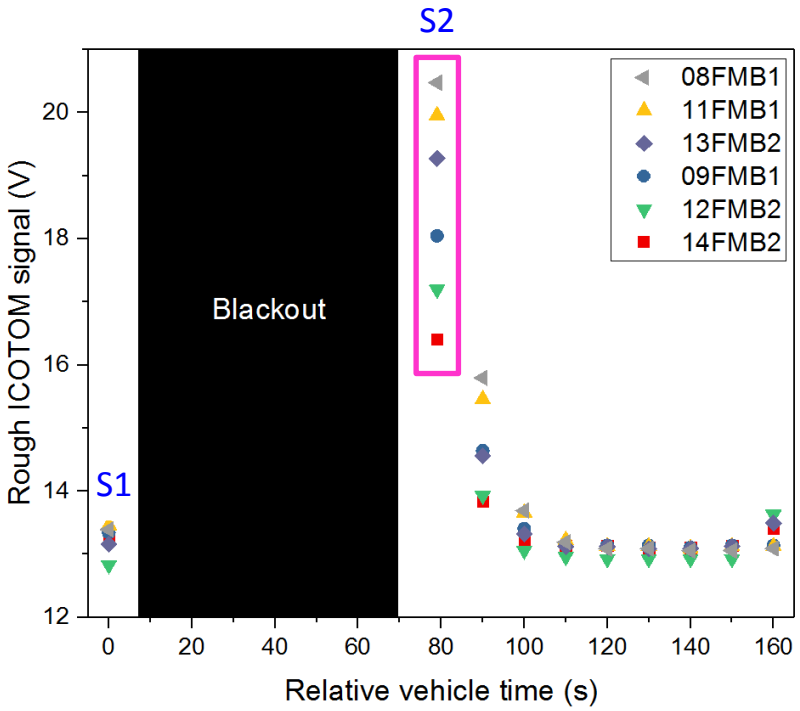

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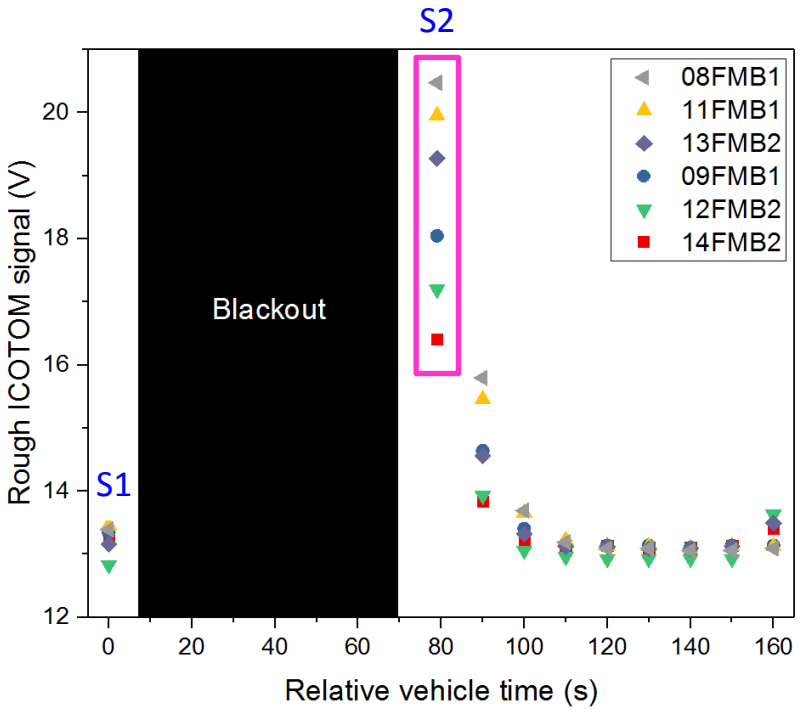
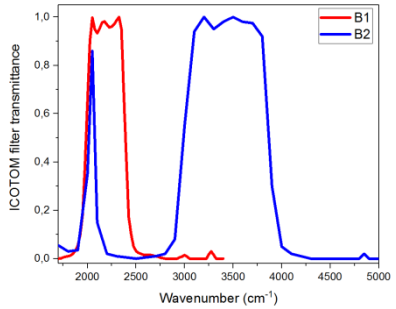


Hemispheric irradiance - 115 s after the entry interface point (S2):

14FMB2 : 1.63 ± 0.03 kW.m^{-2}	COMARS 1	09FMB1 : 5.32 ± 0.17 kW.m^{-2}
12FMB2 : 1.76 ± 0.10 kW.m^{-2}	COMARS 2	11FMB1 : 5.23 ± 0.35 kW.m^{-2}
13FMB2 : 2.66 ± 0.11 kW.m^{-2}	COMARS 3	08FMB1 : 8.17 ± 0.55 kW.m^{-2}

DLR total radiometer (close to ICOTOM 8 and 13) : 9 ± 1,2 kW.m^{-2} (Gülhan et al., JSR, 2018)

Sum of irradiance measured by ICOTOM 08FMB1 et 13FMB2 (minus the 2000 cm^{-1} peak contribution) : 10,3 ± 0,9 kW.m^{-2}



Main uncertainties:

- ICOTOM (COMARS housing) temperature : ±3K
- Flight models – Spare models relative behaviour

Important remark

Results are given as hemispheric irradiance but the ICOTOM collection half-angle is 17,5°.

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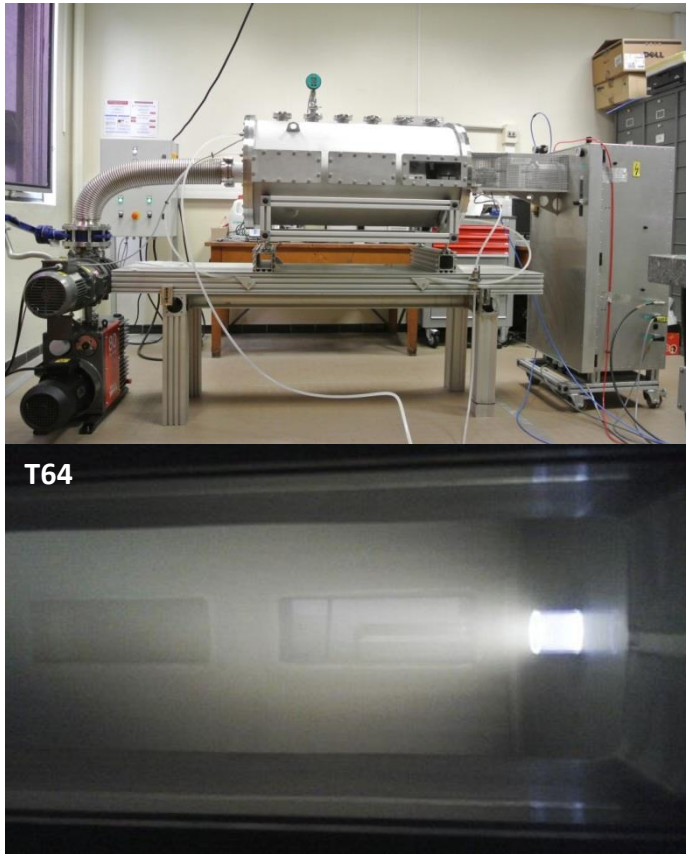
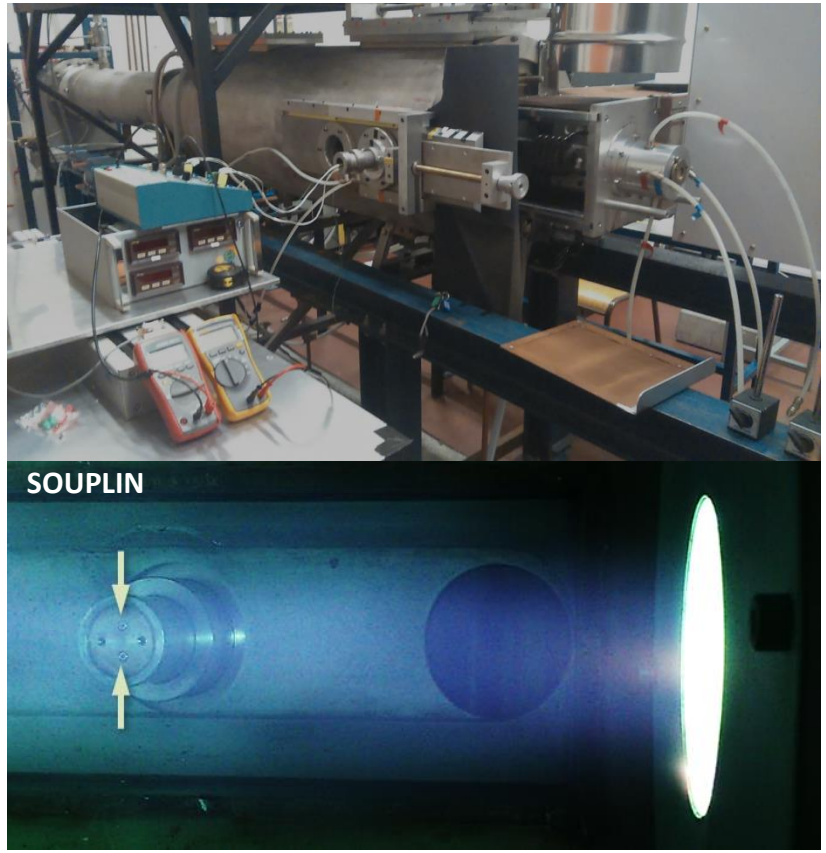
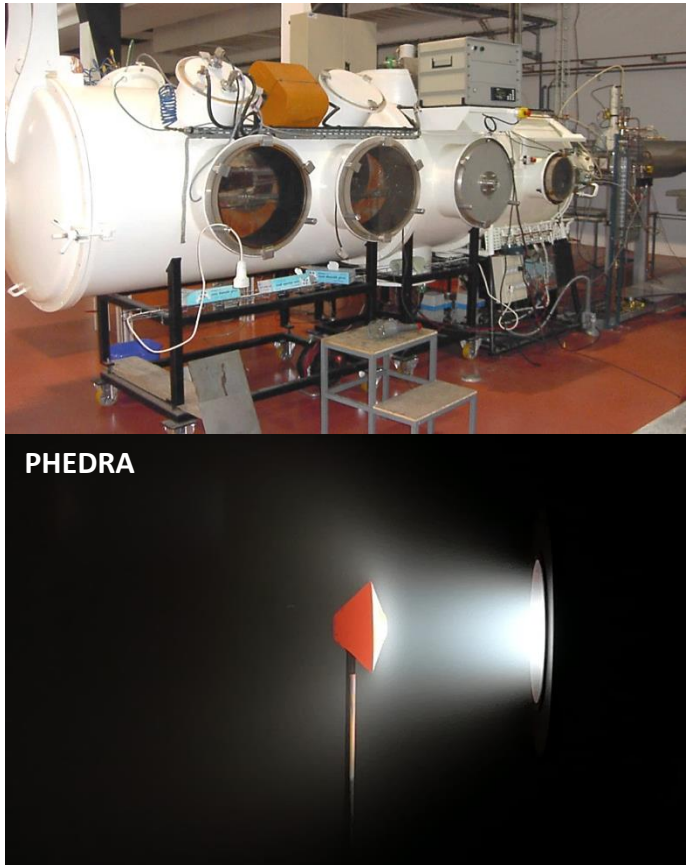
3. Experimental studies

Three facilities : different plasma conditions and rebuilding opportunities

- ICP (subsonic) intermediate enthalpy (low power, low flow rate) – low pressure (T64)
- ICP (subsonic) intermediate enthalpy (intermediate power and flow rate) – intermediate pressure (SOUPLIN)
- Arcjet (supersonic) high enthalpy – low pressure with model (PHEDRA)

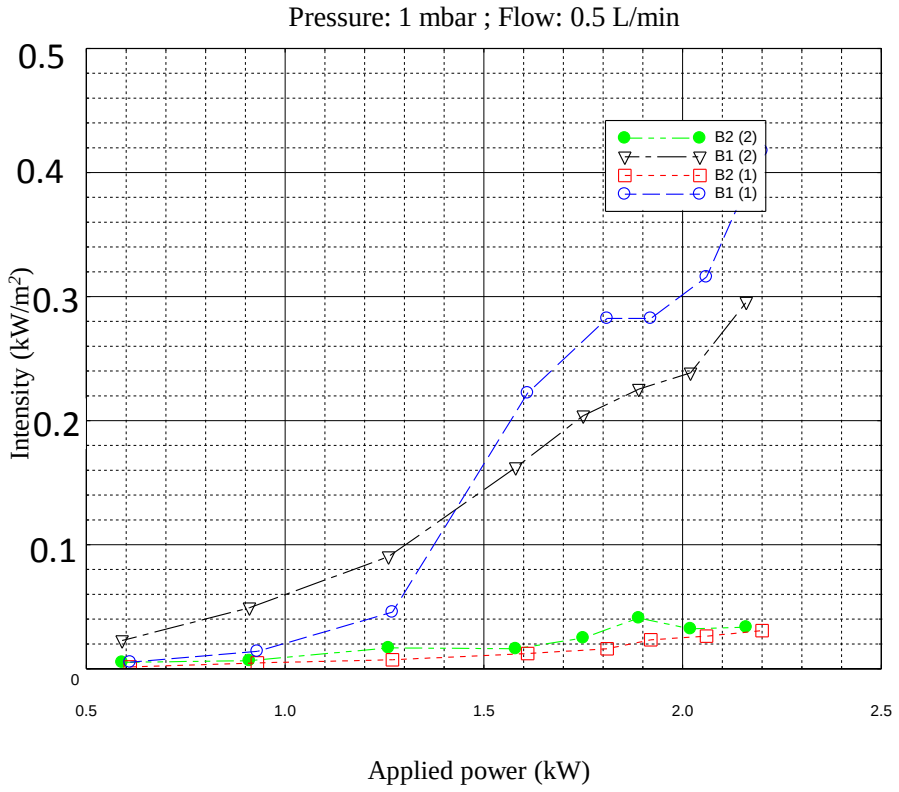


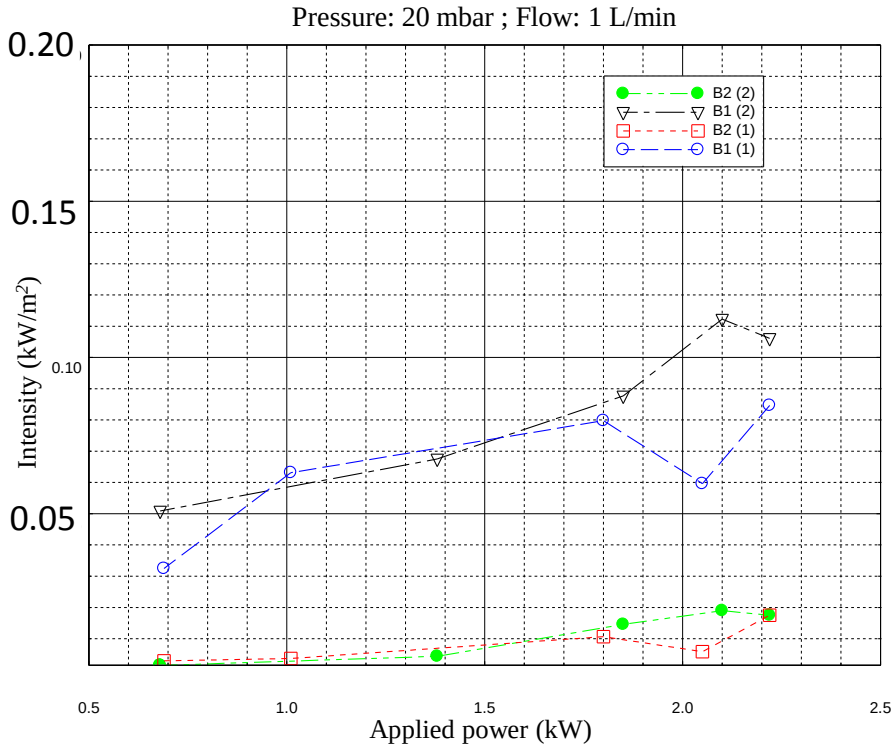




ICP low enthalpy – low pressure (0,1-2 Pa)

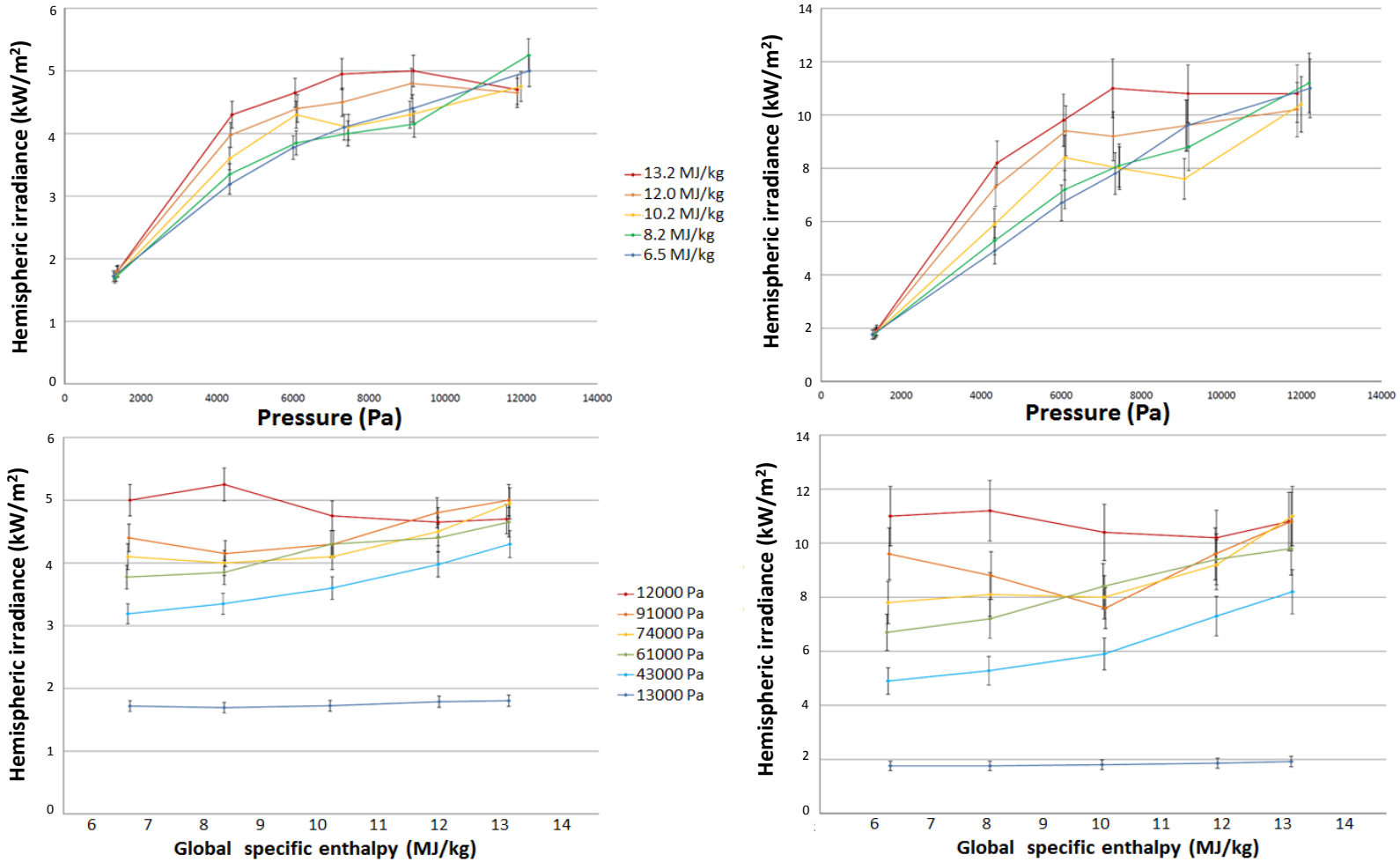
- **Planned : IR spectroscopy**
- **Planned : Interferometry (electron density measurements)**
- **Done : ICOTOM measurements**





ICP intermediate enthalpy (2-13 MJ/kg) – intermediate pressure (1-12 kPa)

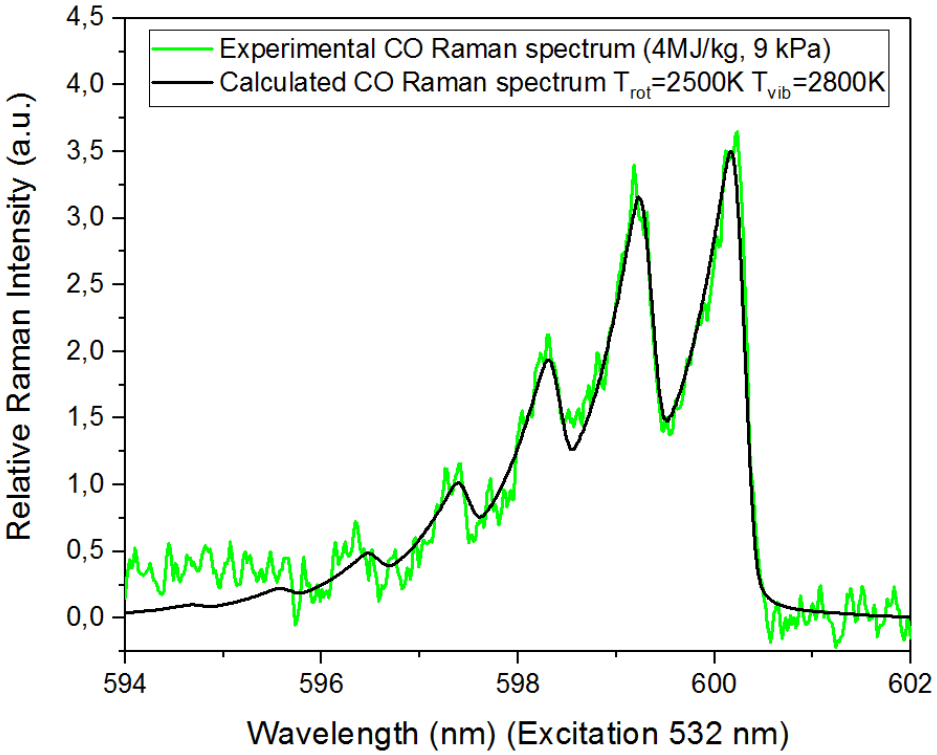
- **Done : ICOTOM measurements**



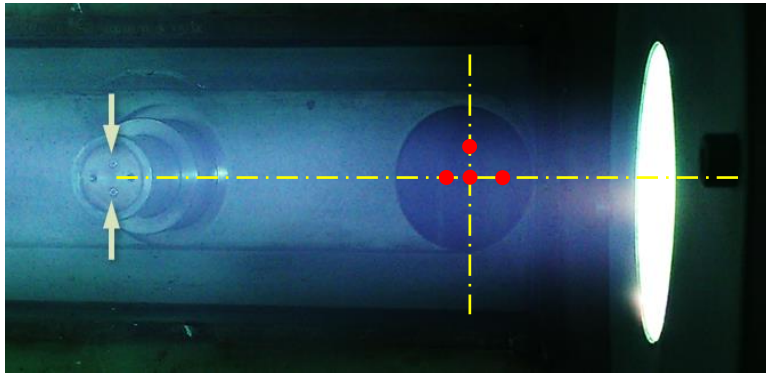
3. Experimental studies (SOUPLIN)

ICP intermediate enthalpy (2-13 MJ/kg) – intermediate pressure (1-12 kPa)

- **Done : CO Raman spectroscopy**



Position	Pression	Enthalpie	Densité (m^{-3})	Fraction molaire	Tr/Tv (K)
Aval +2 cm	6 kPa	4 MJ/kg	9,8E+22	0,68	3100 / 2600
		5 MJ/kg	5,8E+22	0,39	3000 / 3400
		6 MJ/kg	5,2E+22	0,35	3000 / 3900
		9 MJ/kg	4,0E+22	0,25	2800 / 5000
	9 kPa	4 MJ/kg	1,6E+23	0,62	2500 / 2800
		5 MJ/kg	1,0E+23	0,38	2400 / 3500
		6 MJ/kg	7,4E+22	0,28	2500 / 4200
		9 MJ/kg	5,3E+22	0,19	2300 / 5500
Centre 0 mm	6 kPa	4 MJ/kg	1,0E+23	0,68	3000 / 3000
		5 MJ/kg	8,4E+22	0,56	3000 / 3300
		6 MJ/kg	6,4E+22	0,39	2800 / 4000
		9 MJ/kg	5,0E+22	0,33	3000 / 5000
	9 kPa	4 MJ/kg	7,7E+22	0,33	2800 / 3100
		5 MJ/kg	6,5E+22	0,28	2800 / 4200
		6 MJ/kg	5,8E+22	0,25	2800 / 4800
		9 MJ/kg	5,0E+22	0,17	2300 / 6000
Amont -1,5cm	6 kPa	4 MJ/kg	1,8E+22	0,08	2000 / 3000
		5 MJ/kg	1,5E+22	0,07	2000 / 3300
		6 MJ/kg	1,1E+22	0,05	2000 / 4800
		9 MJ/kg	9,2E+21	0,04	2000 / 6000
	9 kPa	4 MJ/kg			
		5 MJ/kg			
		6 MJ/kg			
		9 MJ/kg			



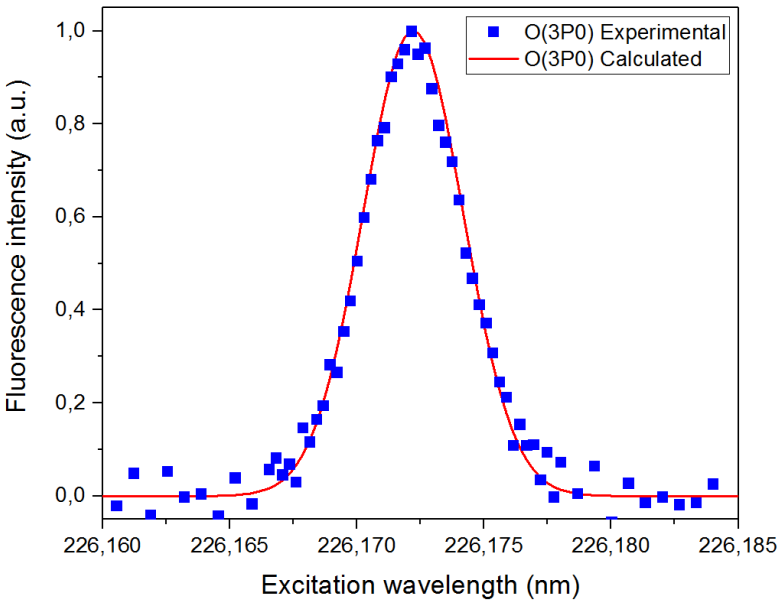
Position	Pression	Enthalpie	Densité (m^{-3})	Fr. molaire	Tr/Tv (K)
Radial +2 cm	6 kPa	4 MJ/kg			
		5 MJ/kg	4,8E+22	0,22	2000 / 3000
		6 MJ/kg	4,6E+22	0,21	2000 / 3300
		9 MJ/kg	3,7E+22	0,17	2000 / 3800
	9 kPa	4 MJ/kg	1,0E+23	0,31	2000 / 2900
		5 MJ/kg	8,4E+22	0,26	2000 / 3500
		6 MJ/kg	7,8E+22	0,24	2000 / 3500
		9 MJ/kg	7,2E+22	0,22	2000 / 4000

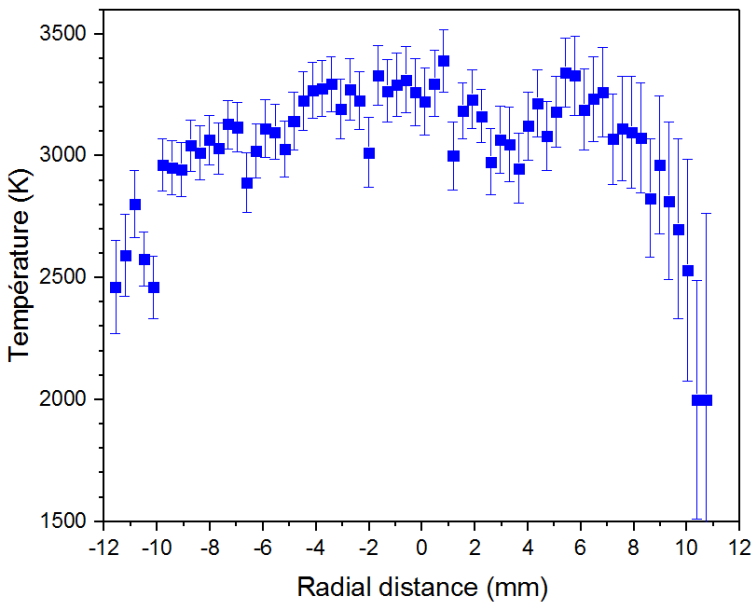
- Uncertainties on densities: 20%
- Uncertainties on T_{vib} : 100 K (if ΔT_{rot} =0, T_{vib} probably smaller and reduced nonequilibrium)
- Uncertainties on T_{rot} still too large because of the remaining background

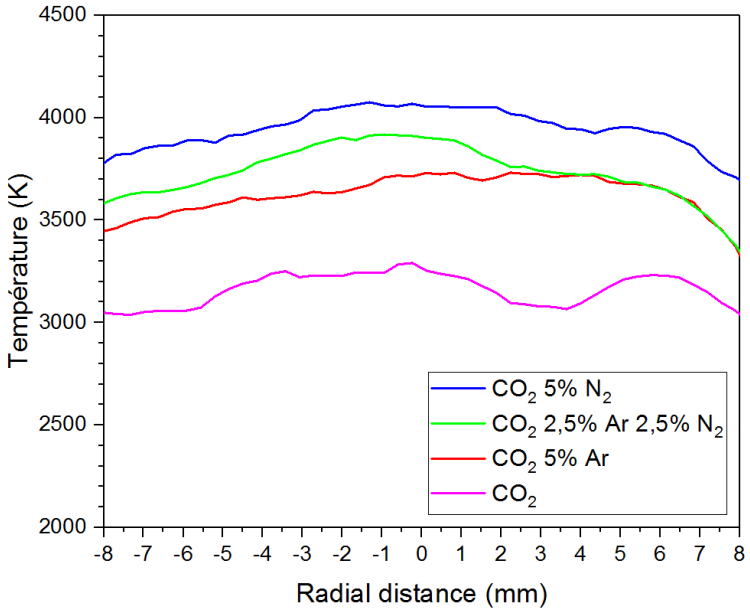
3. Experimental studies (SOUPLIN)

ICP intermediate enthalpy (2-13 MJ/kg) – intermediate pressure (1-12 kPa)

- **Done : O two-photon absorption laser-induced fluorescence (TALIF)**





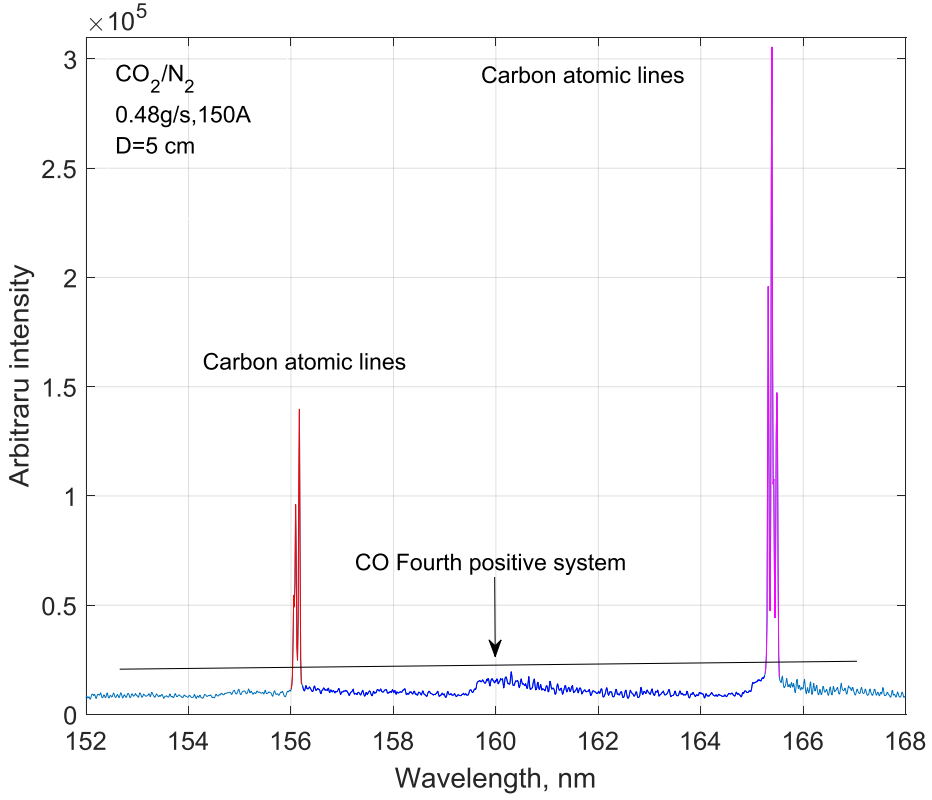


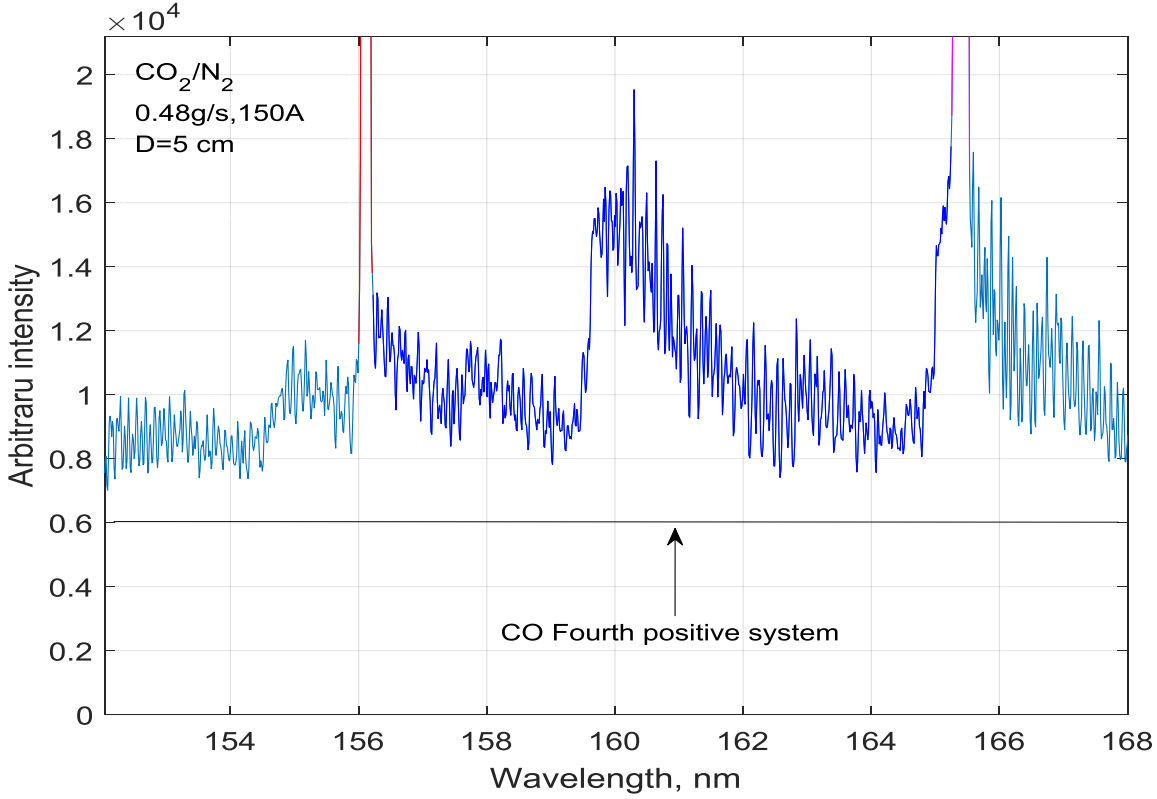
- Dynamic excitation model for O fluorescence intensity
- Uncertainties on translation temperature: ±150K
- Density determination by calibration with xenon (post-processing in progress)
- Increasing translation temperature with small amounts of nitrogen and argon

3. Experimental studies (PHEDRA)

Arcjet high enthalpy (20 MJ/kg) – low pressure (2 Pa)

- **Done : ICOTOM measurements (very low signal: to be assessed)**
- **Done : IR spectroscopy (low signal: disturbed by the model own radiation)**
- **Done : VUV measurements**





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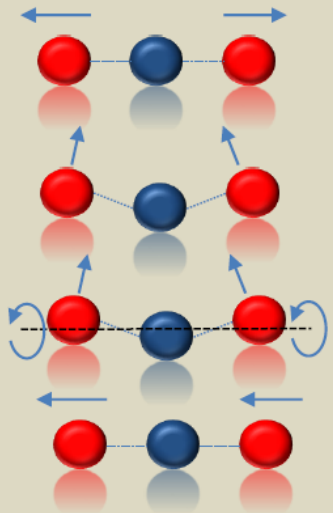
CO_2 vibrational energy structure to be used in the kinetic model

CoRaM-Mars

- CO_2, N_2, Ar and derived species
- Electronic specific
- Vibrational specific
- Before this work:
  - decoupled vibrational modes
  - no Fermi resonances
  - no intermode exchanges
  - not suitable with radiat. calcul.

Movement	Name	i	$\omega_i(cm^{-1})$	$\omega_i(eV)$	Quantum Nb
	Symmetrical stretching mode	1	1353,65	0,16782	v_1
	Bending mode	2	672,83	0,08342	v_2
	Bending-induced rotation				l_2
	Asymmetrical stretching mode	3	2396,30	0,29710	v_3

$$E(v_1, v_2, l_2, v_3, J=0) = E(v_1\, v_2^{\,l_2}\, v_3, J=0)$$
$$= \sum_i \omega_i \left(v_i + \frac{g_i}{2}\right) + \sum_{i,j} x_{ij} \left(v_i + \frac{g_i}{2}\right)\left(v_j + \frac{g_j}{2}\right) + x_{ll}\, l_2^2$$
$$+ \sum_{i,j,k} y_{ijk} \left(v_i + \frac{g_i}{2}\right)\left(v_j + \frac{g_j}{2}\right)\left(v_k + \frac{g_k}{2}\right) + \sum_i y_{ill} \left(v_i + \frac{g_i}{2}\right) l_2^2$$
$$+ \sum_{i,j,m,n} z_{ijmn} \left(v_i + \frac{g_i}{2}\right)\left(v_j + \frac{g_j}{2}\right)\left(v_m + \frac{g_m}{2}\right)\left(v_n + \frac{g_n}{2}\right)$$
$$+ \sum_{i,j} z_{ijll} \left(v_i + \frac{g_i}{2}\right)\left(v_j + \frac{g_j}{2}\right) l_2^2 + z_{llll} l_2^4$$

Tashkun S.A. *et al.*, JQSRT **60** 5, 785-801, 1998

$E_d = D_0 = 5{,}4533\ eV$

$D_e = 5{,}7672\ eV$

$v_1 \in [0{,}35],\ v_2 \in [0{,}68],\ l_2 \in [0, v_2],\ v_3 \in [0{,}20]$

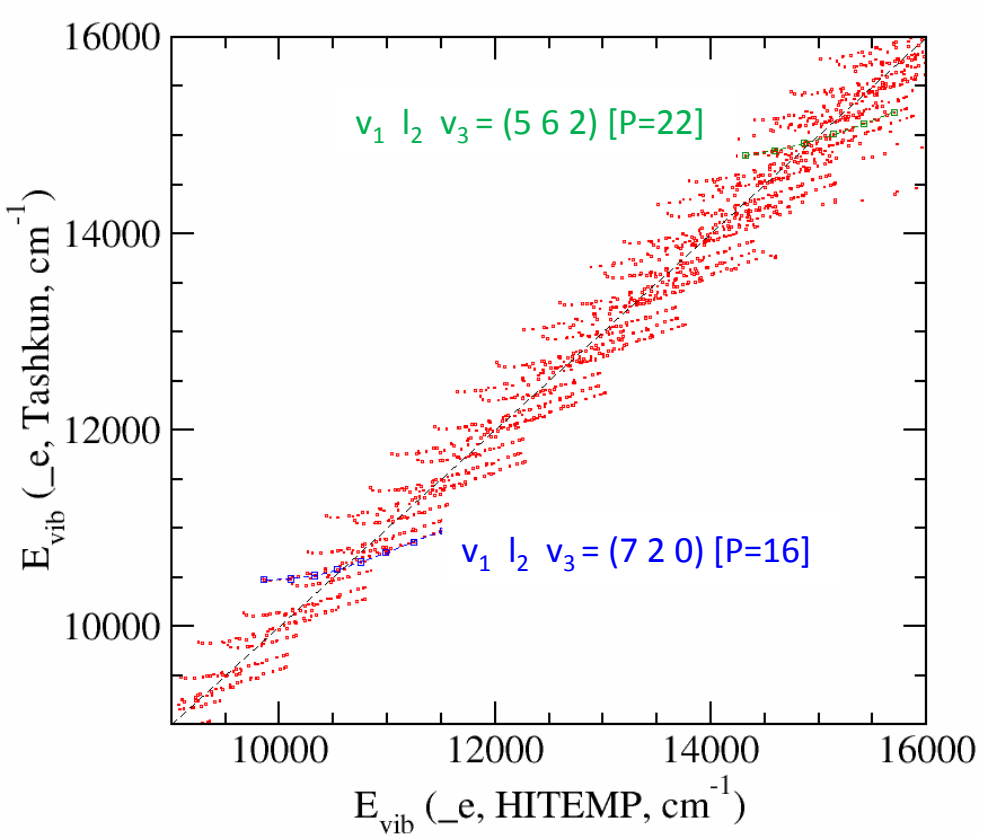
Harmonic oscillator :

$v_1 \in [0{,}31],\ v_2 \in [0{,}65],\ l_2 = 0,\ v_3 \in [0{,}18]$

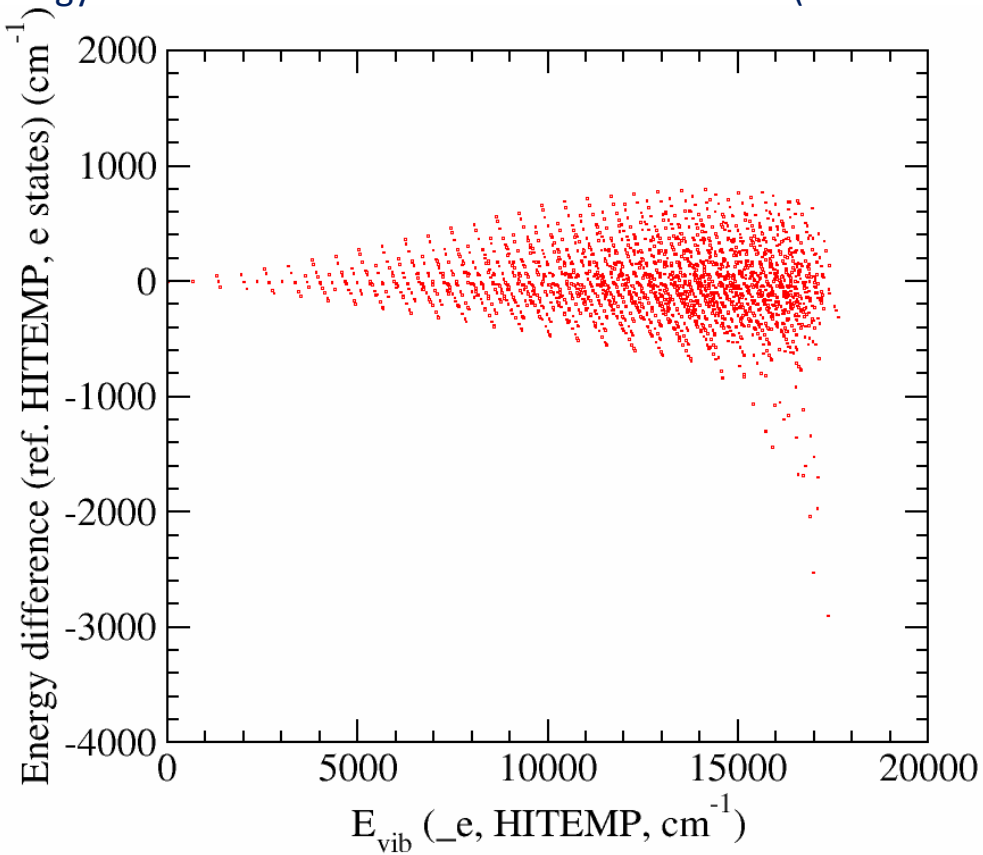
CO_2 vibrational energy structure to be used in the kinetic model

Differences between Tashkun used for kinetic calculations and HITEMP used for radiation calculations

Comparison between Tashkun and HITEMP energy levels



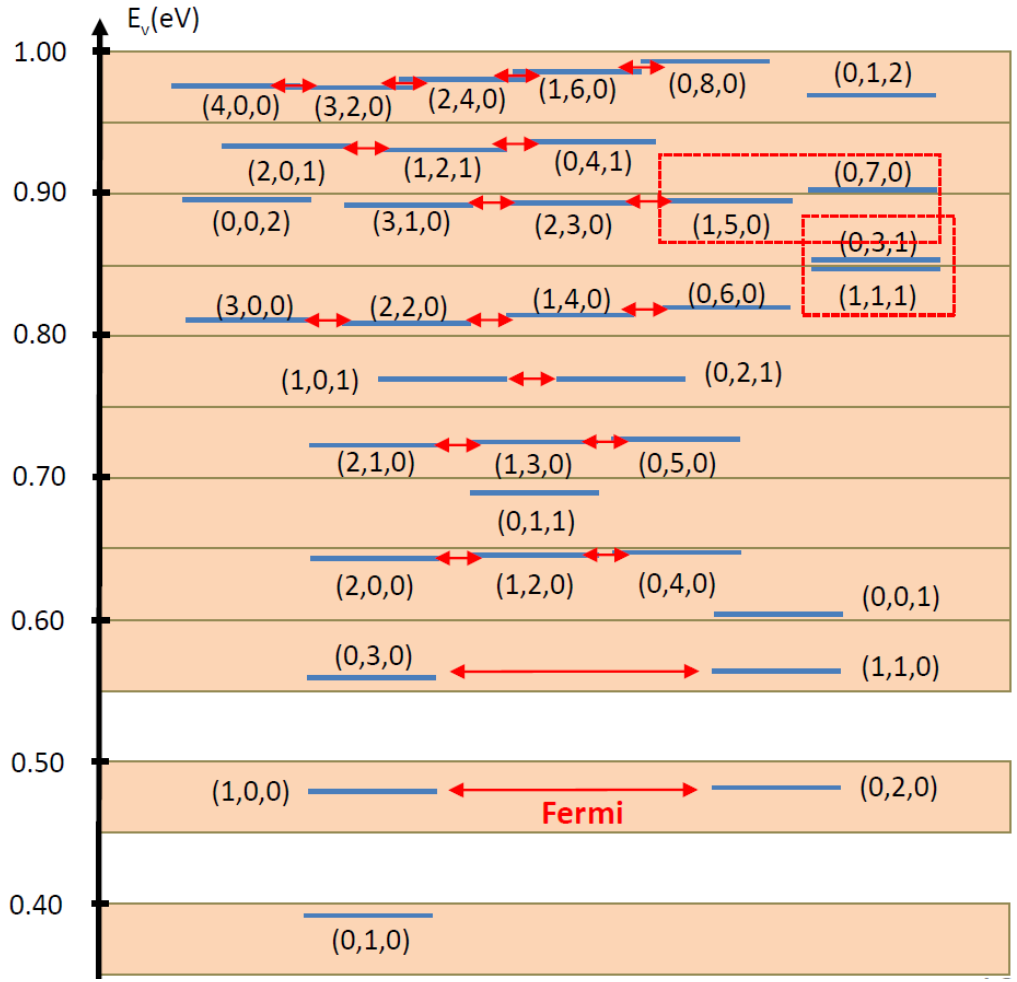
Energy differences between Tashkun and HITEMP (ref. HITEMP)



Methology and kinetics of grouping

$\Delta E = 0{,}05\ eV$

VT	$v_2 \pm 1 \rightarrow v_2$
	$v_3 \pm 1 \rightarrow v_3$
VV'$_{12}$	$v_1 \pm 1, v_2 \mp 2 \rightarrow v_1, v_2$
VV'$_{23}$	$v_2 \pm 3, v_3 \mp 1 \rightarrow v_2, v_3$
VV'$_{123}$	$v_1 \pm 1, v_2 \pm 1, v_3 \mp 1 \rightarrow v_1, v_2, v_3$
VV	$v_m \pm 1, w_m \mp 1 \rightarrow v_m, w_m$



$n = 6, g = 27$

$n = 4, g = 17$

$n = 5, g = 17$

$n = 5, g = 18$

$n = 2, g = 4$

$n = 3, g = 12$

$n = 1, g = 2$

$n = 4, g = 10$

$n = 2, g = 6$

$n = 2, g = 4$

$n = 1, g = 2$

Purpose

- Use the results of the s-t-s model
  - with radiative transfer calculations
  - with fluid dynamic calculations
    - suitable description (done)
    - reduced model (in progress)

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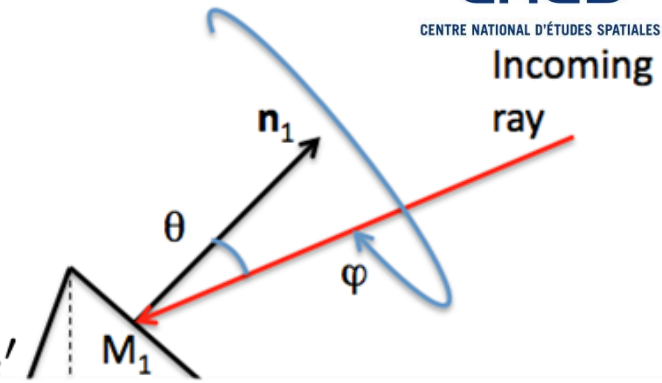
Incident radiative flux prediction



Ray tracing

$$q_\sigma^{\mathrm{inc}}(M_1) = \int_{\varphi=0}^{2\pi} \int_{\theta=0}^{\frac{\pi}{2}} I_\sigma(M_1, \theta, \varphi) \sin\theta \mathrm{d}\theta \mathrm{d}\varphi$$

Radiative Transfer Equation

$$I_\sigma(M_1, \theta, \varphi) = \int_{s_\infty}^{s_{M_1}} \frac{\eta_\sigma}{\kappa_\sigma}(s') \frac{\partial}{\partial s'} \tau_\sigma(s_{M_1}, s') \mathrm{d}s'$$

$$\tau_\sigma(s_{M_1}, s') = \exp\left(-\int_{s_{M_1}}^{s'} \kappa_\sigma(s'') \mathrm{d}s''\right)$$

Radiative properties

$$\eta_\sigma = \sum_{ul} \frac{A_{ul}}{4\pi} hc\sigma_{ul} n_u f_{ul}(\sigma - \sigma_{ul}),$$

$$\kappa_\sigma = \sum_{ul} (n_l B_{lu} - n_u B_{ul}) h\sigma_{ul} f_{ul}(\sigma - \sigma_{ul}),$$

Level populations for CO and CO_2 $\quad n_u,\ n_l\ ?$

CO_2 vibrational level populations

Fermi polyad grouping

$$\{v_1 l_2 v_3 r\},\ r = 1,..,v_1 + 1$$

$$n^{\text{polyad}}_{\{v_1 l_2^{l_2} v_3\}}$$

3-Temperature model

$$T_{v_{12}},\ T_{v_3},\ T_r$$

Splitting v_3/v_{12} mode

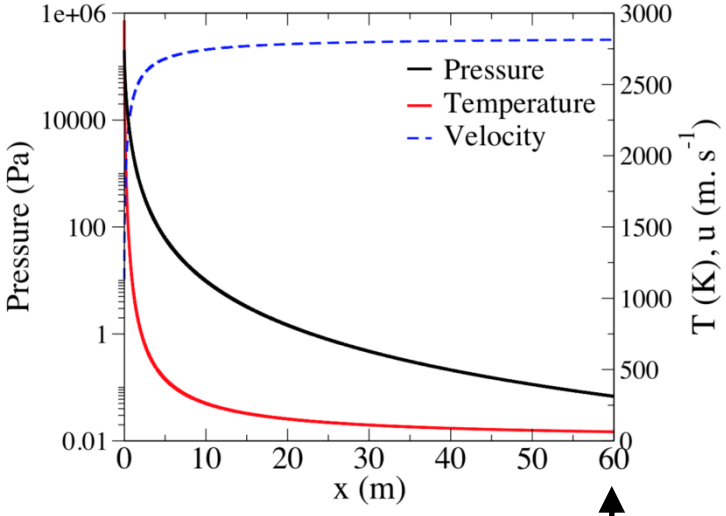
$$E^{v_3}\{v_1 l_2^{l_2} v_3 r, p, J\} = E^{vib}\{00^0 v_3 1, e, J'\}$$

$$E^{v_{12}}\{v_1 l_2^{l_2} v_3 r, p, J\} = E^{vib}\{v_1 l_2^{l_2} v_3 r, p, J\} - E^{v_3}\{v_1 l_2^{l_2} v_3 r, p, J\}$$

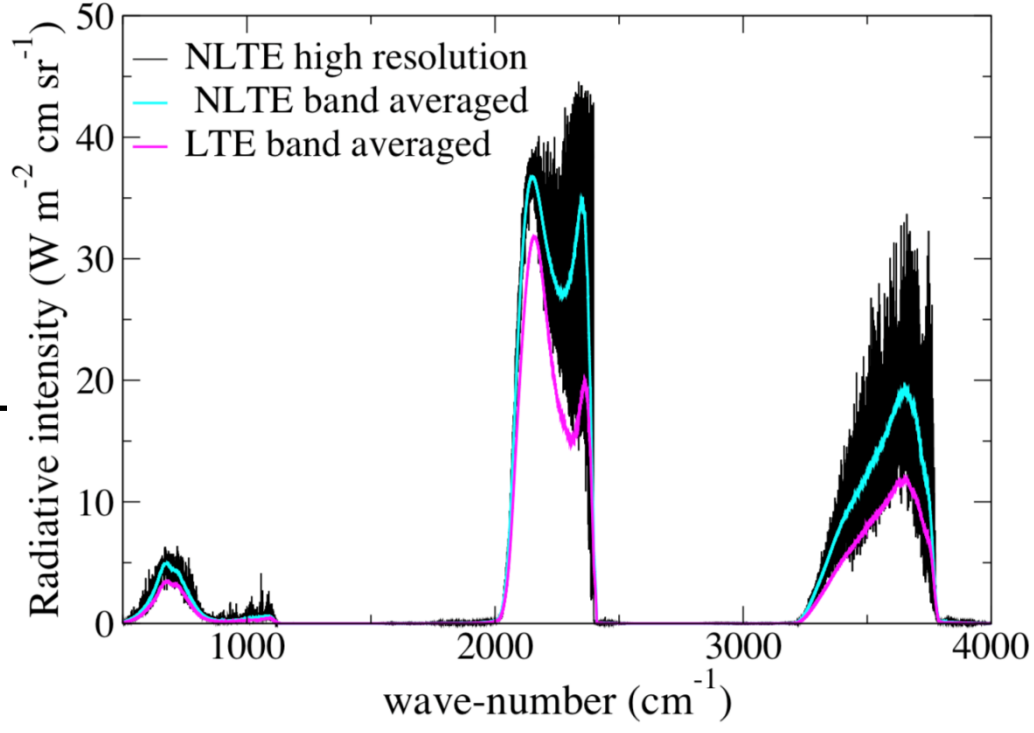
$$n_{u/l} = n_{CO_2} Ab_I \frac{2J_{u/l}+1}{Q_I(T_r, T_{v_{12}}, T_{v_3})} \exp\left(-\frac{E^{rot}\{u/l\}}{k_b T_r} - \frac{E^{v_{12}}\{u/l\}}{k_b T_{v_{12}}} - \frac{E^{v_3}\{u/l\}}{k_b T_{v_3}}\right)$$

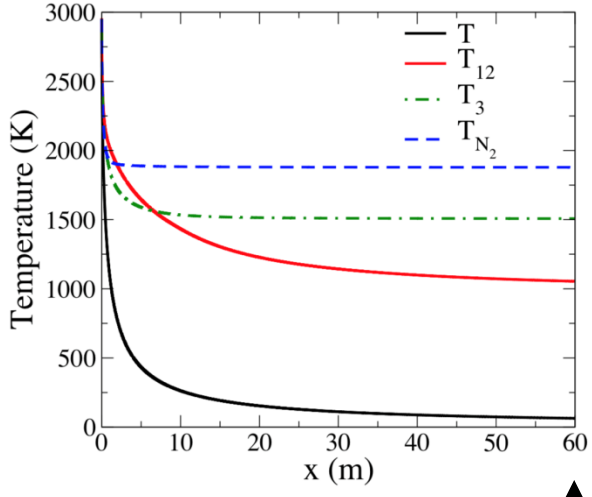
5. Non equilibrium radiative transfer calculations

Example of application to a conical nozzle expanding jet in 70%N_2, 20%CO_2, 10%H_2O



Freezing of vibrational populations:
increases radiative intensity





OUTLINE

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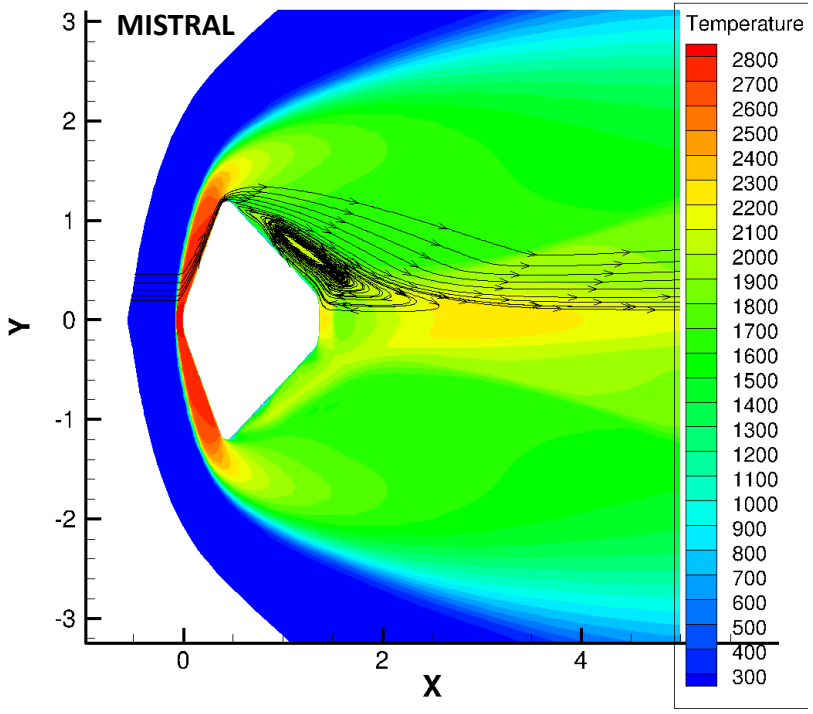
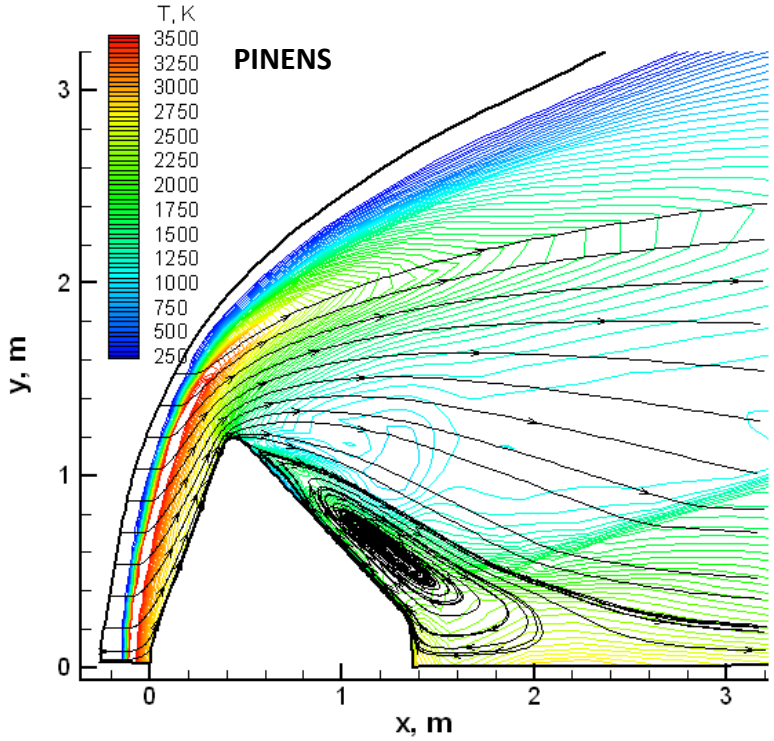
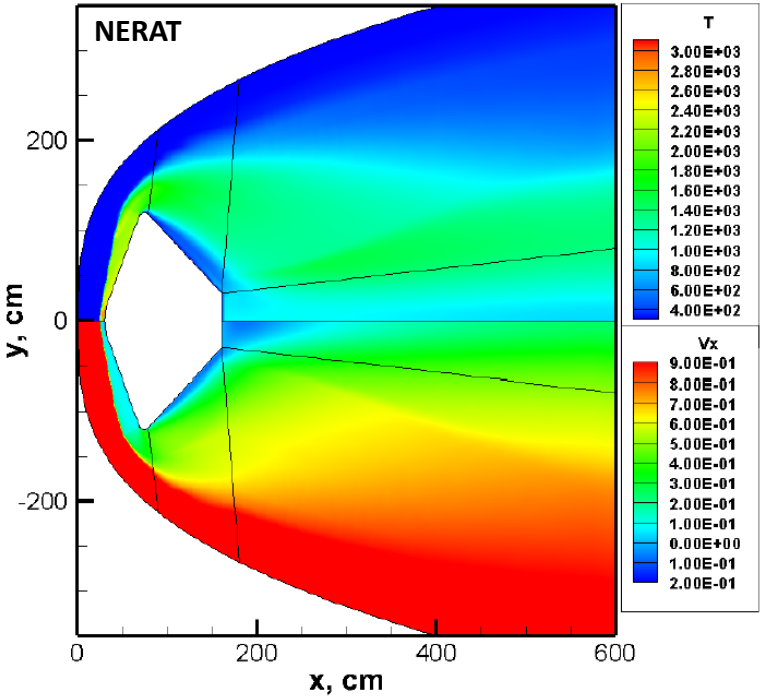
Three different approaches and simulation codes

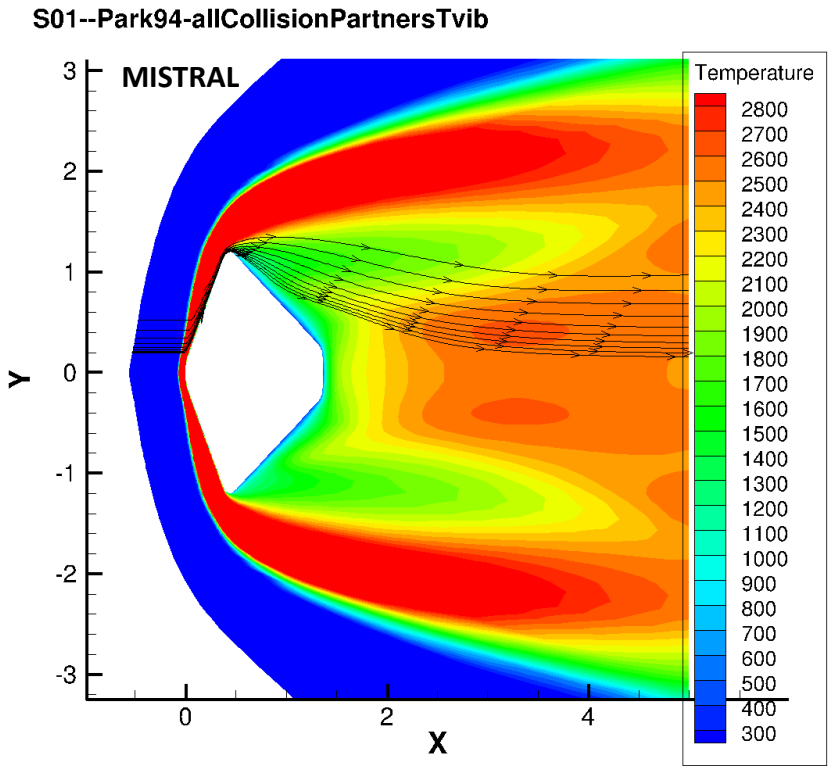
- Engineer-oriented, able to integrate advanced model (MISTRAL)
- Academic, able de deal with radiative transfer (ray tracing) and state-to-state model (PINENS)
- Global approach with surface interactions, turbulence and specific fluxes (NERAT)

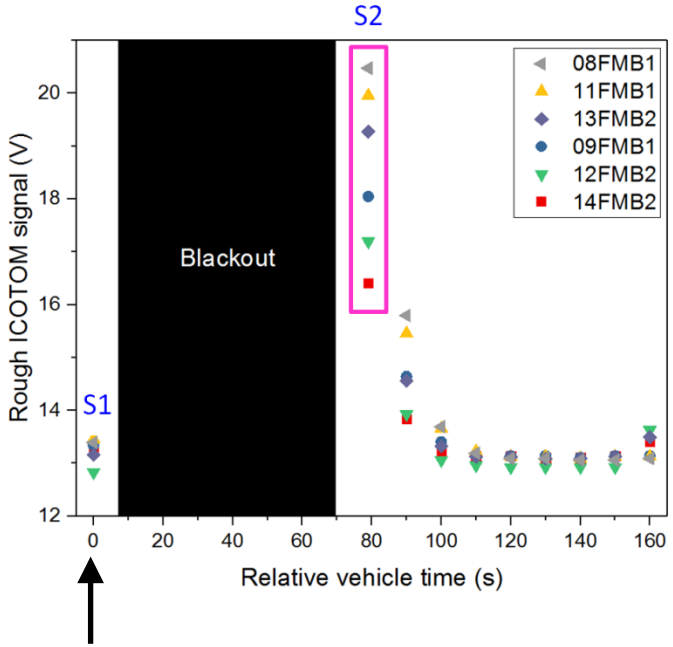


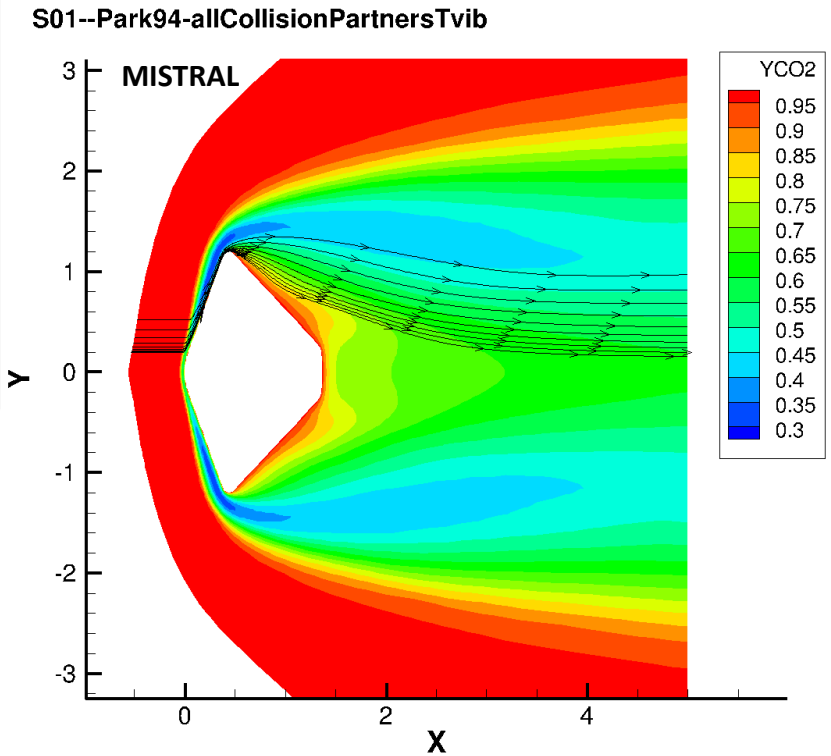




Flow calculations before the blackout (S1)





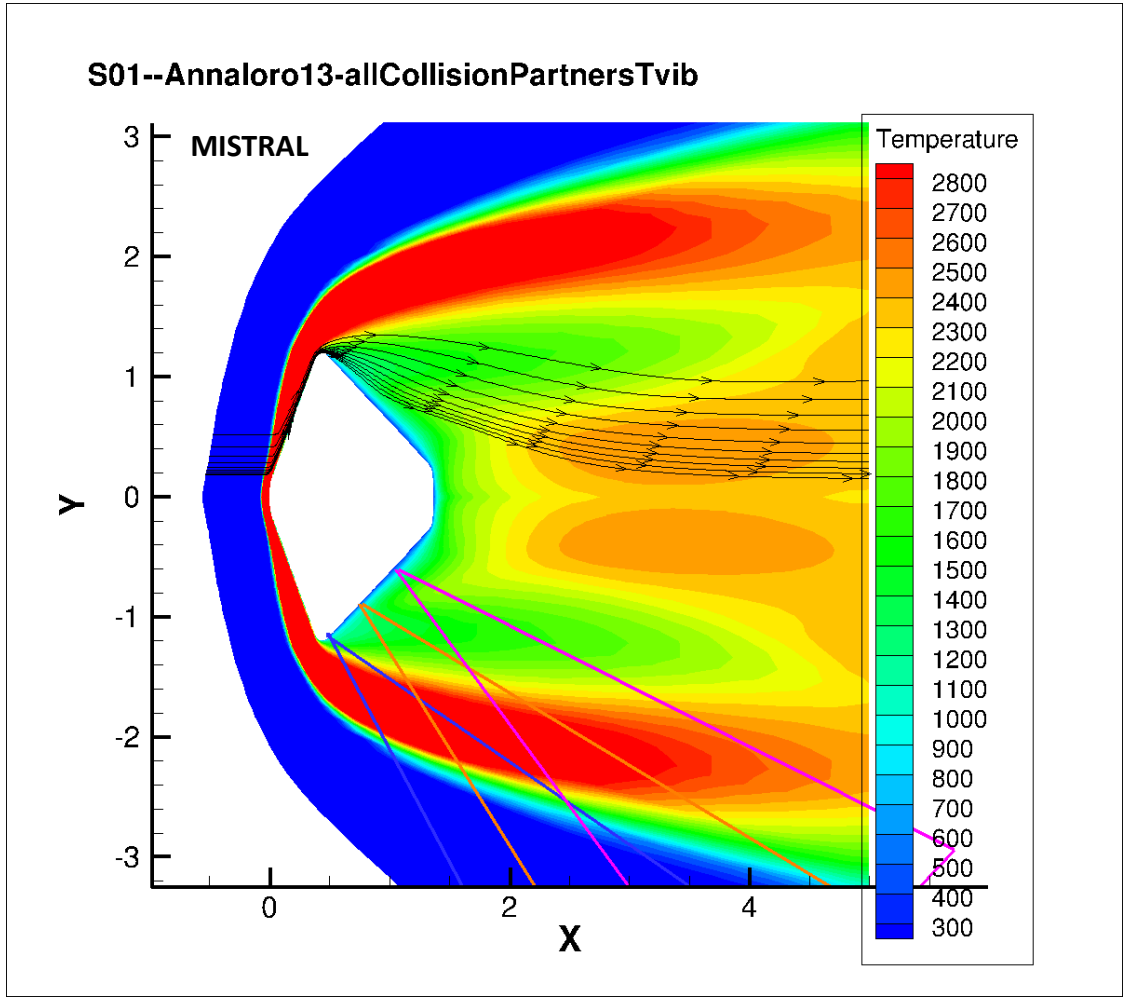


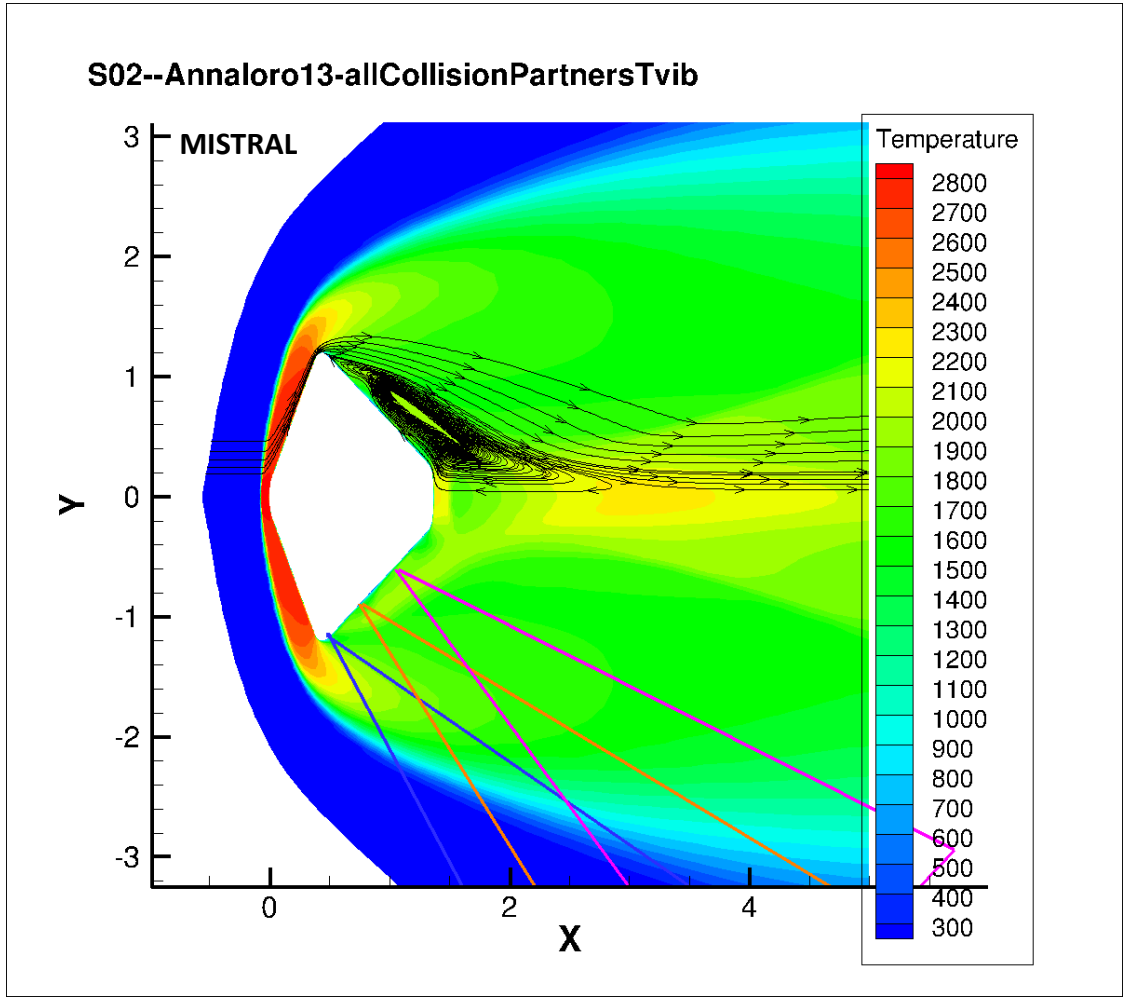
S1 calculations

- H=82 km, V=5,8 km/s, p=0,16 Pa
- Park94 kinetic model
- Two-temperature model
- Strong CO_2 dissociation – High temperature
- Low radiation

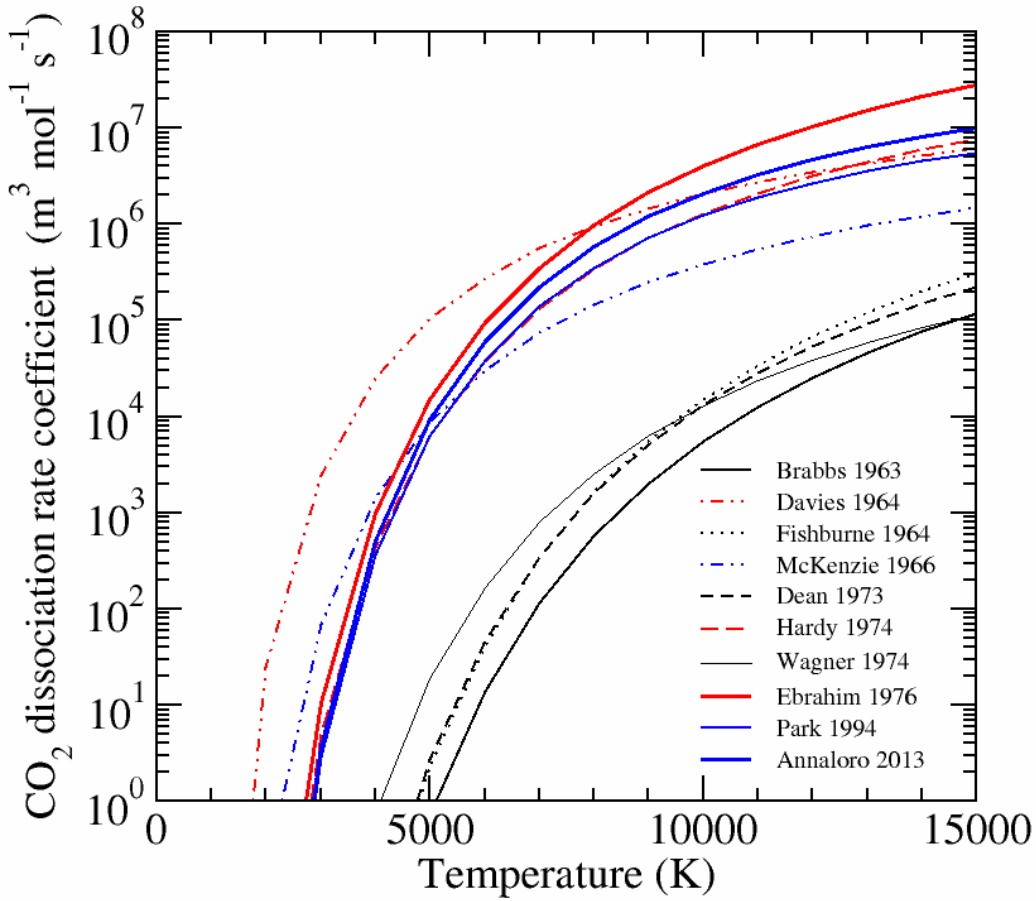
6. Flowfield (Mistral)

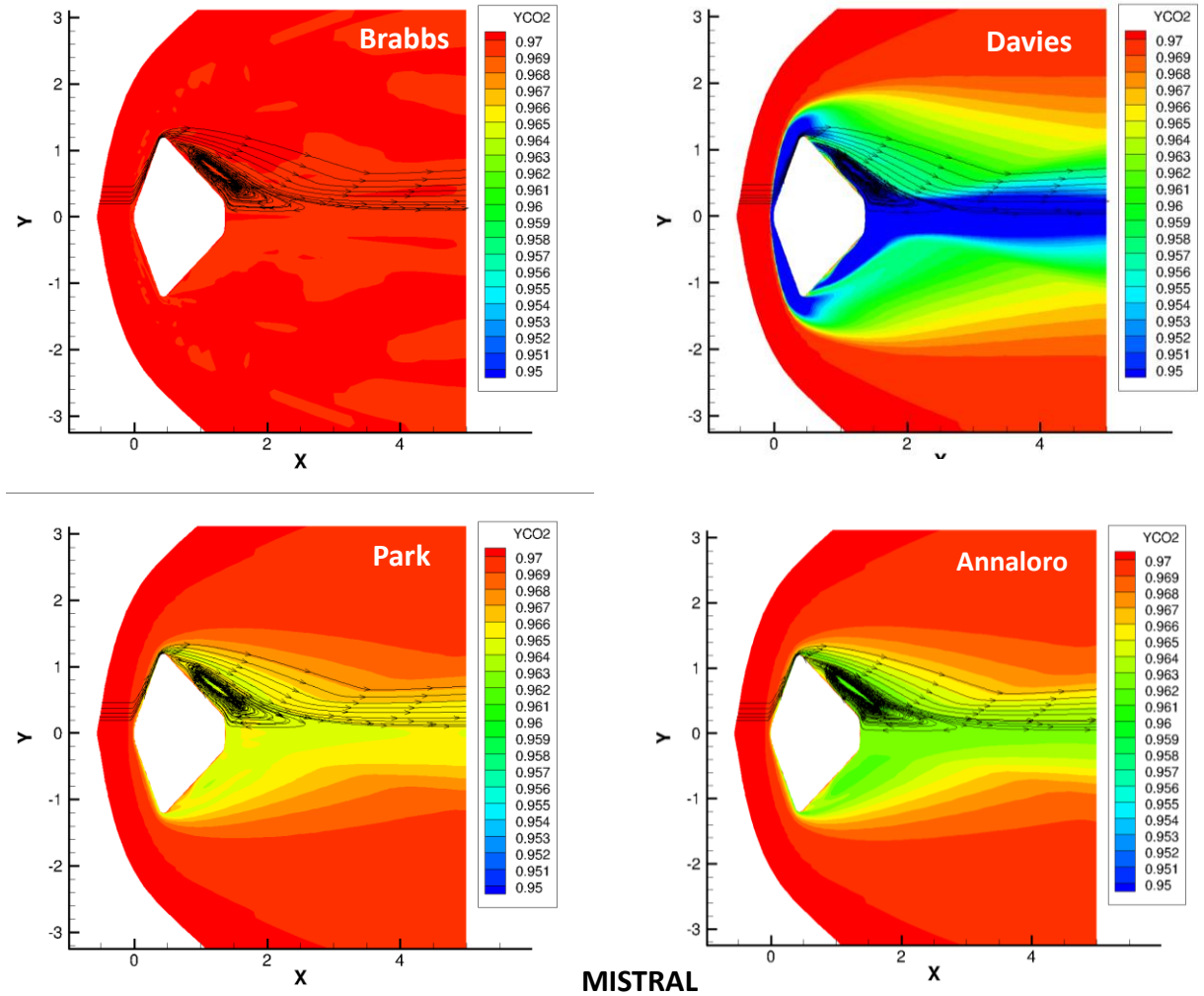
Calculations in the ICOTOM collection cone





Influence of the CO_2 dissociation rate (S2)



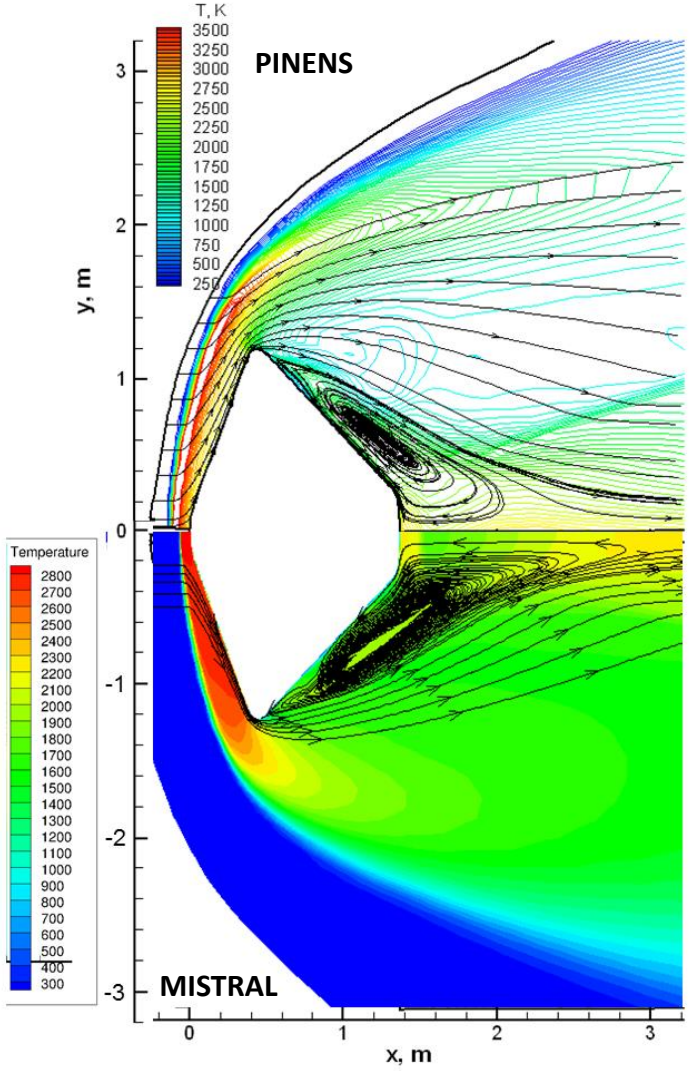


MISTRAL

Sensitivity of the flow field to the numerical calculation (MISTRAL and PINENS)

PINENS (S2)

- Time-implicit integration
- Academic - Fortran
- State-to-state
- Chemistry : reduced CoRaM-Mars
- Radiative transfer (ray tracing)

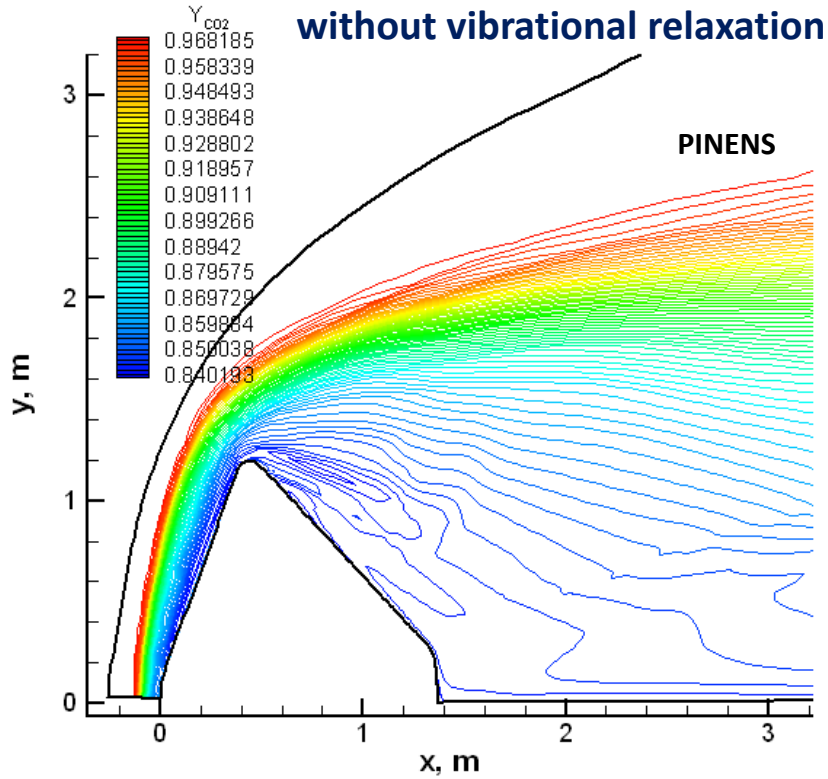


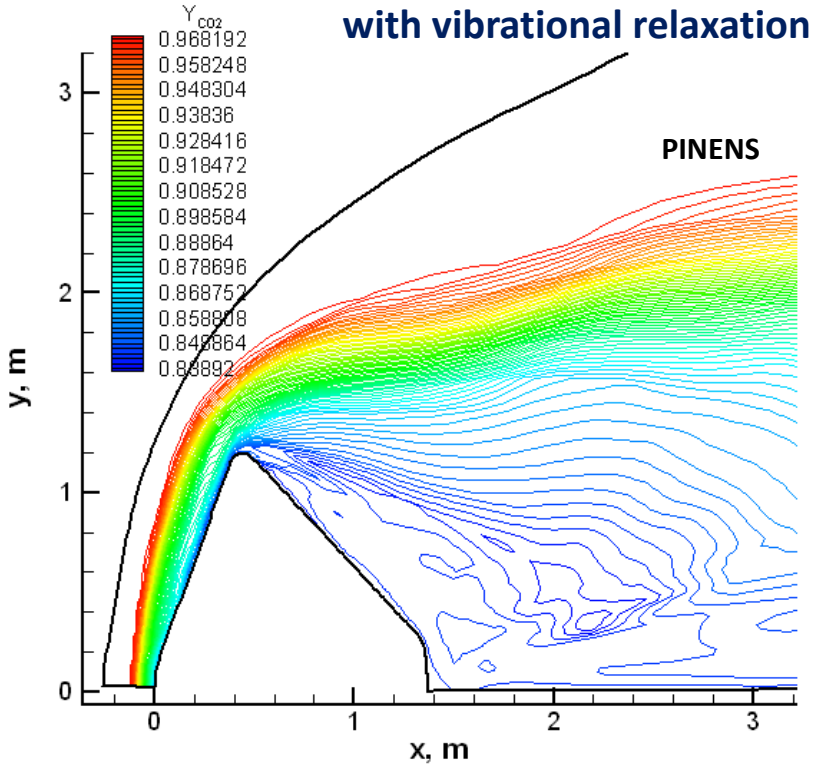
MISTRAL (S2)

- Time-implicit or explicit integration
- Company – C++
- Multi-temperatures
- Chemistry : Park
- No radiative transfer

6. Flowfield (Pinens)

CO_2 mole fraction contours without and with vibrational relaxation (S2)

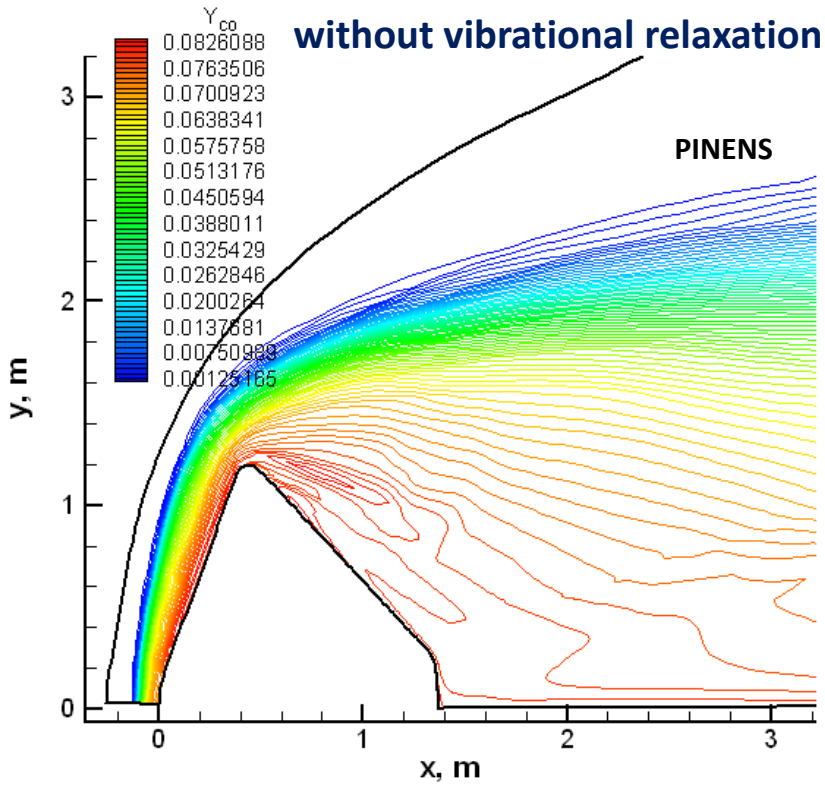


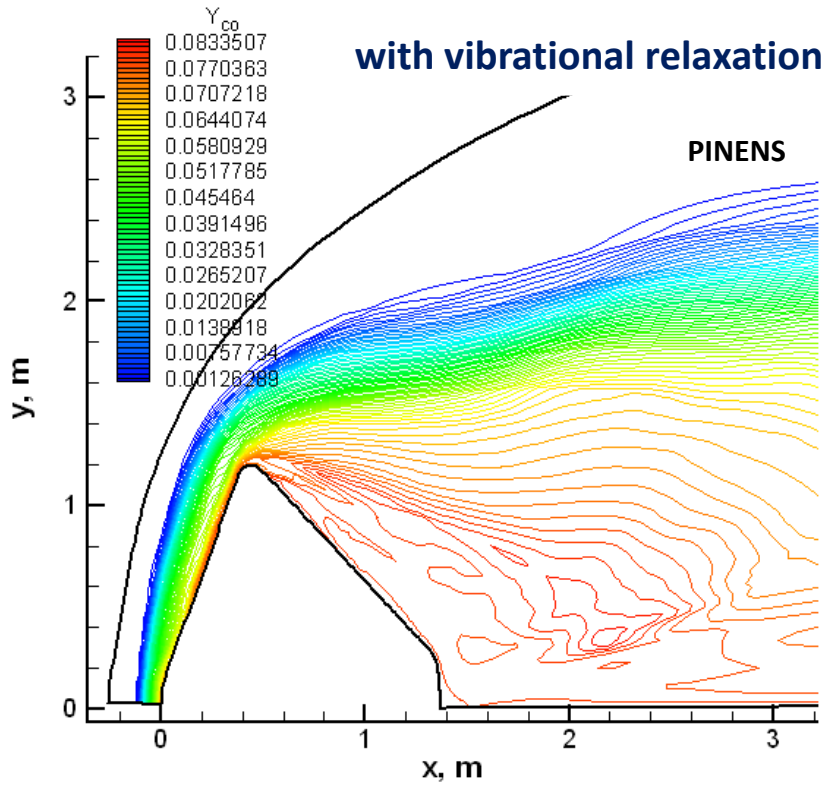


- Reduced CO_2 dissociation when independent vibrational temperatures are considered (the driving temperatures are lower) in the front layer.
- Lower CO_2 recombination close to the wall in the afterbody environnement with vibrational relaxation (non-equilibrium)

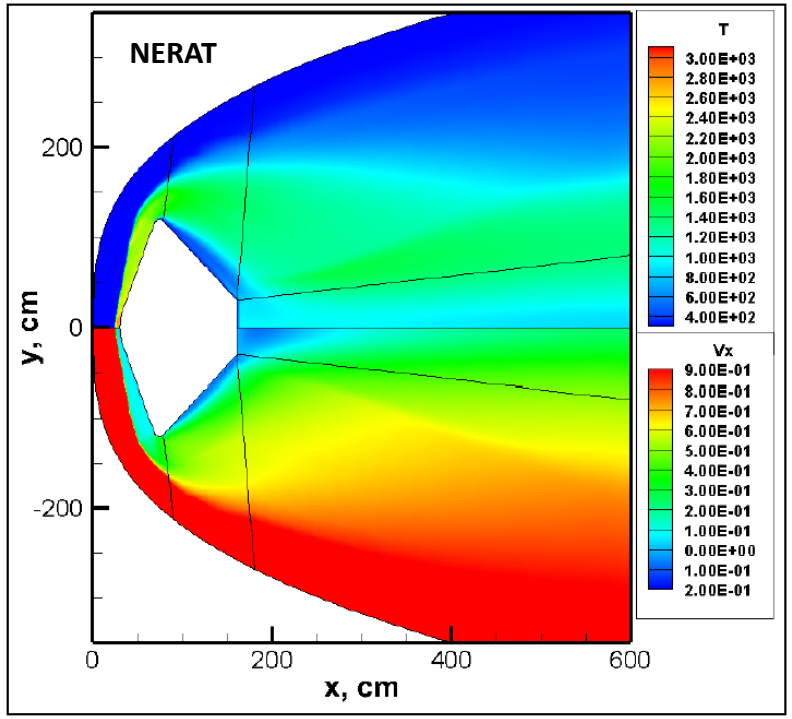
6. Flowfield (Pinens)

CO mole fraction contours without and with vibrational relaxation (S2)

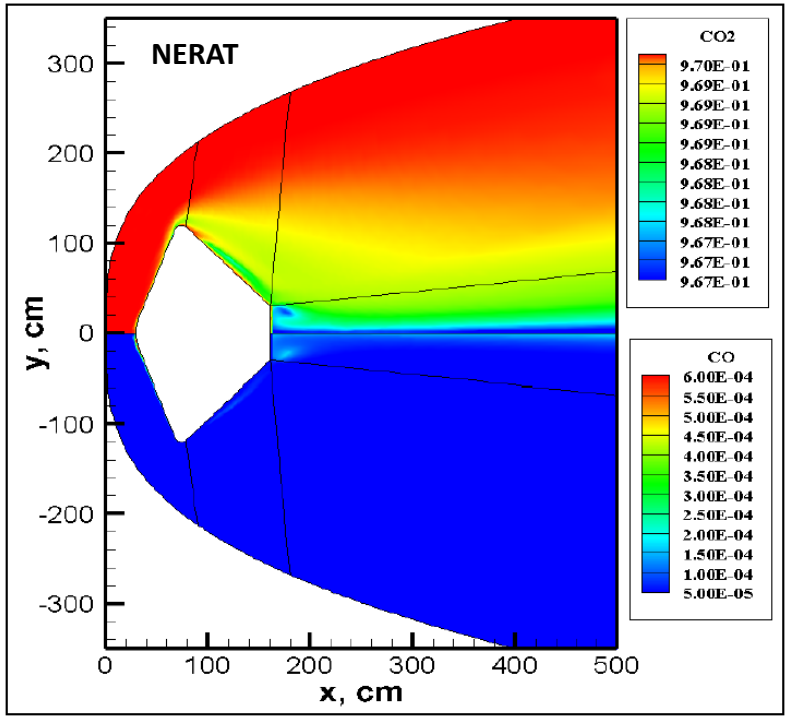




Flowfield rebuilding with NERAT (involved in the Schiaparelli design) – point S2



Translational temperature and longitudinal velocity distribution

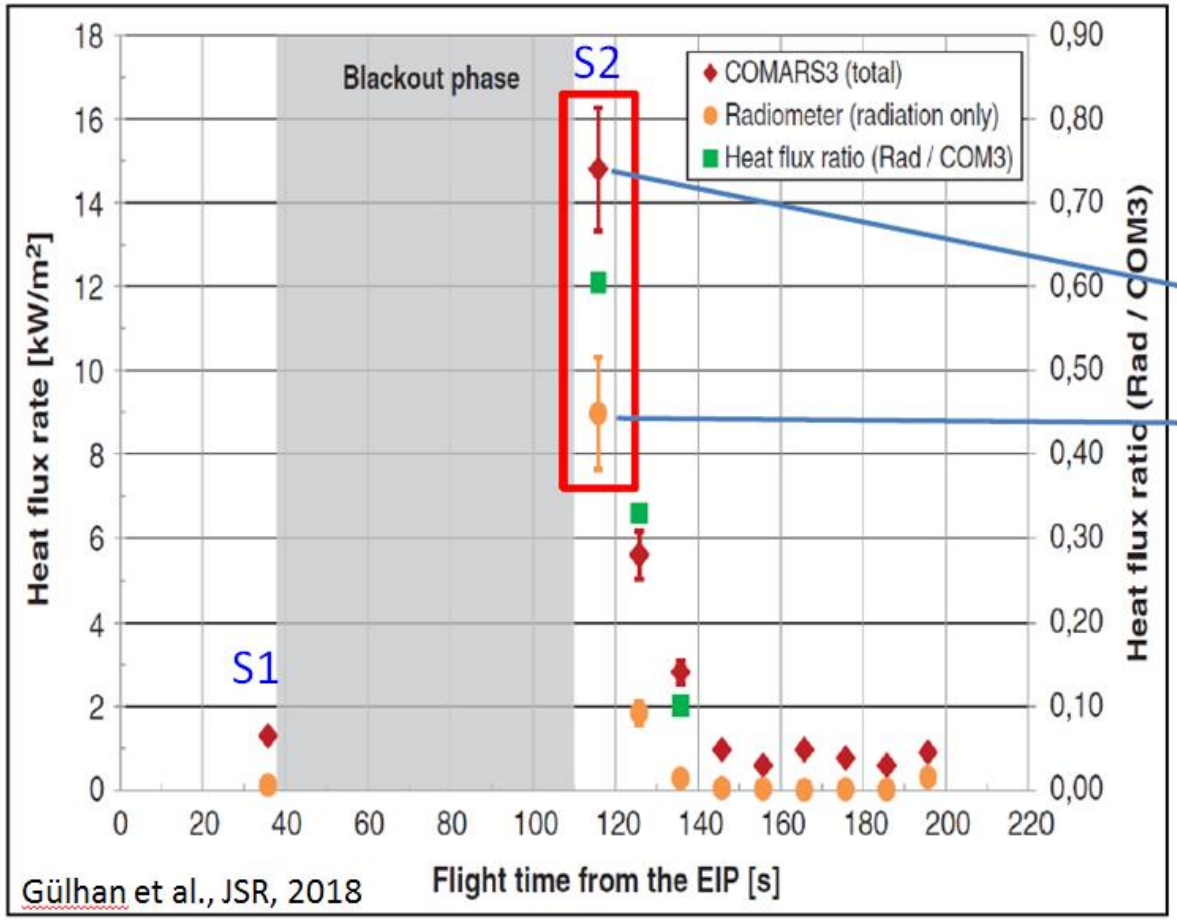


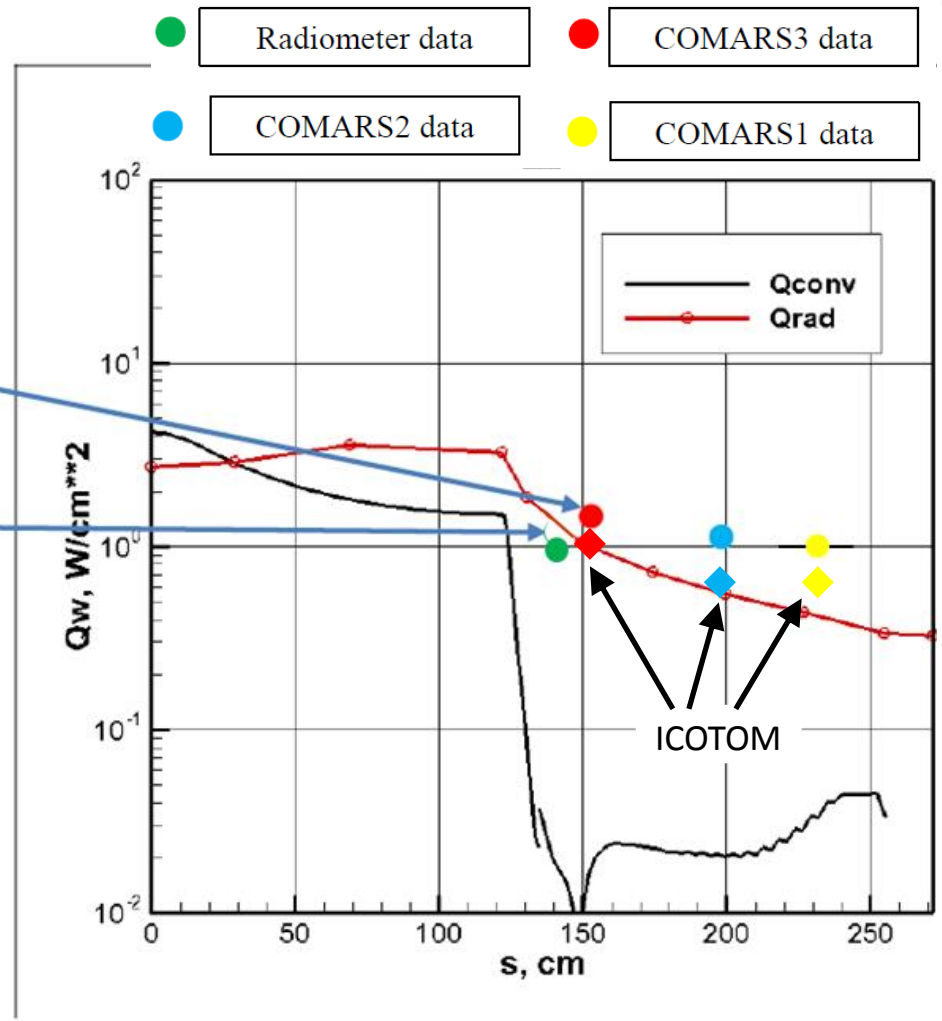
CO2 and CO molar fractions

- Catalytic/Non catalytic: no significant influence of the catalycity on the heat fluxes
- Satisfying estimation on the total radiative flux density compared to full radiometer flight data
- Strong underestimation of the convective flux density: disagreement with COMARS fluxmeters (about one order of magnitude)

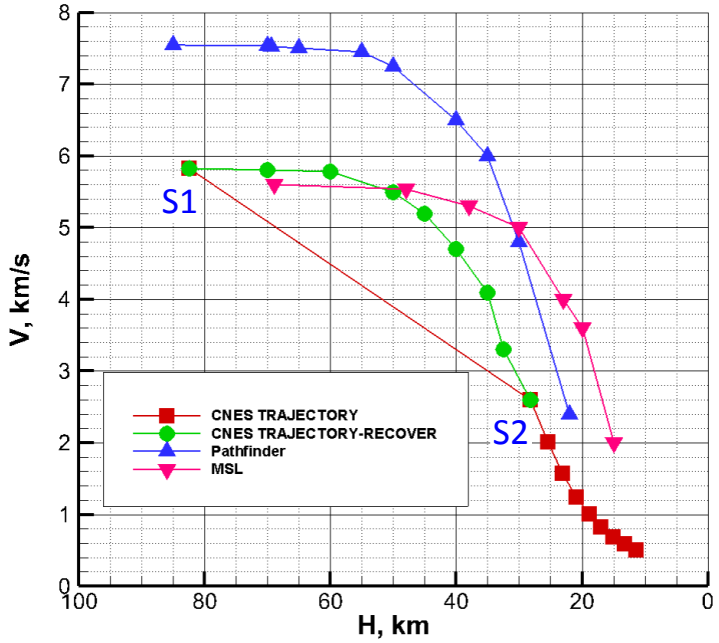
6. Flowfield (NERAT)

Radiative and Convective flux densities (S2)





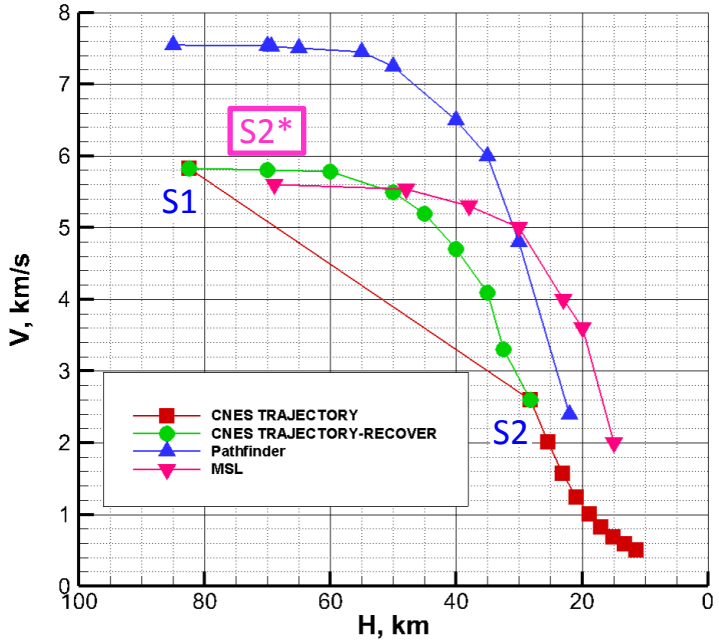
Prediction during the blackout: trajectory rebuilding



№	H, km	V_∞, km/s	ρ_∞, kg/m^3	p_∞, Pa	p_∞, erg/cm^3,	T_∞, K
1	82,467	5,82938	5,092E-06	0,16	1,6	165,5
2*	70,000	5,80000	2,500E-05	0,75	7,5	166,8
3*	60,000	5,78500	8,200E-05	2,1	21,	169.2
4*	50,000	5,50000	2,500E-04	8,2	82,	178,3
5*	45,000	5,20000	5,400E-04	17	170,	180
6*	40,000	4,70000	7,700E-04	25	250,	183
7*	35,000	4,10000	9,500E-04	33	330,	187
8*	32,500	3,30000	1,150E-03	49	490,	189
2	28,202	2,59541	1,542E-03	56,56	565,6	191,58

6. Flowfield (Nerat): towards radiation prediction

Prediction during the blackout: trajectory rebuilding



№	H, km	V_∞, km/s	ρ_∞, kg/m^3	p_∞, Pa	p_∞, erg/cm^3	T_∞, K
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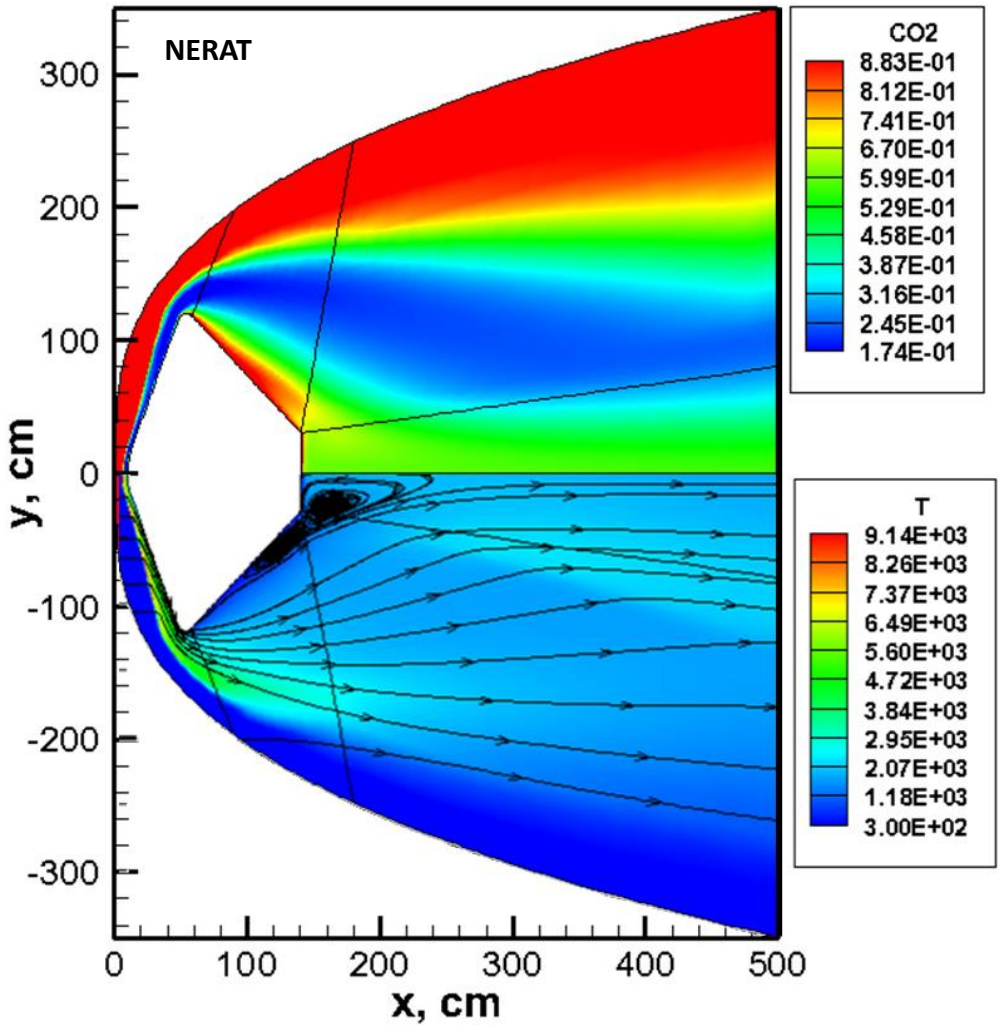
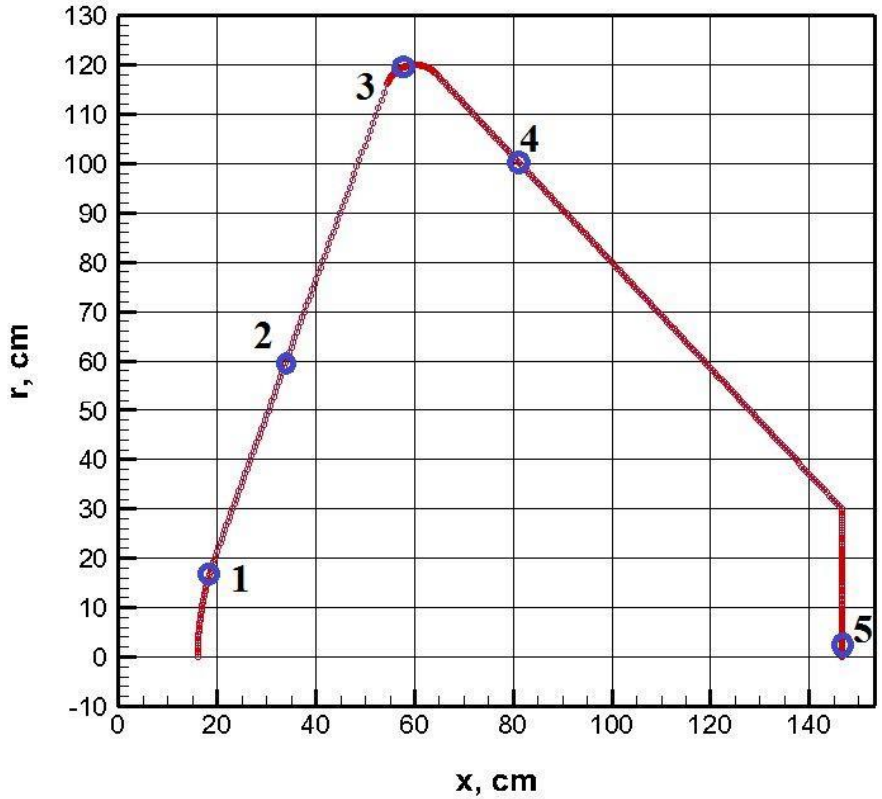
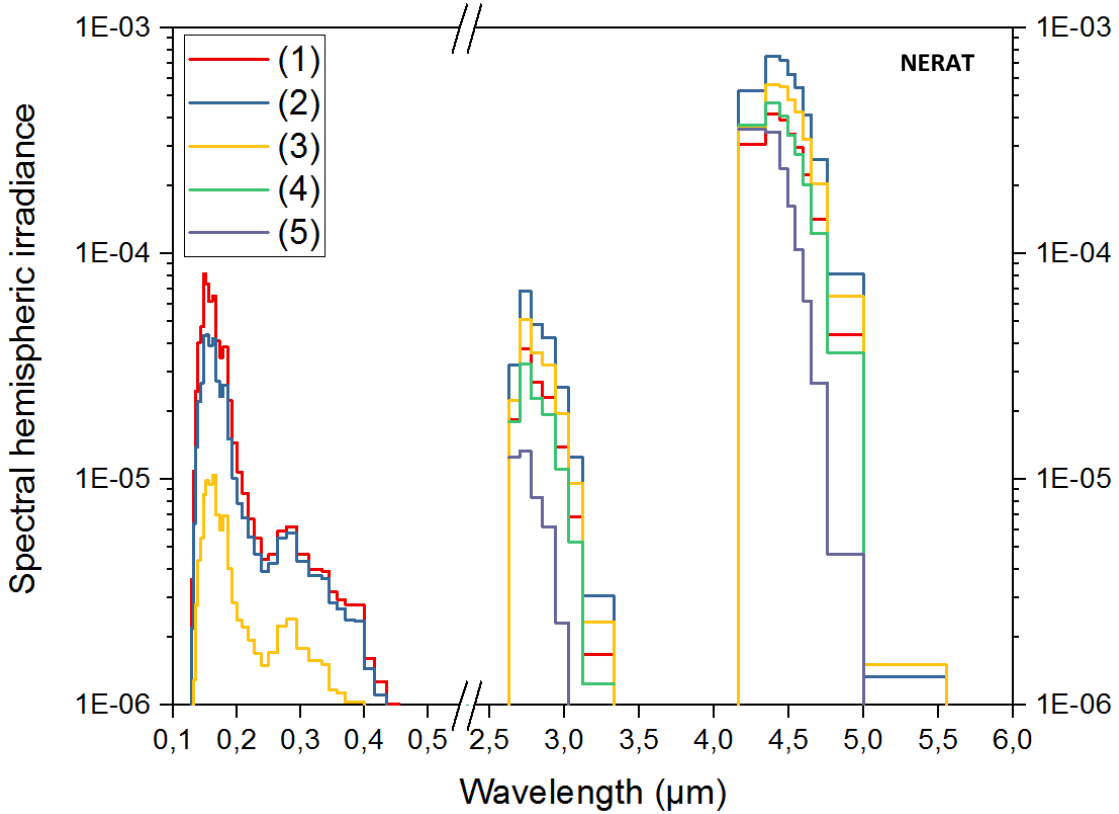


Prediction during the blackout : Spectral results (S2*)





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6. Summary, Conclusions and Outlooks

- Calibrated ICOTOM flight measurements are available.
- Documentation of CO_2 plasma experimental database is in progress.
- Improvements of chemical kinetics and radiative model of CO_2 infrared radiation were done.
- Three different codes are rebuilding the aerothermochemical environment
  - Different levels of complexity towards the assessment of non-equilibrium radiation on the backshield
- First comparisons between preliminary calculations and flight data show differences
  - Moderate about the ICOTOM and total radiative flux measurements
  - Critical about the COMARS fluxmeter measurements

- 3D calculations taking into account the probe attitude
- Code validation (flow, chemistry, radiation) in the ICOTOM collection cone. Prediction on the whole hemisphere.
- Reduced CR implementation
- Narrow band model for CO_2 radiation
- Experiment rebuilding

- Open final meeting (beginning of 2020)

ACKNOWLEGMENTS

- CNES (André Dubus) for the financial support of the activity
- Ali Gülhan and the DLR team for the ICOTOM calibration and integration
- ESA, TAS-I, DEIMOS for the post-processing of flight data
- Amelia for the attitude reconstruction

Exomars - ICOTOM

REBUILDING OF ICOTOM RADIOMETER DATA DURING SCHIAPARELLI MARTIAN ENTRY

J. Annaloro[1], P. Boubert[2], A. Bultel[2], M.C. Druguet[3], E. Duffour[4], P. Hébert[1], M. Jacquot[2], V. Lago[5], M. Lesage[2], S. Menecier[4], P. Omaly[1], F. Perisse[4], N. Rembaut[5], P. Rivière[6], A. Soufiani[6], M. Spel[7], D. Vacher[4], S. T. Surzhikov[8] , D. Yatsukhno[8]

[1] CNES [2] CORIA [3] IUSTI [4] Institut Pascal [5] ICARE [6] EM2C [7] R.Tech [8] IPM