Static versus Dynamic Plume Infrared Signature Measurements and Simulations

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Abstract

Knowledge of missile infrared signature (IRS) is required for the design and performance assessment of Missile Warning Systems (MWS). Missile IRS comes mainly from the plume radiation and depends on the rocket motor features as well as the missile altitude, speed and viewing angle with respect to the sensor. The estimation of speed and altitude dependencies requires simulations in order to complete ground detailed measurements. ONERA developed a chain of simulation tools called PRECISE to achieve infrared signature prediction. The multi-disciplinary project SIMBA2 (acronym for Ballistic Missile Signature in French) was setup to validate simulated results by comparison with experimental results.

Several trials were conducted featuring a solid rocket motor inside a supersonic annular free stream, in order to simulate the effect of a Mach 2 flying missile on the plume. The LP13 motor solid propellant contained no aluminum so as to get an alumina particle-free plume. A Medium-Wave and a Long-Wave Infrared (MWIR and LWIR) multispectral cameras and a MWIR spectrometer recorded the trials with and without free stream. In order to pre-calibrate all optical instruments, IRS plume simulations were performed on existing alumina-free plumes:

- Static CRV7-C15: the plume was computed by DLR (German Aeronautic Research Center) with REP code [1] as a NATO test-case [2],
- Dynamic CRV7-C15: the plume was computed by ONERA with REP code with a 256 m/s free stream as a NATO test-case [3],
- Static "Alumina-Free plume": the plume was computed by ONERA with CFD code CEDRE [4] for another motor, with the same propellant composition as LP13 motor.

The paper will present the chain of simulation tools and the simulated results for all three plumes. Then the experimental setup will be described and the IR measurements will be compared, first against each other, then against the simulated results. The discrepancies will be discussed. Finally, perspectives on SIMBA2 project will be drawn.

1. Introduction

Infrared space surveillance sensors are the most effective systems to detect and track proliferating ballistic missiles during their boost phase. These sensors have to be designed and optimized upon realistic infrared signatures of rocket plumes. The lack of observations in operational conditions leads to the use of simulations. ONERA developed a chain of simulation tools called PRECISE to achieve infrared signature prediction. The multi-disciplinary project SIMBA (French acronym for Ballistic Missile Signature) was setup to validate the simulated results from PRECISE by comparison with experimental results [5].

Project SIMBA2 has started in 2021 for 4 years to study supersonic reactive and turbulent plumes for signature applications. It is divided in two main parts. The first part deals with the study of post-combustion (reheat) as a function of altitude and speed. It will feature trials in wind tunnels and in a vacuum tank, with corresponding LES and RANS simulations. The second part will tackle the problem of the plume in rarefied atmosphere, with chemical and radiative disequilibria. Dedicated simulation tools will be developed and tested.

Project SIMBA2 first experiment took place in September 2021 at ONERA center of Fauga Mauzac (south-west of France) and aimed at investigating the impact of free-stream velocities on plumes. Several trials were conducted featuring a solid rocket motor inside a supersonic annular free stream, in order to simulate the effect of a Mach-2 flying missile on the plume. The LP13 motor propellant contained no aluminum so as to get an alumina particle-free plume. A Medium-Wave and a Long-Wave Infrared (MWIR and LWIR) multispectral cameras and a MWIR spectrometer recorded the trials with and without free stream. In order to pre-calibrate all optical instruments, three IRS computations were performed on alumina-free plumes available at ONERA. The RANS (Reynold-Average Navier-Stokes) and LES (Large-Eddy Simulation) simulations corresponding to the SIMBA2 free-stream trials will be performed later in 2022: the results and their comparison to the measurements will be published in a future paper.

This paper will first present the chain of simulation tools and the simulated results for all three plumes in section 2. Then the experimental setup will be described and the IR measurements will be presented and compared, first against each other in section 3, then against the simulated results in section 4. The discrepancies will be discussed. Finally, perspectives on SIMBA2 project will be drawn.

2. Infrared Signature Plume Simulations

2.1 Simulation chain PRECISE

The infrared signature (IRS) modelling of rocket plumes is a challenging problem involving rocket geometry, propellant composition, combustion modelling, trajectory calculations, fluid mechanics, atmosphere modelling, gas and particles radiative properties, and radiative transfer through the atmosphere. ONERA developed a chain of simulation tools in order to achieve the infrared signature prediction of rocket plumes. This chain, named PRECISE (Plateforme de Recherche pour l'Evaluation de la CInématique et des Signatures d'Engins), encompasses several in-house codes: first, COPPELIA is a thermodynamic equilibrium code that computes the motor specific impulse, the temperature, the gaseous species composition, and the species in condensed phase, such as alumina and soot particles, in the combustion chamber as a function of the propellant composition and the motor chamber pressure. The chamber temperature, pressure and gaseous and particle composition, the rocket speed, altitude and geometry are used to initialize ONERA Computational Fluid Dynamics (CFD) code CEDRE for the plume flow field computation. CEDRE [4] is a multiphysics computational tool for numerical simulation in the field of energetics, with particular emphasis on propulsion applications. The aerothermochemical cartography of the plume computed by CEDRE is transposed on a structured mesh for the last step of the modelling chain: the radiative transfer computation. Our infrared signature computation tool, named SIR, takes as input the pressure, temperature, mass fraction of H_2O, CO_2, CO, HCl, alumina and soot particle density and temperature. It can perform radiative transfer computation in a hot non-scattering medium with either a line-by-line model or a statistical narrow band model called RGM3000 [6][7]. The scattering media are dealt with using the SHDOM solver [8].

2.2 IR signature of alumina-free plumes for pre-calibration

In order to pre-calibrate all optical instruments, IRS plume simulations were performed on alumina-free plumes available at ONERA:

- Static CRV7-C15: the plume was computed by DLR (German Aeronautic Research Center) with REP code [1] as a NATO test-case [2],
- Dynamic CRV7-C15: the plume was computed by ONERA with REP code with a 256 m/s free stream as a NATO test-case [3],
- Static "Butalite motor": the plume was computed by ONERA with CFD code CEDRE [4] for another motor, with the same solid propellant composition as LP13 motor.

CRV7-C15 pressure ratio Pch/Pexit is about 40, while "Butalite motor" is 10.7, and LP13 is expected to be about 8.8. "Butalite motor" thrust is about 3270N, while LP13 is expected about 880N. Figure 1 presents the temperature profiles on the centerline of each plume. The "Butalite motor" nozzle seems to be almost adapted to the ambient pressure: very small recompression cells are visible by comparison to the static and dynamic CRV7-C15 plumes. The maximum temperature at 2m from the nozzle, visible mainly for the "butalite" and the static CRV7-C15 plumes, is characteristic of the reheat phenomenon: the rich mixing ratio leads to unburnt species in the plume that burns when mixing with atmospheric oxygen.

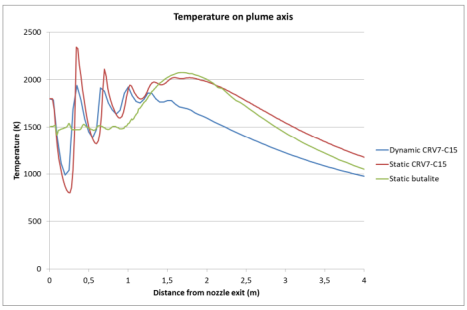

Figure 1 : Comparison of temperature centerlines for each available alumina-free plume

Spectral intensities for the whole plumes, seen from the side (90° from the motor front view), with no atmospheric propagation (source intensity), were computed in Short-Wave Infrared (SWIR, 0.9-2.5 µm), Medium-Wave Infrared (MWIR, 2.5-5 µm) and Long-Wave Infrared (Long-Wave Infrared), which correspond to the spectral bands of the optical instruments used during the trials. The computation was performed using the statistical narrow band model RGM3000 based on Curtis-Godson approximation [9], which takes into account the spectral correlations in case of multiple layers of gas with different physical conditions. Voigt line profiles inside a narrow band are also considered using the empirical formulation of [10], where a Doppler mean broadening [11] in a narrow band is combined to the Lorentz mean broadening. The radiative species considered are H_2O, CO_2, CO and HCl. Results are presented on Figure 2, first in wavelength (µm), then in wavenumber (cm^{-1}) on MWIR band. We can notice that static CRV7-C15 plume intensity is globally higher than the dynamic plume for the same motor. The static butalite plume intensity is higher than CRV7-C15 plumes intensities, but the spectrum shape is a bit different around 3700 cm^{-1}.

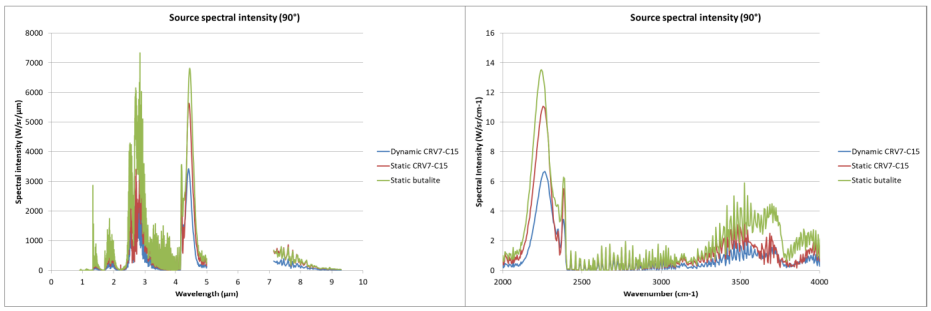

Figure 2 : (left) Source spectral intensity in wavelength (in µm), (right) same in wavenumber (cm^{-1}) on spectral band 2.5-5 µm (MWIR)

3. Experimental campaign: LP13 motor in an annular free stream

3.1 Trial setup

In order to simulate the effects of speed on the plume, a specific setup was developed by the Propulsion Laboratory of ONERA in 2014. A wind tunnel creates an annular free stream around the bottom of a solid propellant motor. The blowing machine is fed by three pipes (1). Pressurized air is stilled in a still room (2) where pressure can be adjusted, then exits through the annular convergent (3) and the neck which has an inner diameter of 100mm and an outer diameter of 112 mm (4).

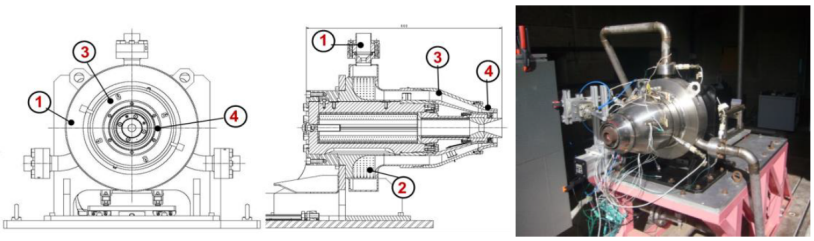

Figure 3 – Annular free stream generator

The LP13 motor used for this trial will also be used in a future campaign in a vacuum tank in order to simulate and analyze altitude effects on the plume. The nozzle neck diameter is 28.2 mm, and the nozzle exit diameter is set to 40 mm for this trial. The propellant is a butalite that was made by ONERA: 82% PA (perchlorate d'ammonium), 11% PBHT (polybutadiène hydroxytéléchélique). The chamber pressure is about 11.5 bar and the nozzle exit pressure is 1.38 bar, which gives an under expanded jet plume.

Three trials were performed:

- trial #1 on September 15th 2021: with free stream, Mach 2
- trial #2 on September 23rd 2021: no free stream
- trial #3 on September 29th 2021: with free stream, Mach 2

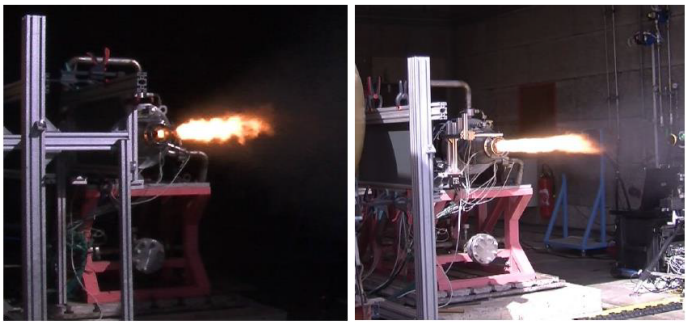

Figure 4 : (Left) Trial #2: no free stream, (Right) Trial #3: with free stream

Figure 5 compares the pressure evolutions during every trial. Trials #1 and #3 (labelled respectively 20 and 22 on the figure) are almost identical, except for the end of the combustion. Those trials are reproducible. Trial #2 (labelled 21) exhibits a slightly lower pressure: this trial was not reproducible, which is a shame since it is the only trial recorded without free stream.

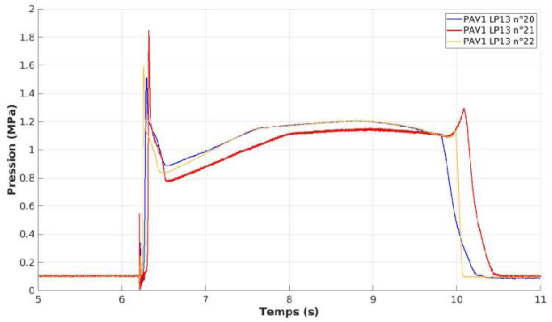

Figure 5 – Comparison of pressure evolutions in the motor chamber for every trial

3.2 Optical measurements

Four cameras and one spectrometer were used during the campaign:

- GEVcam: SWIR camera on spectral band 0.9-1.7 µm. This camera malfunctioned: no measurements were exploitable.
- NOXANT: MWIR camera on spectral band 2.5-5µm. Horizontal Field-of-View (HFOV)=10°
- MWIR-XS: MWIR multispectral camera (4 bands) on spectral band 2-5µm. HFOV=64°
- SC2: LWIR multispectral camera (4 bands) on spectral band 7.2 – 8.5 µm. HFOV = 38°
- MicroSPOC: MWIR spectrometer on spectral band 2.5-5 µm. HFOV = 0,6°

Instruments were set up on a turret at the top of a mast towering up to 2.5m (see Figure 6). The distance between the optics and the nozzle exit plane was 2.6m.

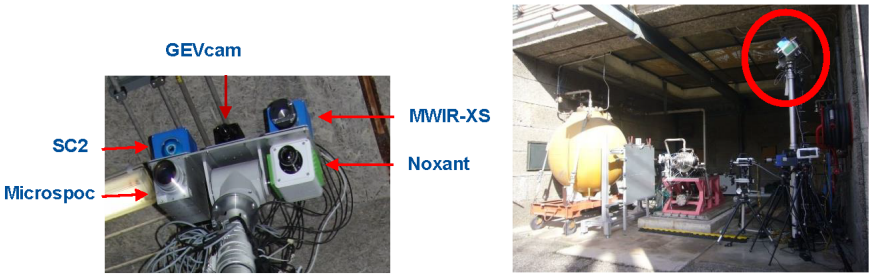

Figure 6 : Optical instruments setup

The results presented on Figure 7 are contrast radiances: the radiance measured before the trial was removed to the following images. Therefore, radiance is zero before the plume is fired. Intensities on Figure 8 are calculated by summing pixels with plume radiance, then multiplying by the pixel size in the plume plane. Results are presented for trials #2 and #3: results for trial #1 are almost identical to trial #3. Images on Figure 7 were acquired 3.5s after the fire start.

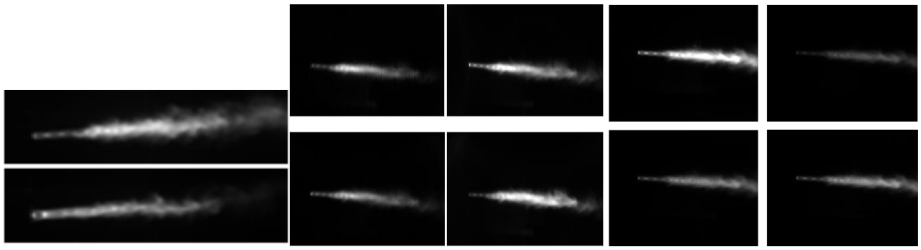

Figure 7 : Left: Panchromatic camera Noxant 2.5-5 µm (top: no free stream, bottom: with free stream)
Middle: Multispectral camera MWIR-XS 2-5 µm
Right: Multispectral camera SC2 7.2 – 8.5 µm

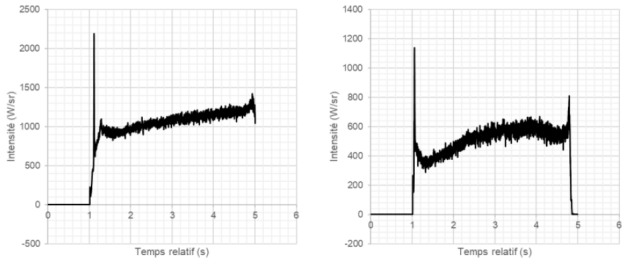

Figure 8 – Intensity evolution (calibration beginning 1s before trial start), measured by Noxant camera.
Left: trial #2, right: trial #3.

We can see on Figure 7 that the plume seems longer without free stream. At least four recompression cells are visible on several spectral bands. Comparing Figure 8 and Figure 5 shows that the intensity evolution is well correlated to the pressure chamber evolution. Intensity for the static trial (#2) is higher than for the dynamic trial (#3) on Figure 8 and on Figure 9 , such as it was observed for CRV7-C15.

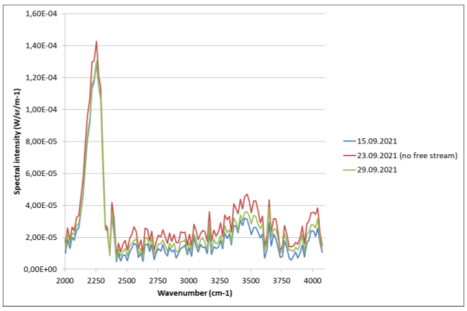

Figure 9 : Microspoc measured spectra on 2,5 – 5 µm (red: no free stream, blue/green: with free stream)

For cameras with spectral bands inside Microspoc spectral band, consistency between measurements can be assessed. On Figure 10, Microspoc measurements during trial #2 were spectrally integrated over one sub-band of MWIR-XS camera, and the measured radiance by MWIR-XS was spatially integrated over the Microspoc FOV. There is an excellent agreement between both inferred intensities, which means that both measurements are consistent. This excellent consistency can be found for every sub-band of MWIR-XS inside Microspoc spectral band and for the Noxant camera, for every trial.

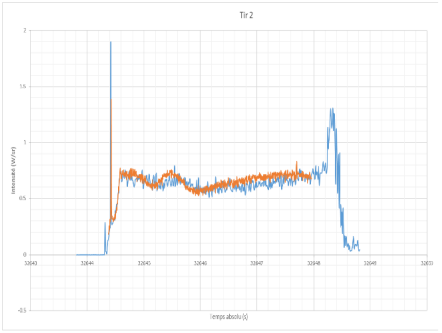

Figure 10 : Comparison of the spectrally integrated Microspoc intensity (orange) and the intensity of the MWIR-XS camera integrated in the Microspoc FOV (blue)

4. Comparison between experimental results and simulated results for precalibration

4.1 Comparison with MicroSPOC spectra

The spectral intensity measured in Microspoc FOV (2.6 cm diameter at 52 cm from the nozzle exit plane) was compared to the simulated intensity in the same FOV for all three plumes described in 2.2, taking into account the atmospheric propagation along the 2.6m distance between the sensor and the plume. The simulated results were averaged over 15 cm^{-1} in order to get a spectral resolution closer to Microspoc measurements. Figure 11 shows quite a good agreement between the measurements and CRV7-C15 simulations (left graph) and "butalite motor" simulations (right graph), for the spectrum shape and the intensity levels, even though the simulated plumes do not correspond to the measured ones. This may be explained by the fact that Microspoc Field of View is very small and covers a small part of the plumes where similar phenomena occur. Regarding the static / dynamic trends, the same evolution can be noticed for CRV7-C15 and LP13: intensity is slightly higher in static mode, probably

because the plume is a little bit wider without free stream. The spectral shape of the "butalite motor" plume is closer to the LP13 measured spectrum, which is consistent with the propellant being the same for both motors.

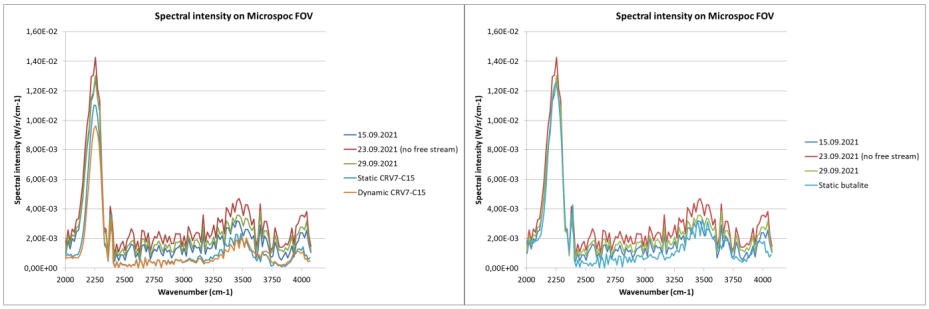

Figure 11 : Comparison of averaged spectral intensities measured by Microspoc for every trial with simulated intensities in Microspoc FOV for each of the three plumes (CRV7-C15 on left, "butalite" plume on right)

4.2 Comparison with intensities from camera radiance images

Intensities such as presented on Figure 8 were issued from images of every sub-band of the multispectral cameras and from the panchromatic camera Noxant. The localization of the corresponding spectral bands on the plume spectrum is presented on Figure 12. MWIR-XS-1 spectral band is outside plume gas emission, in order to record the possible particle radiation. The other spectral bands sample the gas emission spectrum.

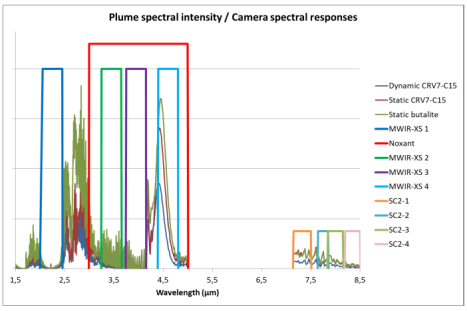

Figure 12 : Localization of the spectral bands of every panchromatic and multispectral camera with respect to the spectra of the simulated plumes (from Figure 2 left)

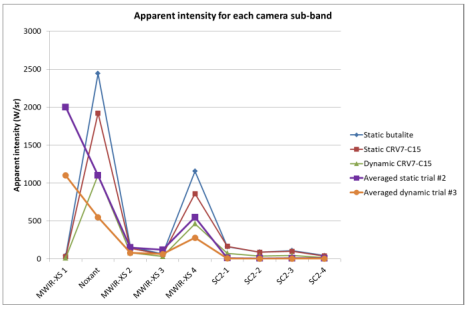

Figure 13 : Comparison of measured and simulated apparent intensities for each camera sub-band

Simulated apparent intensities were computed from the spectra presented on Figure 2 but taking into account the atmospheric transmission on the 2.6 m path from the plume to the sensors, then integrating on the spectral band of each camera. Figure 13 compares the simulated apparent intensities for each plume with the averaged measured intensities for the static trial #2 and the dynamic trial #3 of LP13 motor. Noxant and MWIR-XS-4 show higher intensities because their spectral bands encompass the CO2 emission peak at 4.3 µm. Static plume intensity is always higher than dynamic plume intensity for the same motor, whatever the spectral band. The most striking discrepancy comes from MWIR-XS-1: the simulated spectra exhibit almost no radiation in this spectral band, while the measurements show a high intensity. Since no significant gas emission is expected in this area, a possible explanation is particle radiation. Since the fired motor was alumina-free, those particles may be soot particles, which were not modeled in the simulated spectra. Soot particles have a black body emission which is prominent in SWIR due to their temperature, which is why they have less impact in the other camera sub-bands in MWIR. On Figure 11, the "offset" of Microspoc measurements with respect to the simulated spectra could be due to the soot particle blackbody radiation. When simulating the LP13 plume, care should be taken in the modeling of soot particle emission.

One of the goals of the precalibration simulations was to estimate the radiance levels to be expected by the instruments. However, no simple rule of thumbs can be applied to estimate radiance levels of alumina-free plumes from one motor to another. Post-trials analyzes such as presented on Figure 14 enable to relate approximately LP13 intensities to CRV7-C15 (factor ~2/3) and "butalite motor" (factor ~1/2) intensities, but there are no straightforward relationships with the motor main characteristics such as thrust or pressure ratios.

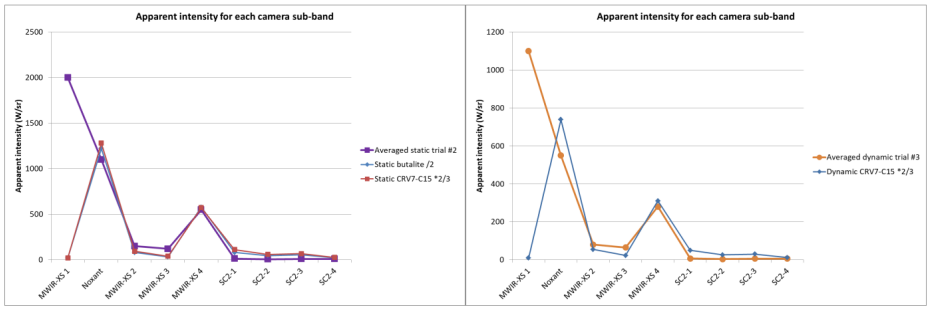

Figure 14 : Proposed approximations from simulations

5. Conclusion and perspective

We presented here spectral and imaging measurements recorded during the trials of an alumina-free motor LP13 in an annular free stream to simulate Mach 2 flying missiles. These measurements have been compared to simulations performed before the trials on available alumina-free plumes (CRV7-C15 and "Butalite motor") to precalibrate the optical instruments for the campaign. The MWIR spectrometer measurements already show a good agreement with the simulated results on a small FOV. The comparison of intensities on the whole plume shows greater discrepancies because the LP13, CRV7-C15 and "Butalite motor" plume shape, size and structure are

different. No simple relationship was found between plume intensities and motor characteristics. One of the camera sub-band seems to show evidence of soot particles, which were not modeled in the simulations.

In 2022, RANS and LES simulations of LP13 trials will be performed, then comparisons will be made between the dedicated simulations and the measured images and spectra presented here, hopefully with yet a better agreement. These measurements and simulations will be used to validate the speed dependency at ground level. Other campaigns and measurements will be performed in a vacuum tank in order to validate the altitude dependency. The missile infrared signature model will then be compared to missile observations in flying conditions (variable speed and altitude) during NATO campaign.

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