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**DESIGN OF A SIMULATOR FOR THE FUEGO
INSTRUMENT OPTICAL SYSTEM:
AN APPLICATION TO THE FEASIBILITY PHASE**

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ABSTRACT - This article presents the numerical simulator developed in the scope of the European Fuego project. After a brief introduction of this project and the mission, the assumed instruments are also briefly described. The simulation tool (called also the simulator) is then presented. The architecture of the programs and their functions are broadly explained. An application example provides information on the concrete use of the simulator.

The purpose of this presentation is to explain the possibilities of the simulator. Although each part of the simulator is described, the theoretical solutions are not closely analysed. The application example shows the wide range of possibilities of the simulator in the scope of fire detection.

1. INTRODUCTION

Presentation

Due to the large amount of forest areas burnt in Europe every year, the fire hazard study is a crucial key for several states of the European Community. As in the other technological domains, the space technologies offer their own solutions for fire fighting. A large panel of studies have proved the possibility of using remote sensing images to detect and process fires [Dozier 1981] [Robinson 1988] [Lee, Tag 1990] [Chuvieco, Martín 1994].

In light of this, the European industrial company INSA (Spain) proposed a space system devoted to the forest fire fighting, named Fuego [Martín Rico, 1996]. In 1996, the European Commission DG-XII agreed to fund a study of the payload for the Fuego mission. Led by INSA, this study is being carried out by an industrial team: Officine Galileo (Italy), Sema Group (France), INTA (Spain) and two Spanish research centres (INIA and CIF).

2. THE FUEGO MISSION

The Fuego instrument is still under construction. Therefore, the numerical values given in this section are not yet completely frozen.

The fires should be detected within the shortest time possible. From the point of view of the fire fighting force, fires should be detected within a delay less than 15 minutes [Gonzalo, Cruz 1997], [Martín Rico, Gonzalo 1997]. The fires to be detected should be greater than 10 m², with a temperature over 500 K. A finer spatial resolution is so required. At nadir, a spatial resolution about for 30 m x 30 m is sufficient. The spatial localisation of the fires needs to be less than 300 m x 300 m (1 σ) at nadir. This accuracy is required by the fire fighting force, in order to take the most adapted path to reach the fire areas. Over this imprecision, it becomes more difficult to access directly and rapidly to the fire areas.

The Fuego mission is designed to take into account all these requirements. It consists of a constellation of mini-satellites. At present, up to nine satellites will compose this constellation. The

orbit of the satellites will be strongly inclined from the equator (47.5°), to obtain a complete coverage of the Mediterranean countries in the optimal revisit times.

The altitude of the satellite is around 600 km. When detecting fires, the possible swath is about 2,500 km. This large swath is required to scan the risky areas when the satellite is off track. To achieve this large field of view, it is possible to turn the camera in the across track direction and to change the attitude of the satellite in the along track direction. The allowed steering angles are about $\pm 60^\circ$ from the nadir. Figure 1 represents the view configuration of one satellite.

Figure 1. Viewing configuration for one mini-satellite. The steering capabilities of the camera allow to scan large areas.

At least two cameras should be used in the satellite to compute the temperature and the size of the fire

- The first camera has a Middle InfraRed (MIR, $3.5 \mu\text{m}$) sensor, due to the emission peak of the fire. This camera has a high spatial resolution. At nadir, this resolution is about $30 \text{ m} \times 30 \text{ m}$. The field of view of this camera is about 5° . The sensor is a line of about 1660 pixels.
- The second camera has a Thermal InfraRed (TIR, $9 \mu\text{m}$) sensor. The spatial resolution is lower than the MIR camera: at nadir, the pixel size is $120 \text{ m} \times 120 \text{ m}$, but the field of view is also about 5° . The sensor is a line of about 420 pixels.

Other cameras could be added in the payload in the visible or near infrared wavelengths. The cloud cover should be analysed in order to scan only cloudless areas.

The fire fighting force needs only to be alerted when a real forest fire is detected on Earth. It is also a necessary requirement to detect false alarms. Merging data from middle infrared and thermal infrared spectral bands seem to be a good solution.

Another functionality of the satellite payload is to supply monitoring images. At the control station, the users can program the scanning of specific burning areas, for monitoring the advancement of the fire. In this case, the wanted images are provided by the MIR camera.

3. THE NUMERICAL SIMULATOR

3.1 The purpose of the simulator

The simulator presented in this article responds to the basic question: is the designed payload able to detect fire? This question implies another one, which may be more useful for the designer: how does the payload digitise the Earth surfaces when fires are located inside them? Due to the physics of the

Earth and the camera systems, these questions are not easy to answer. The simulator helps the designer to solve the main problems, and helps also the designer to achieve one or more solutions

3.2 The organisation of the simulator

The simulator is a chain composed of several isolated modules. These modules are processed in a specific order as shown in Figure 2.

Figure 2. Global organisation of the simulator. Six categories: Phenomena studied, Earth, Atmosphere, the Geometry, the Camera and the Data processing.

The modules are presented now according to their categories.

3.3 The studied phenomena

Due to its open architecture the simulator can process several physical phenomena. In our case, the main phenomenon to analyse is the fire. The corresponding module provides the crucial signals to the rest of the modules. The smoke is also studied to understand and ascertain if its participation is significant in the detection.

3.3.1 The Fire

A lot of studies have been done for the modelisation of the fire [Dozier 1981] [Robinson 1988] [Lee, Tag 1990] [Chuvieco, Martin 1994]. For the Fuego project, the main parameter in describing a fire is its radiance. The Planck's law gives the emitted energy spectrum of a black body (and so the radiance), from its own temperature. It can be written in $W \cdot m^{-2} \cdot str \cdot \mu m$ by:

$$L(\lambda, T) = \frac{c_1}{\lambda^5} \cdot \frac{1}{e^{\frac{c_2}{\lambda T}} - 1}$$

where $c_1 = 1.1905 \times 10^8 W \cdot m^{-2} \cdot str \cdot \mu m^4$ and $c_2 = 1.4385 \times 10^{-2} \mu m \cdot K$. The Figure 3 shows the radiance (in $W \cdot m^{-2} \cdot \mu m$) of several black-bodies. The energy emitted increases greatly, when the temperature increases also. The peak of the Planck's function moves towards the narrow wavelengths.

The radiance spectrum of a fire is not exactly the same as that of the black body due to the absorption and emissivity of the fuel [Palmer 1976]. Fires can be considered as grey body. The spectrum difference between black and grey bodies is assumed constant. In this way, the Planck's law can be applied to grey bodies, and so to the fires. In the same way, this law can be also applied to the Earth's surface, the smoke and the atmosphere.

Figure 3. Examples of radiance spectra. The radiance axis is given in a log-scale. When the temperature increases, the wavelength of the maximum of radiance decreases. The radiance of the Earth's surface is often approximated by a black body at 300 K.

3.3.2 The smoke

At a first glance, the smoke can be modelised as a mask localised over the fires. This mask has two main properties: a transmittance and a radiance. The ground and the smoke can be considered as a radiative source with the radiance:

$$L_{over} = T_{smk} \cdot L_{under} + L_{smk}$$

- L_{under} is the total radiance emitted from the Earth. It includes fire, ground and eventually other phenomena.
- T_{smk} is the transmittance of the smoke. This value is given between 0 and 1. Opaque smoke has a value of 0. No radiance emitted from the ground passes through the smoke. Otherwise, a thin smoke layer will have a transmittance close to 1.
- L_{smk} is the radiance of the smoke. This radiance is not constant in altitude, but in the current model it is assumed as such. The smoke radiance should be less than the radiance of the fire. Also, Planck's law is used to compute the radiance from the temperature.

3.4 The ground

The ground part of the simulator gathers the Earth's physics linked to the ground surface. The global radiance stemming from the ground is created by several phenomena. Inside the simulator, only the ground radiance and the radiance supplied by the reflectance of the Sun over the ground surface are taken into account.

3.4.1 The ground radiance

A first assumption is to consider the ground surface as a black body. Like the fire and the smoke, the Earth has its own emissivity, so Planck's law is not accurately followed. However, for the needs of the current simulator, the approximation of the Earth's radiance computed by the Planck's law is sufficient, particularly for the MIR and TIR spectral bands. Figure 3 displays the radiance law for a black body at 300 K, assumed for an Earth's surface at 27 °C.

3.4.2 The Sun reflection radiance

The Sun irradiates the Earth surface. A large amount of this energy is acquired by the ground and so emitted in the TIR spectral band. The other part of the energy is therefore reflected to the atmosphere: this is the so-called Sun reflection radiance. In typical cases, the radiance provided by the Sun reflection on Earth is weak in the MIR and TIR spectral bands.

3.5 The atmosphere

The signal emitted by the fires can be greatly modified, and occulted if clouds are located over the fires. At the top of the atmosphere, the radiance of the Earth can be approximated by:

$$L_{earth} = T_{atm} \cdot L_{over} + L_{atm}$$

- L_{over} corresponds to the Earth's radiance just over the smoke.
- L_{atm} is the radiance of the atmosphere, observed at the top of the atmosphere, at 150 km. This parameter depends mainly on the atmospheric components. The radiance of the clouds is included in this parameter.
- T_{atm} is the transmittance of the atmosphere. As in the previous parameter, this value depends on the atmospheric components. The high transmittance of 1 is never reached in the MIR and TIR spectral bands, due to the intrinsic absorption of the atmosphere.

To obtain accurate simulations, the atmosphere model used in the simulator is supplied by the Modtran software. This tool allows the user to configure the atmospheric model according to his requirements [Kneizys *et al.* 1988] [Ottle, Stoll 1993] [Desjardins *et al.* 1990]. This tool also manages cloud cover, and then allows the user to analyse its impacts on the signal detection. Many case studies can be carried out.

3.6 The viewing configuration

The view of the Earth by the satellite is already shown in the Figure 1. Each satellite of the constellation is able to modify its attitude, in order to perform the image acquisition on the desired Earth areas. The images acquired in such conditions are distorted: the pixels of the sensors correspond to rectangles (or squares) and are projected onto the sphere of the Earth.

At nadir the spatial resolution of the MIR camera is about 30 x 30 m². With a roll or pitch angle of 60 °, the resolution increases over 160 x 160 m². The MIR camera has one long line of 1,660 pixels.

The current module performs the projection of each pixel of the camera on the Earth surface. Each corner of one pixel is geo-localised on ground. The algorithm cannot be described here due to its length [Larson, Wertz 1992].

3.7 The on-board optic

The optical properties of the cameras are modelised. In this part, two functions are simulated: the conversion of the Earth radiance into irradiance and the transfer function. The noises from parasite lights, noises generated by temperature of the optical package (frame, locking system, etc.) are not yet integrated in the simulator.

3.7.1 The radiance to irradiance conversion function

For the camera device, the irradiance of the focal plane is required to be computed. This irradiance is used to convert photon energy into electron energy (see Figure 3.8).

A complex optical instrument with many lens, mirrors, etc. can be modelised by one unique theoretical lens, as shown in Figure 4. The beam corresponds to the optical path (or solid angle) of one pixel. The notations are:

- α : off-axis angle of the beam. This is the inner angle for the beam, corresponding to one pixel, inside the optical system. This angle is considered as weak, so it is often neglected in the computations. This is not the steering angle of the camera;
- f : focal length, called also the f-stop;
- Φ : theoretical aperture of the optical system. This aperture should be the diameter of the entrance lens;
- H : distance between the Earth observed area and the camera. If the view is off-nadir, this value is larger than the altitude;
- $\Delta\Omega$: The solid angle of the beam.
- δS : focal array reached by the beam. This is the area of one pixel.
- ΔS : ground array creating the beam. This is the projection of one pixel on the Earth.

Figure 4. Model for the optical instrument of the camera

The model used for simulating the optical instrument is given by [Avignon *et al.* 1994]:

$$E_{[J/s/m^2 \text{ or } W/m^2]} = L_{[J/s/m^2 \text{ str}]} \times \frac{\pi}{4} \times \left(\frac{\Phi_{[m]}}{f_{[m]}} \right)^2 \times \tau_{opt} \times \cos^4 \alpha.$$

The irradiance E can be easily computed from the input radiance L . The term $\cos^4 \alpha$ can be left out in the most common computations because α is weak. τ_{opt} is the transmittance of the optical system.

3.7.2 The transfer function

Every acquisition system, like the optic one, has its transfer function. The corresponding band-pass filter produces a smoothing of the details of the images. The effect of the transfer function on the image can be computed via the Point Spread Function (PSF) [Jain 1989]. Generally, the PSF has a limited spatial extension. In terms of pixels, this function can be given by little windows, say 3×3 or 5×5 pixels. The values of this matrix are computed by the optical system designers. A convolution of the image with the PSF window can be computed by:

$$out(l, c) = \sum_{l_psf} \sum_{c_psf} psf(l_psf, c_psf) \cdot in(l - l_psf, c - c_psf),$$

where in and out are the input and output images. Each pixel of the input image is convoluted with the PSF window.

3.8 The on-board electronic

The electronic device converts the photonic energy into digital numbers. The structure of current module is subdivided into three main components: the sensor, the amplifier and the Analog to Digital Converter (ADC). A crucial point of the simulator is to process the noises ($\langle I' \rangle^2$) of the complete system, in parallel with the image (the signal $\langle I' \rangle$). The main electronic noises are considered separately for the sensor, the amplifier and the A-D Converter. The readout of the electronic and the A-D conversion are also simulated in order to be most realistic as possible.

The table below gathers the three physical models used to simulate the signal in the acquisition chain [Holst 1996] [Wolfe, Zissis 1993].

Device name	Physical model
Sensor	$\langle v[V] \rangle = \frac{q}{C} \times \eta_{[e^- \text{ ph}]} \times E_{[ph \cdot m^2 \cdot s]} \times \Delta t_{[s]} \times A_d[m^2]$ $E_{[ph \cdot m^2 \cdot s]} = \frac{\bar{\lambda}}{hc} E_{[W \cdot m^2]} \text{ irradiance in photons}$ <p> $q \cong 1.6021892 \cdot 10^{-19} \text{ C}$: Electron charge. $h \cong 6.626176 \cdot 10^{-34} \text{ Js}$: Planck's constant. $\bar{\lambda}$: central wavelength of the sensor. A_d : area of one pixel element. C : Capacity of the sensor. η : quantum efficiency of the sensor. Δt : Integration time </p>
Amplifier	$\langle V[V] \rangle = v[V] \times Gain[V/V] + Bias[V]$ <p> $Gain$: Gain of the amplifier $Bias$: Bias of the amplifier </p>
A-D Converter	$\langle DN \rangle = \text{Int} \frac{V[V] - V_{\min}[V]}{V_{\max}[V] - V_{\min}[V]} 2^N$ <p> $V_{\min}$, $V_{\max}$: the minimum and maximum tensions N : number of level for the quantization </p>

The table below gathers the noise models used in the simulator.

Noise sources	Noise model
Sensor	$\langle \text{signal} \rangle_{e^-}^2 = \eta_{[e^- \text{ ph}]} \times E_{[ph \cdot m^2 \cdot s]} \times \Delta t_{[s]} \times A_d[m^2]$
Dark current	$\langle \text{dark current} \rangle_{e^-}^2 = \frac{I_{obx} \Delta t}{q}$ <p>I_{obx} : dark current</p>
Reset noise	$\langle \text{reset} \rangle_{e^-}^2 = \frac{kTC}{q^2}$ <p>T : Temperature of sensor at the focal plane.</p>
Amplifier	The noises of the amplifier depend on the components chosen. These noises are supplied by the electronic system designers.
A-D Converter	$\langle \text{ADC} \rangle_{e^-}^2 = \left(\frac{C}{q} \times \frac{V_{\max} - V_{\min}}{2^N \sqrt{12}} \right)^2$

3.9 The detection algorithm

At present, the detection module is simulated by a simple algorithm, because the Fuego system is still under development. Merely the MIR Digital Number (DN) image is used to perform the detection. A DN threshold depending on the DN background classifies the fire pixels from the background. For the pixels detected as fires, the resulting information is the position (in latitude, longitude) of these pixels. A map of the fires is also provided to have their spatial extensions.

In the future, in the scope of the technical specifications of the Fuego project [López *et al.*, 1997], the detection algorithm will product a more complete information set for one fire: the location, temperature and the percentage of fire inside one pixel. A merge of the MIR and TIR images should be implemented. By using more complex algorithms [Dozier 1981] [Matson, Dozier 1981], more useful information on the fire could be obtained.

3.10 Global remarks

The accuracy of the current models is sufficient for our use. However, it is possible to improve the accuracy of the simulations with more complete models.

The modules of the simulator are created for processing the middle and thermal infrared systems. However, other spectral bands could be processed without changing the whole list of programs.

4. AN APPLICATION EXAMPLE

The current section illustrates the concepts of the simulator defined previously on a simple run. Typical fires must be detected.

4.1 The fires

Each module requires a set of parameters as input. In addition, each module needs as input one or more signals. The fires data correspond to image files, which can be obtained from real maps of fires acquired during experimental missions. However, these data files can be also easily created by drawing them with standard graphics tools, such as Paint Shop Pro or Photo Shop. The two following figures show fires drawn by the user.

Figure 5. A fire image file. Black corresponds to hot fire, while white corresponds to areas without fires. This fire is defined as several localised little hot spots.

In order to allow the simulator to process other cases, the spatial resolution of the fires is not fixed. The size of the fires is attached to other parameters, arbitrarily fixed to 3 m x 3 m. In this case, one pixel of the image corresponds to an area of 3 m x 3 m.

Figure 6. Two extended fires. The line corresponds to typical front evolution of fires. Hot fires are also drawn in the images.

For each digital number (given in the range from 0 to 255) of the image, a temperature is associated by a linear law, in range from 500 K to 1 000 K for example.

4.2 The results

Due to its structure, the user is able to follow the computations at every step of the simulation chain.

- The user can check the input parameters of all the modules of the chain.
- The programs can be stopped momentarily in order to understand the current results
- The output data of every program can be displayed. The user can see clearly the evolution of the signal (fires) in this chain.
- The log file provides useful runtime information. This allows errors to be found easily

The simulator can generate images of the fires (see Figure 7 and Figure 8) at the output of the electronic device. These images represent the view of the TIR and MIR cameras when seeing the fires on Earth. Four images are generated: the signal and the noise images of the TIR and MIR cameras. In the following images, only the signal images are presented. Figure 7 displays the MIR image acquired of the fires.

Figure 7. View of the Earth with the MIR camera. Signal only.

In our example, the spatial resolution is about 40-50 m x 40-50 m, but in this picture, the resolution is degraded because the figure is adapted to the length of the paper. The Figure 8 shows how the TIR camera observes the same fires.

Figure 8. View of the Earth with the TIR camera. Signal only.

The TIR image is more blurred than the MIR image, because the spatial resolution is less than the MIR. It is about 400 m x 400 m. The image shown in Figure 9 is obtained at the end of the simulation chain.

Figure 9. Detection of the fire.

The resulting image is a classification of the pixels. The black pixels correspond to the fire while the white ones correspond to the background. This application shows the wide range of possibilities of the simulator. The design of a payload system is simplified with this tool. Furthermore, other modules can be added to take into account new phenomena.

5. CONCLUSION

The purpose of the current simulator is to help the design of optical systems in the scope of the Fuego project.

The simulator provides solutions not only for the payload of the satellite, but also for understanding the physics of the Earth. The actual models used in this simulator cover various domains: the **fire**, the **smoke**, the **ground**, the **atmosphere**, the **viewing configuration**, the **optic**, the **electronic** and the **detection**.

The open structure of the simulator allows the user to work on several case studies. For example, if a user is interested by marine studies, he can improve the current system by adding new modules. The older modules, which are not useful for this study (e.g.: the fire module) can be removed from the simulation chain. The programs dedicated to the modules can be written in the language and workshop required by the user.

The simulator currently reaches the space borne systems. There is no basic transformation of the simulator to be applied to air borne systems, if the algorithms used for the cameras are applied with caution. Furthermore, while the system is devoted to simulate the infrared instruments, other spectral bands could be processed without basic modification to the system.

The open architecture of the simulator allows processing of other technological domains: **radars**, SAR, altimeters, etc. An effort has been made to allow processing in these domains without modifying the control panel of the simulator.

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