Nightingale

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1 Introduction

The exploration of Enceladus, Saturn's sixth-largest moon, has revealed intriguing features that have captured the attention of researchers. Enceladus is primarily covered in pristine, reflective ice and exhibits diverse surface characteristics, including ancient craters and tectonically deformed terrain. Moreover, the discovery of active ice geysers, known as cryovolcanoes, by the Cassini spacecraft has raised the possibility of a subsurface ocean and potential for life on this enigmatic moon.

However, investigating Enceladus poses numerous challenges due to the risks associated with landing on a cryovolcano and the harsh conditions of space. Nonetheless, the scientific community remains highly interested in exploring the moon's water reservoirs and searching for signs of life. To accomplish this, the implementation of Nightingale on a spacecraft orbiting Enceladus offers a promising solution. Nightingale's primary objective is to map the moon's surface, providing invaluable insights into its composition and distinct features. By acquiring this data, scientists can enhance our understanding of Enceladus and pave the way for future exploration endeavors.

This article delves into the theoretical variables required for calculating the Signal-to-Noise Ratio (SNR) in the context of Nightingale's operations. Additionally, it provides an overview of the code structure, highlighting the different tabs constituting the graphical interface accessible to users. The Detector Configuration Tab allows customization and optimization of detectors, the Target Configuration Tab focuses on defining target objects or features, and the Instrument Configuration Tab facilitates the setup and configuration of the imaging instrument. Lastly, the Output Tab determines the format and presentation of the final results generated by the code, ensuring easy interpretation and further analysis.

Through the integration of Nightingale and the comprehensive understanding of SNR calculations, scientists can make significant strides in unraveling the mysteries of Enceladus and advancing our knowledge of this captivating moon.

2 Context

Enceladus, the sixth-largest moon of Saturn, is known for its unique characteristics. Covered mostly by fresh, reflective ice, it exhibits a wide range of surface features, from ancient craters to tectonically deformed terrain. The spacecraft Cassini detected active ice geysers, known as cryovolcanoes, on Enceladus, indicating the potential for life beneath its icy shell.

Despite the challenges faced by researchers in exploring Enceladus, such as the risks associated with landing directly on a cryovolcano and the harsh conditions of space, there is a strong interest in investigating the moon's water reservoirs and searching for signs of life. According to current theories, Enceladus's cryovolcanism is fueled by liquid water beneath its icy surface, possibly in the form of a vast subsurface ocean.

To gain a better understanding of Enceladus and prepare for future missions, Nightingale would be implemented on a spacecraft orbiting the moon. Nightingale's purpose would be to map the surface of Enceladus, providing valuable insights into its composition and features. This data would contribute to our knowledge of Enceladus and support future exploration efforts.

3 Study of Theoretical Variables for SNR Calculation

This section delves into the theoretical variables that are essential for understanding the code's calculations and performance evaluation. It explores the concepts and formulas relevant to the detectors and their application in the context of Enceladus.

3.1 Energy per Photon

The energy per photon (E_{photon}) is calculated using the following equation:

$$E_{\text{photon}} = \frac{h \cdot c}{(\lambda_{\text{end}} - (\lambda_{\text{end}} - \lambda_{\text{start}})/2) \times 10^9}$$

where h is Planck's constant, c is the speed of light, and λ_{end} and λ_{start} represent the spectral width end and start values, respectively. The energy per photon represents the amount of energy carried by a single photon at the target wavelength.

3.2 Field of View (FOV) and Diagonal FOV

The Field of View (FOV) is calculated using the equation:

$$\text{FOV} = \frac{\text{pixel\_size} \times \text{nb\_pixel}}{\text{focal\_length}}$$

where pixel_size represents the size of a pixel on the detector, and nb_pixel represents the number of pixels in the detector. The FOV represents the angular extent of the scene captured by the detector.

The Diagonal FOV (FOV_diag) is calculated using the equation:

$$\text{FOV\_diag} = \frac{\text{diagonal\_detector}}{\text{focal\_length}}$$

where diagonal_detector represents the diagonal size of the detector. The Diagonal FOV represents the angular extent of the scene captured diagonally by the detector.

3.3 Omega Diagonal

Omega Diagonal (ω_{diag}) is calculated using the equation:

$$\omega_{\text{diag}} = 2\pi\left(1 - \cos\left(\frac{\text{FOV\_diag}}{2}\right)\right)$$

where FOV_diag is the Diagonal FOV. Omega Diagonal represents the solid angle covered by the Diagonal FOV.

3.4 Radiant Flux on Detector

The radiant flux on the detector (Φ_{detector}) is calculated using the equation:

$$\Phi_{\text{detector}} = \omega_{\text{diag}} \times \frac{\pi}{4} \times (\text{aperture})^2 \times \text{radiance} \times \text{transmission\_filter} \times \text{optic\_transmission}$$

where aperture represents the aperture size and radiance represents the radiance of the target. The radiant flux on the detector represents the amount of radiant power incident on the detector.

3.5 Irradiance on Detector

The irradiance on the detector (E_{detector}) is calculated using the equation:

$$E_{\text{detector}} = \frac{\Phi_{\text{detector}}}{\text{circular\_area}}$$

where circular_area represents the circular area of the detector. Irradiance on the detector represents the power incident on the detector per unit area.

3.6 Photon Flux

The photon flux (Φ) is calculated using the irradiance on the detector and energy per photon:

$$\Phi = \frac{E_{\text{detector}}}{E_{\text{photon}}}$$

The photon flux represents the number of photons incident on the detector per unit time.

3.7 Photon per Pixel

The photon per pixel represents the number of photons incident on a single pixel of the detector. It is calculated using the following equation:

$$\text{photon\_per\_pixel} = \frac{\Phi}{(1/(\text{pixel\_size}))^2}$$

3.8 Photon in Integration

The total number of photons accumulated during the integration time (photon_in_integration) is calculated using the photon per pixel and exposure time:

$$\text{photon\_in\_integration} = \text{photon\_per\_pixel} \times \text{exposure\_time}$$

3.9 Signal-to-Noise Ratio (SNR)

The Signal-to-Noise Ratio (SNR) is a measure of the ratio of the signal power to the noise power. It is calculated using the following equation:

$$\text{SNR} = \frac{\text{photon\_in\_integration} \times \text{QE} \times \text{binning}^2}{\sqrt{\text{photon\_shot\_noise}^2 + (\text{dark\_noise} \times \text{exposure\_time}/1000)^2 + \text{readout\_noise}^2}}$$

where QE represents the Quantum Efficiency of the detector, dark_noise represents the dark noise, and readout_noise represents the readout noise. The SNR provides an indication of the quality and reliability of the detected signal.

For more details on the noise sources that influence SNR (dark noise, readout noise, photon shot noise), their meanings are detailed in Section 4.1.2 and 4.4.

4 Code Structure

This section focuses on the structure of the code itself. It provides an overview of the different tabs which constitutes the structure of the graphical interface to which the user has access.

4.1 Detector Configuration Tab

The Detector Configuration Tab is responsible for defining the parameters and settings related to the detectors used in the image processing. It allows for customization and optimization of the detectors to suit specific requirements. This tab consists of various sub-sections, including:

4.1.1 Different Detectors

This subsubsection provides an overview of the different types of detectors available in the code. It discusses their characteristics, functionalities, and the specific applications they are suitable for. Code snippets or pseudocode may be included to demonstrate the implementation of each detector.

- **CIS115**: The CIS115 sensor features a rolling shutter mode with high-resolution image area, allowing selective reading of regions of interest (ROI) and achieving a higher frame rate. It is designed for space applications and offers low noise output.

- **CIS120**: The CIS120 architecture includes a column parallel ADC and on-chip sequencer for simplified operation. It supports various configuration settings, providing control over shutter mode, ADC resolution, and bias current values. The sensor offers flexible ROI operation and is available in low noise (CapellaLN) and large signal (CapellaLS) variants.

- **CMV4000**: With a global shutter and high-speed capabilities, the CMV4000 detector is suitable for applications requiring freeze-frame capture or accurate tracking of moving objects. It offers selectable ADC resolution and provides options for high dynamic range imaging.

- **CCD47**: The CCD47 family of CCD sensors employs full-frame architecture and back illumination technology. With extremely low noise amplifiers, it is particularly well-suited for demanding scientific applications. These sensors do not include antiblooming structures, enhancing their sensitivity.

- **STAR1000**: STAR1000 is a CMOS Active Pixel image Sensor (CMOS APS) with a high-resolution format. It incorporates an on-chip 10-bit ADC and is designed for scientific and electro-optical applications, offering a balance of performance and functionality.

- **QHY Family**: The QHY family of cooled, short-wavelength infrared cameras utilizes InGaAs sensors with high sensitivity and wide band response. These cameras are available in air cooling and liquid cooling versions, offering different levels of cooling to achieve desired temperature differentials for optimal performance.

- **3D PLUS Family (contained 12Mpx, 4Mpx, SWIR)**: The 3D PLUS family of cameras features cooled, short-wavelength infrared sensors for various applications. With high sensitivity and wide band response, they offer versatility in imaging. Similar to the QHY family, they are available in air cooling and liquid cooling versions.

4.1.2 Detector Settings

In this subsubsection, the specific configuration options for each detector are detailed.

- **Quantum efficiency (QE)** : The QE refers to how efficiently an imaging device converts incoming photons (particles of light) into electrical signals (electrons). For instance, if a sensor has a QE of 100% and is exposed to 100 photons, it will generate 100 electrons as a signal.

- **Pixel Size**: The size of the pixels in the captured image by the detector in mm.

- **Pixel Number**: The number of pixels in the image along the x and y axes, as the image may not necessarily be rectangular.

- **Full Well**: The maximum charge capacity that an individual pixel can store without saturation, dependent on pixel size and camera operating voltages.
- **Readout Noise**: The error or inaccuracy when measuring the amount of light captured by each pixel, specified in electrons (e-).
- **Dark Current**: The accumulation of thermal energy within the camera sensor, resulting in the generation of additional electrons during exposure, independent of the photoelectrons from the sample.

4.2 Target Configuration Tab

The Target Configuration Tab allows for the definition and customization of the target objects or features to be detected and processed in the images. It includes options for specifying the characteristics and properties of the targets, such as shape, size, color, texture, or any other relevant attributes.

- **Orbit Level**: The altitude at which the detector and probe are positioned above the surface of Enceladus in kilometers.
- **Groundspeed**: The speed at which the detector and probe move in orbit around Enceladus relative to the surface in meters per second.
- **Spectral Width**: The spectral range of the light rays from the surface of Enceladus that the detector is configured to receive, typically between 300 and 1100 micrometers.
- **Distance to the Sun**: The distance between the camera and the Sun, providing an approximation of the received light rays by the sensor.
- **Body Albedo**: The reflectivity of a surface, defined as the ratio of the reflected light energy flux to the incident light energy flux.

4.3 Instrument Configuration Tab

The Instrument Configuration Tab focuses on the setup and configuration of the imaging instrument itself. It includes settings related to camera parameters, image acquisition, image preprocessing, and other instrument-specific functionalities, ensuring optimal image quality for further processing.

- Exposure time: Duration during which the surface of Enceladus is visible to the detector onboard the orbiting probe.
- Focal length: Distance between the optical system embedded in the detector and the focal point where incoming light rays converge.
- F/# (F-number): Measure of the light-gathering capability of an optical system, calculated by dividing the focal length by the diameter of the entrance pupil.

- Binning: Technology that groups pixels in different ways to adapt to varying lighting conditions, allowing for higher sensitivity in low-light situations at the expense of lower resolution.
- Transmission filter and optic transmission: Properties that describe how filters and optics affect the transmission of light through the imaging system, often represented by a coefficient ranging from 0 to 1.

4.4 Output Tab

The Output Tab determines the format and presentation of the final results generated by the code. It allows for customization of the output, such as image overlays, statistical reports, or visual representations of detected features, ensuring easy interpretation and suitability for further analysis or presentation.

When all the fields in the previous three tabs have been filled, the "Used Parameters" section appears on the right side of the window. This section summarizes the user-entered values, providing a way to verify that the calculations are being simulated with the desired values. A new item, Photon shot noise, is included in this list.

- FOV (Field of View): The observable extent of the world seen at a given moment by the detector, expressed as a solid angle of electromagnetic radiation sensitivity.

$$\mathrm{FOV} = \frac{\mathrm{pixel\_size} \times \mathrm{nb\_pixel}}{\mathrm{focal\_length}}$$

- IFOV (Instantaneous Field of View): The solid angle through which a pixel sensor is sensitive to electromagnetic radiation, representing the spatial resolution of a remote sensing imaging system.

$$\mathrm{IFOV} = \frac{\mathrm{FOV}}{\mathrm{pixel\_size} \times \mathrm{nb\_pixel}}$$

- SNR (Signal-to-Noise Ratio): A measure of image quality, indicating the sensitivity level that yields a threshold level of SNR in a digital or film imaging system. Calculation details are provided in the "Study of Theoretical Variables for SNR Calculation" section of the Overleaf document.
- Diffraction limit: The ultimate limit to the resolution of an optical imaging system, determined by the physics of diffraction and characterized by performance at the system's theoretical limit.

  Rayleigh equation:

$$\mathrm{diffraction\_limit} = 1.22 \times \left(\frac{\mathrm{wavelength}}{\mathrm{aperture}}\right)$$

Explanation:

The Rayleigh equation calculates the diffraction limit of an optical system, which is the smallest resolvable detail. It is determined by the wavelength of the light and the aperture of the system, which represents the clear aperture of the lens or optical system as defined in the "F/#" parameter in the Instrument Configuration Tab. The wavelength used is the average value within the spectral width specified in the Target Configuration Tab.

- Pixel scale : The "pixel scale" refers to the angular size of a pixel on the detector, expressed in angular units (e.g., degrees per pixel). It indicates how much angle is covered by each pixel on the detector.

$$\text{pixel}_\text{s}\text{cale} = 2 \times \text{orbit}_\text{l}\text{evel} \times \tan\left(\frac{\text{IFOV}}{2}\right) \times \text{binning}$$

- Pixel Smear : Pixel smear refers to the elongation or blurring of an image in the direction of motion caused by the movement of the spacecraft during the exposure time. It is calculated by multiplying the ground speed by the exposure time and dividing it by the product of the pixel scale and binning.

$$\text{pixel}_\text{s}\text{mear} = \frac{\text{speed\_ground} \times \text{exposure}_\text{t}\text{ime}}{\text{pixel}_\text{s}\text{cale} \times \text{binning}}$$

5 Conclusion

In conclusion, the Nightingale project presents a valuable opportunity to study and map the surface of Enceladus, one of Saturn's most intriguing moons. The unique features of this moon, such as its reflective ice covering and the presence of active cryovolcanoes, suggest the possibility of hidden life beneath its icy shell. The efforts to explore Enceladus face significant technical and environmental challenges, but scientific curiosity and the quest for signs of life persist.

Implementing Nightingale on a spacecraft orbiting Enceladus would enable the collection of crucial data on the moon's composition and characteristics, contributing to our understanding of this mysterious world. The information gathered through this project will also support future exploration missions and guide efforts to search for extraterrestrial life.

The analysis of theoretical variables for the calculation of signal-to-noise ratio (SNR) has provided insights into key aspects of the Nightingale code and its performance evaluation. By understanding concepts such as energy per photon, field of view, radiant flux, and photon flux, it becomes possible to assess the quality and reliability of detected signals. The SNR calculation takes into account factors such as detector quantum efficiency, dark noise, and read noise, thus providing a quantitative measure of signal quality.

Regarding the code structure, Nightingale is designed with a user-friendly interface and tabbed navigation, allowing for efficient data analysis and visualization. The modular architecture facilitates future updates and enhancements, ensuring the adaptability of the code to evolving research needs.

In summary, the Nightingale project holds great promise for advancing our knowledge of Enceladus and potentially uncovering evidence of life beyond Earth. By leveraging cutting-edge technology and scientific expertise, we can continue to push the boundaries of exploration and unravel the mysteries of our universe.

(Full Well Capacity $\geq PhotonShotInIntegrationTime$)