

Accurate performance assessment of LIMB-to-LIMB observations from space-based optical instruments

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ABSTRACT

Accurate performance assessment of instruments with a wide field of view remains challenging, as a single LIMB-to-LIMB field of view combines surface-viewing and atmospheric limb-viewing regions with significantly different observation geometries and radiometric conditions. While NADIR, off-NADIR, and LIMB observations are individually well established in current performance models, their continuous combination across the complete field of view is not yet adequately represented within ESA Future EO modelling capabilities. This paper addresses this gap by implementing a LIMB-to-LIMB observation module as an extension of an existing Instrument Performance Calculator developed within ESA's Future EO.

The mission concept requiring such a modeling capability is the Earth Climate (ECO), a candidate mission for Earth Explorer 12, which aims to measure the Earth Energy Imbalance through accurate measurements of the Total Outgoing Radiation. The ECO observation concept considers wide field of view cameras whose field of view covers the Earth's surface and extends into the atmosphere beyond the apparent edge of the Earth on both sides.

Keywords: Wide Field-of-View, LIMB-to-LIMB observation, Instrument performance modeling, Earth Radiation Budget

1. INTRODUCTION

Accurate performance assessment of wide field of view (WFOV) Earth observation instruments can become challenging when a single field of view (FoV) simultaneously includes both surface-viewing and atmospheric limb-viewing regions. These regions are characterized by significantly different observation geometries and radiometric conditions. While surface-viewing observations, such as those performed by EarthCARE,¹ and limb-viewing observations, such as those performed by ALTIUS,² are individually well established and commonly implemented in performance models, their continuous combination across a single WFOV requires a more advanced geometrical and radiometric treatment. WFOV themselves are not unprecedented in Earth observation instrumentation, for example, Sentinel-5P/TROPOMI³ employs an across-track FoV of approximately 108° in a nadir-viewing configuration. The particular challenge considered here therefore arises not from the WFOV alone, but from the continuous combination of surface-viewing and limb-viewing geometries within the same FoV.

The observation configuration addressed in this work spans continuously from the atmospheric limb on one side of the Earth, across the Earth's surface, to the atmospheric limb on the opposite side, and is hereafter referred to as LIMB-to-LIMB (L2L) observation. As illustrated in Figure 1, some instrument lines of sight (LoS) intersect the Earth's surface, while others pass through the atmosphere without intersecting the surface. These two viewing regimes are hereafter referred to as surface-viewing and limb-viewing observations, respectively.

A mission concept requiring such an observation capability is the Earth Climate Observatory (ECO), a candidate mission for Earth Explorer 12. ECO aims to measure the Earth Energy Imbalance (EEI), which describes the difference between the incoming solar radiation and outgoing Earth radiation within the Earth system*. Radiative components relevant to the determination of EEI are:

1. Incoming Solar Radiation (ISR) – The total solar radiation incident on the Earth from the Sun.
2. Total Outgoing Radiation (TOR) – The total radiation emitted and reflected back from the Earth system to space.
3. Reflected Solar Radiation (RSR) – The portion of solar radiation reflected by the Earth's surface, atmosphere, and clouds.
4. Outgoing Long-wave Radiation (OLR) – The thermal radiation emitted by the Earth and its atmosphere.

*The Earth system comprises the surface and atmosphere, including clouds, and can be considered as a system that receives incoming solar radiation and reflects or emits radiation back to space.

The relationship between these radiative components is described by Eq. 1 and 2:

$$EEI = ISR - TOR \quad (1)$$

$$TOR = RSR + OLR \quad (2)$$

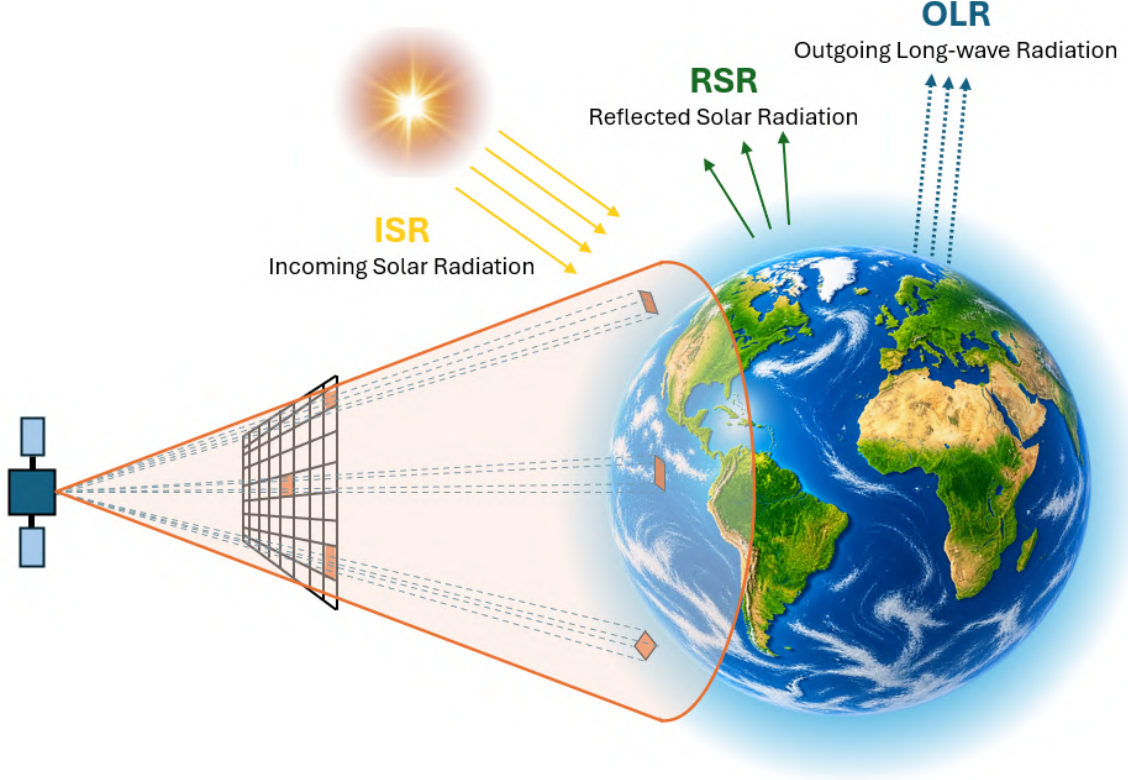


Figure 1: Schematic representation of the L2L observation concept. The blue dashed lines indicate the instrument LoS, while the orange markers represent spatial samples across the field of view. LoS intersecting the Earth correspond to surface-viewing observations, whereas LoS passing through the atmosphere without intersecting the surface correspond to limb-viewing observations. The complete FoV extends from the atmospheric limb on one side of the Earth, across the Earth's surface, to the atmospheric limb on the opposite side.

Accurate determination of the EEI therefore requires precise measurements of the TOR. One of the objectives of ECO is to observe TOR at kilometeric to deca-kilometric spatial resolution with global Earth coverage using WFoV cameras operating from Low Earth Orbit, while enabling scene identification to support the derivation of global EEI maps.⁴ The FoV considered for these instruments extends beyond the apparent edge of the Earth into the atmosphere on both sides, resulting in the L2L observation geometry as described above.

The performance assessment of such an observation concept requires a modelling framework capable of continuously representing the transition between surface-viewing and limb-viewing geometries across the complete instrument FoV. Typical performance models are designed for either NADIR or LIMB-viewing geometries.⁵ Some geostationary Earth-observation missions are also capable of observing the full Earth disc, but these configurations generally do not account for the atmospheric LIMB.⁶ In contrast, an L2L configuration requires both viewing regimes to be treated consistently within a single observation geometry, while explicitly accounting for the radiance associated with LIMB viewing.

To address this gap, an L2L observation module was implemented as an extension of the existing Instrument Performance Calculator developed within ESA FutureEO. The framework enables the simulation of complete L2L observation geometries based on the orbital configuration and instrument parameters, and provides the geometrical basis for radiance assignment and subsequent instrument performance assessment, such as signal-to-noise calculations.

2. MODEL DESCRIPTION

The simulation is implemented in Python as an extension of an existing performance model developed within ESA FutureEO. Figure 2 presents the computational pipeline described in the following sections. To generate the complete L2L geometry, the pixel grid, and associated LoS angles must first be computed or provided as inputs.

The pixel LoS can be either directly provided to the program as LoS against detector position or derived from the instrument focal length and detector geometry using the rectilinear assumption in Eq. 3. Rectilinear assumption is used to compute LoS angel in both across-track and along-track directions. Alternatively, the user may specify the desired spatial sampling distance at the Earth's surface, from which the program estimates the corresponding LoS directions and instrument focal length based on the observation geometry. Once the LoS angles have been established, the corresponding LoS vectors are computed and transformed into the Earth-Centered, Earth-Fixed (ECEF) coordinate system. Surface intersections and atmospheric tangent points are then determined using either a spherical or an ellipsoidal Earth model, selected according to the required level of accuracy. The spherical model approximates the Earth as a sphere with a radius of 6371 km. For the ellipsoidal representation, the model uses the WGS-84 oblate ellipsoid, with an equatorial radius of 6378.137 km and a polar radius of 6356.752 km.

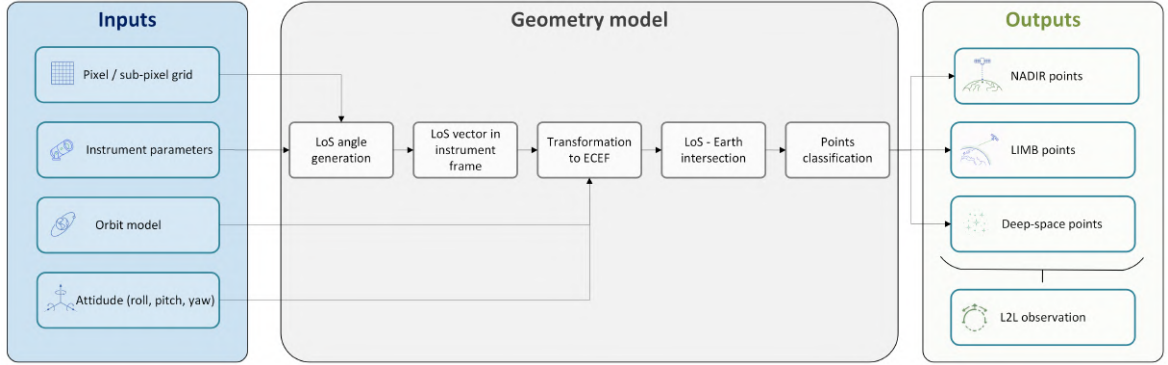


Figure 2: L2L geometry computation pipeline from model inputs to LoS classification and complete L2L observation.

$$\theta_{\text{LoS},i} = \arctan \left(\frac{x_i}{f} \right) \quad (3)$$

where: $\theta_{\text{LoS},i}$ is the line-of-sight angle of the i -th detector pixel, x_i is the position of the i -th detector pixel with respect to the optical axis, and f is the focal length of the instrument.

An important step of the L2L geometry model is the determination of surface intersection points and atmospheric tangent points for the instrument LoS vectors. These points are expressed in the ECEF coordinate system⁷ and represented by three-dimensional coordinates (x, y, z) . Depending on the viewing direction, the resulting points correspond either to surface-viewing samples or to LIMB-viewing samples. They form the basis for subsequent computations of footprints, spatial sampling distances, swath, radiometric performance, etc.

3. THEORETICAL BACKGROUND

The following section explains the theoretical basics of surface points computation and establishes a mathematical framework of the work.

3.1 LoS vector computation

The LoS angle is calculated from the angular deviations in the across-track and along-track directions according to Eqs. 4 and 5.

$$x = \tan(R_y) \quad (4)$$

$$y = \tan(R_x) \quad (5)$$

The normalized LoS vector is then computed according to Eq. 6.

$$\mathbf{v}_{\text{ins}} = \frac{1}{\sqrt{x^2 + y^2 + 1}} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix} \quad (6)$$

3.2 LoS vector transformation to the ECEF

Before calculating the intersection of a pixel LoS vector with the Earth's surface, the vector must be expressed in the ECEF coordinate system. The LoS vector is initially defined in the instrument coordinate frame and is therefore transformed step by step into the global ECEF frame.

The transformation is performed using a sequence of rotation matrices. First, the instrument angle[†] is applied to transform the vector from the instrument frame to the satellite reference frame. The satellite attitude is then included through the roll, pitch, and yaw rotations. The combined attitude rotation matrix is defined as

$$R_{\text{att}} = R_{\text{roll}} R_{\text{pitch}} R_{\text{yaw}}, \quad (7)$$

where the individual matrices describe rotations associated with the satellite roll, pitch, and yaw angles. Their product, R_{att} , transforms the vector from the satellite reference frame to the Local Vertical Local Horizontal (LVLH) frame.

The vector is subsequently transformed from the LVLH frame to the Local Orbital (LO) frame and finally from the LO frame to the ECEF coordinate system. The complete transformation matrix is therefore given by

$$M = R_{\text{LO} \rightarrow \text{ECEF}} R_{\text{LVLH} \rightarrow \text{LO}} R_{\text{att}} R_{\text{ins} \rightarrow \text{sat}}, \quad (8)$$

where $R_{\text{ins} \rightarrow \text{sat}}$ accounts for the orientation of the instrument relative to the satellite body, $R_{\text{LVLH} \rightarrow \text{LO}}$ describes the transformation between the two local orbital frames, and $R_{\text{LO} \rightarrow \text{ECEF}}$ relates the LO frame to the global Earth-fixed frame.

The orientation of the LO frame depends on the selected NADIR reference definition. For geocentric NADIR, the local vertical is aligned with the line connecting the Earth's centre and the spacecraft. For geodetic NADIR, the local vertical is aligned with the normal to the WGS-84 reference ellipsoid at the corresponding ground location. The two directions are identical for a spherical Earth but differ slightly when the Earth's ellipsoidal shape is considered. Consequently, the selected NADIR reference definition changes $R_{\text{LO} \rightarrow \text{ECEF}}$ and thus the resulting LoS direction in the ECEF coordinate system.⁷

[†]The instrument angle describes how the instrument is mechanically tilted with respect to the satellite body.

After combining all rotations, the LoS vector is transformed into the ECEF frame according to

$$\mathbf{v}_{\text{ECEF}} = M \mathbf{v}_{\text{ins}}, \quad (9)$$

where $\mathbf{v}_{\text{ins}}$ represents the LoS vector in the instrument coordinate frame and $\mathbf{v}_{\text{ECEF}}$ represents the same viewing direction in the ECEF coordinate system. The transformed vector can then be used to calculate its intersection with the Earth's surface or its atmospheric tangent point.

3.3 Calculation of the Surface and Limb Intersection Distance

After the LoS vector has been transformed into the ECEF coordinate system, the next step is to determine if and where this vector intersects the Earth. The program allows the Earth to be represented either as a sphere with a radius R_{earth} or as an oblate ellipsoid, defined by the equatorial radius R_e and the polar radius R_p . Hereafter, the computational framework continues with an ellipsoidal Earth approximation.

Let the satellite orbit position in ECEF coordinates be:

$$\mathbf{p} = \begin{bmatrix} p_x \\ p_y \\ p_z \end{bmatrix}, \quad (10)$$

and let the LoS vector in the ECEF frame be

$$\mathbf{v} = \begin{bmatrix} u \\ v \\ w \end{bmatrix}. \quad (11)$$

A point along the LoS can be written as:

$$\mathbf{x}(t) = \mathbf{p} + t\mathbf{v} \quad (12)$$

where t is the distance from the satellite along the viewing direction.

By substituting Eq. 12 into the ellipsoid equation, a quadratic equation in the variable t is obtained. The general form of the quadratic equation is given by Eq. 14.

$$\frac{(p_x + tu)^2 + (p_y + tv)^2}{R_e^2} + \frac{(p_z + tw)^2}{R_p^2} = 1 \quad (13)$$

By solving Eq. 13 we obtain a quadratic equation in the variable of t . Quadratic equation can be generally written as in Eq. 14.

$$At^2 + Bt + C = 0 \quad (14)$$

If we substitute all variables and parameters, we get quadratic Eq. 14.

$$\left[\frac{u^2 + v^2}{R_e^2} + \frac{w^2}{R_p^2} \right] t^2 + 2 \left[\frac{p_x u + p_y v}{R_e^2} + \frac{p_z w}{R_p^2} \right] t + \left[\frac{p_x^2 + p_y^2}{R_e^2} + \frac{p_z^2}{R_p^2} - 1 \right] = 0 \quad (15)$$

The solutions are obtained using the quadratic formula in Eq. 16

$$D = B^2 - 4AC \implies t_{1,2} = \frac{-B \pm \sqrt{D}}{2A}, \quad t = \text{Re}(t_{1,2}) = -\frac{B}{2A} \quad \text{for } D < 0. \quad (16)$$

As illustrated in Figure 3, the discriminant determines the number of intersections between the LoS and the reference ellipsoid.

$$D < 0 \Rightarrow \text{no intersection}, \quad D = 0 \Rightarrow \text{tangent point}, \quad D > 0 \Rightarrow \text{two intersections}. \quad (17)$$

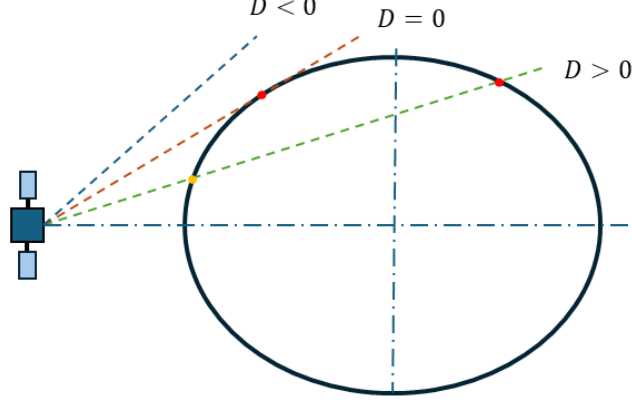


Figure 3: Schematic representation of the LoS to ellipsoid intersection cases described by the value. The green line represents a surface-viewing LoS with two intersections, the orange line represents the tangent case, and the blue line represents an atmospheric observation with no LoS to ellipsoid intersection. In the picture, the Earth ellipsoid is exaggerated.

When the discriminant is positive, the quadratic equation has two real solutions $t_{1,2}$. These two solutions correspond to two intersections of the LoS with the ellipsoid. When the discriminant is negative, the solutions are complex, and the LoS does not intersect the ellipsoid. The corresponding LoS is therefore classified as either LIMB or deep-space viewing. For this case, the distance t is defined by the real part of the complex solutions, $t = \text{Re}(t_{1,2}) = -B/(2A)$, as according to the Eq. 16. The distinction between LIMB and deep-space viewing is then determined by the sign of t . If t is positive, the LoS is classified as LIMB viewing, and if t is negative, the LoS is classified as deep-space viewing. The determined value of t is then substituted into Eq. 12 to calculate the corresponding point in ECEF coordinates.

3.4 Surface and LIMB points computation

Section 3.3 described the computation of a single surface or LIMB point. This section extends the approach to the complete set of instrument LoS directions defined by the detector pixel grid. Firstly, the LoS angles in the across-track and along-track directions are converted into LoS vectors in the instrument coordinate system, as described in Section 3.2. The resulting set of vectors forms a complete grid of viewing directions, with each vector corresponding to one detector pixel. The computation is fully vectorized, allowing efficient processing of grids containing even millions of pixels. Surface or LIMB positions for each pixel are computed according to Eq. 18.

$$\mathbf{v}_{\text{ins}} = f(\theta_{\text{AC}}, \theta_{\text{V}}) \implies \mathbf{v}_{\text{ECEF},i} = M_i \mathbf{v}_{\text{ins}} \implies \mathbf{x}_i(t) = \mathbf{p}_i + t_i \mathbf{v}_{\text{ECEF},i} \quad (18)$$

where, $\mathbf{v}_{\text{ins}}$ are the LoS vectors. The matrix M_i is the transformation matrix from the instrument frame to the ECEF frame at the i -th orbital position. The vectors $\mathbf{v}_{\text{ECEF},i}$ are the corresponding LoS vectors expressed in the ECEF coordinate system. $\mathbf{p}_i$ are satellite positions at the i -th orbital sample, t_i are distances along the LoS directions, and $\mathbf{x}_i(t)$ are resulting points along the LoS in ECEF coordinates.

This framework enables the determination of spatial sample sizes and sampling distances in both the across-track and along-track directions. These quantities can subsequently be used to derive the pixel-dependent spatial resolution.

3.5 Radiance to surface/LIMB points assignment

Once it is known which points are on Earth's surface and which are atmospheric LIMB, radiance can be assigned to each pixel. Top-of-the-Atmosphere radiance is assigned separately for surface and LIMB points, as the two observation regimes generally require different radiance inputs. For both regimes, the radiance can be provided either as a homogeneous scalar value or as spectrally and/or spatially varying radiance values through a handover file.

For **Earth surface points**, the following radiance input formats are supported:

1. **0D radiance input:** A single radiance value is applied uniformly to all wavelengths and all Earth surface pixels.
2. **1D radiance input:** Radiance is defined as a function of wavelength and is identical for all surface pixels.
3. **2D radiance input:** Radiance is defined for each wavelength and each surface viewing pixel within the instrument FoV. Each pixel is assigned a position on Earth given by its longitude and latitude.
4. **3D radiance input:** Radiance is defined for each wavelength and each surface viewing pixel on a two-dimensional flat surface grid on Earth.

For **LIMB points**, the radiance input accounts for the atmospheric viewing geometry and therefore supports different spatial dependencies:

1. **0D radiance input:** A single radiance value is applied uniformly to all wavelengths and all LIMB viewing pixels.
2. **1D radiance input:** Radiance is defined as a function of wavelength and is identical for all LIMB viewing pixels.
3. **2D-1 radiance input:** Radiance is defined as a function of tangent altitude and wavelength.
4. **2D-2 radiance input:** Radiance is defined for each wavelength and each LIMB viewing pixel according to its longitude, latitude, and altitude.

4. RESULTS

This section presents results obtained using the implemented L2L observation model. The examples focus on optical payloads with a WFoV and demonstrate the capability of the model to represent the complete observation geometry, ranging from surface-viewing LoS to atmospheric limb-viewing configurations. The results further illustrate the influence of orbital, instrument, and spacecraft attitude parameters on the resulting FoV coverage.

The two fundamental observation regimes forming an L2L acquisition are illustrated in Figures 4a and 4b. In the surface-viewing case Fig. 4a, the instrument LoS intersect the Earth's surface, whereas in the limb-viewing case Fig. 4b the LoS pass through the atmosphere without intersecting the surface and are characterized by their corresponding tangent points. For the presented examples, the maximum atmospheric tangent altitude was limited to 100 km, in accordance with the observation requirements considered for the ECO mission.

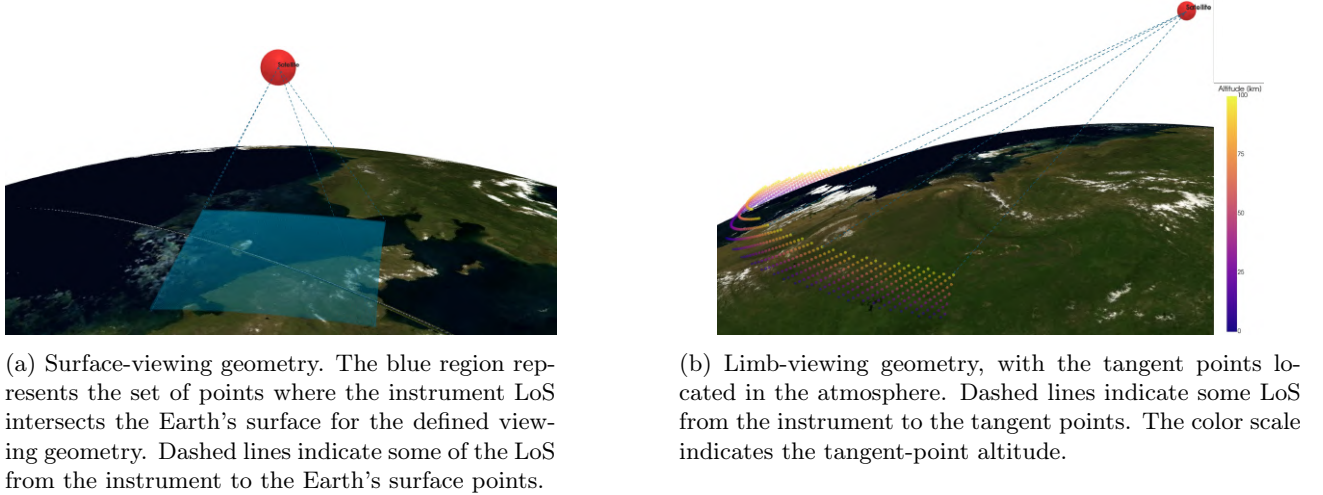


Figure 4: Examples of surface-viewing and limb-viewing observation geometries generated by the model.

Based on the observation geometry, spacecraft orbit, attitude law, and instrument characteristics, the total FoV coverage can be determined. The resulting coverage depends on a combination of orbital, geometrical, and instrument-related parameters. The main model inputs affecting the computed L2L coverage are summarized in Table 1.

Table 1: Main input parameters affecting the computed L2L FoV coverage.

Parameter	Description
Orbit definition	Orbital altitude or Keplerian orbital elements.
Earth model	Spherical Earth model or WGS-84 reference ellipsoid.
Instrument LoS	Together with the detector geometry determines the FoV coverage.
Number of pixels	Number of pixels in across-track and along-track directions.
Pixel size	Physical detector pixel size.
Attitude laws	Spacecraft pointing definition, including pitch, yaw, and roll angles.

4.1 L2L Simulation Example

An example was selected to illustrate the resulting L2L observation geometry and the effect of spacecraft change on the distribution of surface-viewing and limb-viewing LoS within the instrument FoV. The corresponding orbital and instrument parameters are summarized in Table 2. Unless stated otherwise, this configuration is used for the results presented in the following.

The effect of spacecraft roll angle on the observation geometry is illustrated in Fig. 5. In Figures 5a and 5b, the cyan region represents the part of the Earth's surface intersected by the instrument LoS, while the coloured region surrounding the apparent Earth edge represents atmospheric tangent points associated with limb-viewing LoS up to an altitude of 100 km. LoS with tangent altitudes above 100 km are shown in grey and correspond to deep-space viewing. Together, the surface-viewing, limb-viewing, and deep-space regions represent the complete L2L observation geometry. The colour scale indicates the corresponding tangent-point altitude.

Table 2: Input parameters used for the L2L simulation.

Parameter	Value	Parameter	Value
Earth model	Spherical	Instrument focal length	1.5 mm
Orbit type	Circular	Pixel grid	1280×1280 px
Maximum tangent altitude	100 km	Pixel size	$8 \mu\text{m}$
Orbital altitude	750 km	Roll angle	0°
Pitch angle	0°	Yaw angle	0°

For the nominal attitude, the instrument FoV is centred with respect to the apparent Earth disc, resulting in a symmetric distribution of surface-viewing and limb-viewing LoS. Applying a roll angle of 5° shifts the instrument FoV relative to the Earth, as shown in Fig. 5b. Consequently, the distributions of surface-viewing and limb-viewing LoS become asymmetric. The boundary of the observed region is not perfectly circular because the FoV is defined by the square detector geometry specified in Table 2. This results in the local indentations visible in Figs. 5a and 5b.

The orange dashed lines in Figs. 5a and 5b indicate the detector cuts used to generate the profiles shown in Figs. 5c and 5d, respectively. The same vertical cut through the detector centre is used for both spacecraft orientations, providing a consistent comparison between the two cases. This fixed detector cut does not necessarily correspond to the direction of maximum roll-induced displacement. Surface-viewing LoS are shown in cyan, limb-viewing LoS are coloured according to their tangent altitudes, and deep-space viewing LoS are shown in grey. Without attitude rotation, the distribution is symmetric, whereas applying a roll angle results in an asymmetric distribution. The total number of LoS remains identical in both cases.

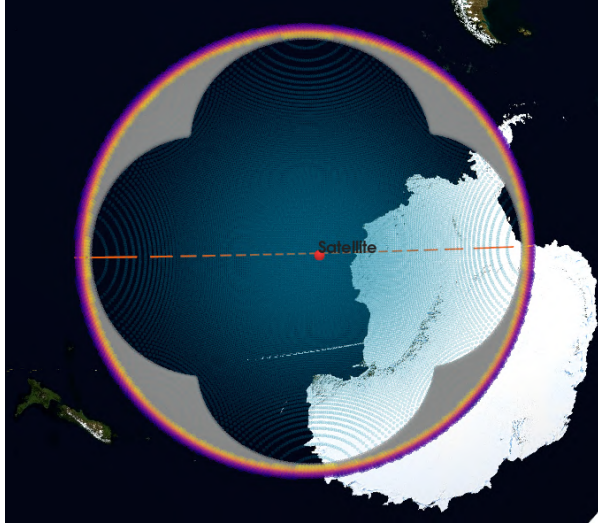
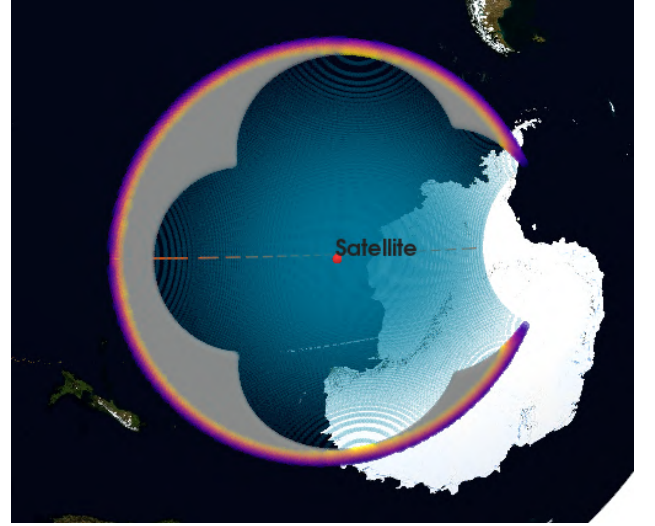
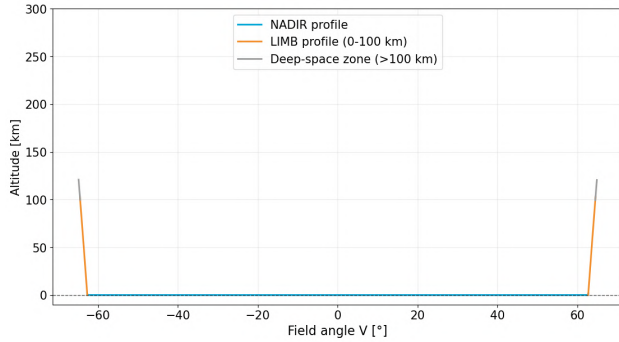
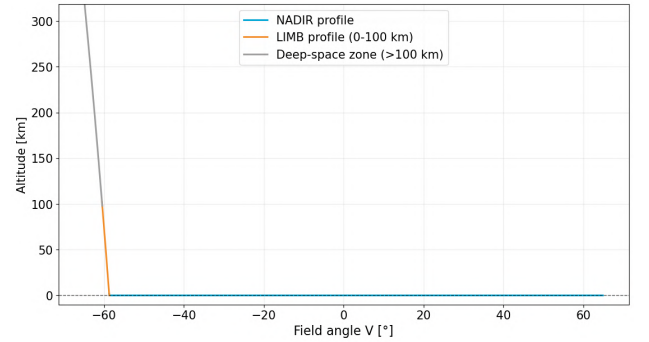

(a) No attitude rotation (pitch = yaw = roll = 0°).

(b) Roll rotation applied – roll = 5° , pitch = yaw = 0° .

(c) No attitude rotation (pitch = yaw = roll = 0°).

(d) Roll rotation applied – roll = 5° , pitch = yaw = 0° .

Figure 5: Effect of spacecraft roll on the L2L observation geometry. In Figures 5a and 5b, the cyan region represents surface-viewing LoS, while the coloured regions represent limb-viewing LoS with tangent altitudes up to 100 km. Deep-space viewing LoS are shown in grey. Applying a 5° roll shifts the FoV relative to the Earth and results in an asymmetric distribution of the different viewing regimes. The orange dashed lines indicate the profiles shown in Figures 5c and 5d.

The results shown in Fig. 5 illustrate how the geometrical classification is applied across the complete detector FoV. Each LoS is classified according to its observation geometry. LoS intersecting the Earth’s surface are classified as surface-viewing, while LoS that do not intersect the surface but have a tangent altitude within the predefined atmospheric range of 0–100 km are classified as limb-viewing. LoS that neither intersect the Earth nor satisfy the tangent-altitude criterion are classified as deep-space viewing.

This geometrical classification provides the basis for assigning the appropriate spectral radiance to each detector pixel. Surface-viewing, limb-viewing, and deep-space LoS can therefore be associated with different radiometric inputs. In the current implementation, deep-space samples are assigned a radiance corresponding to cosmic microwave background radiation at a temperature of approximately 2.7 K.

In the context of the ECO mission, the atmosphere is considered to contribute significantly to the measured TOR up to an altitude of 100 km.⁴ Limb-viewing LoS with tangent altitudes below this threshold are therefore included in the radiometric signal budget. This distinction allows the contribution of the atmospheric limb to be consistently propagated into the subsequent signal-to-noise ratio (SNR) calculation.

To demonstrate the propagation of the L2L scene through the instrument performance model, an SNR calculation was performed. The main radiometric, optical, and detector parameters used for the simulation are summarized in Table 3.

Table 3: Input parameters used for example L2L SNR calculation. The values are based on heritage instrument parameters and were selected to provide a test case and demonstrate the SNR calculation capability of the implemented L2L extension.

Parameter	Value	Unit	Parameter	Value	Unit
NADIR radiance	1×10^8	$\text{W m}^{-2} \text{sr}^{-1} \text{m}^{-1}$	Focal length	2	mm
LIMB radiance	5.0×10^7	$\text{W m}^{-2} \text{sr}^{-1} \text{m}^{-1}$	Entrance pupil size	0.5	mm
Minimum wavelength	400	nm	Pixel grid	1280×1280	px
Maximum wavelength	500	nm	Pixel size	8	μm
Wavelength step	1	nm	Integration time	0.75	ms
Coating transmission	0.7	–	Quantum efficiency	0.7	–
Number of coated surfaces	1	–	Detector fill factor	1.0	–

The resulting detector-level SNR distribution is shown in Figure 6. For the configuration considered here, the SNR reaches approximately 160 near the centre of the FoV and gradually decreases to approximately 15–20 towards the transition between surface-viewing and limb-viewing observations.

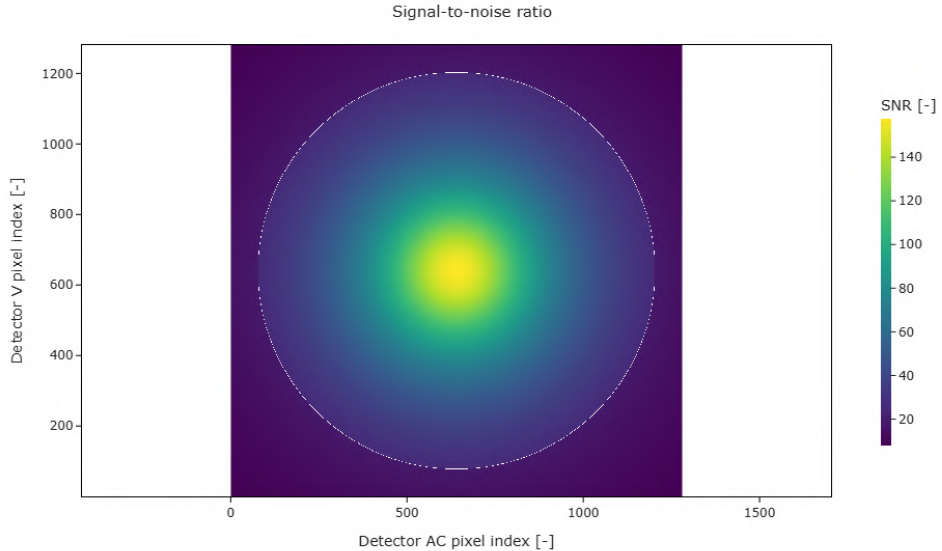


Figure 6: Simulated detector SNR map for the L2L observation configuration defined in Table 3. The white line shows the transition between the surface-viewing and LIMB-viewing LoS.

The presented simulation represents a minimal instrument input configuration, in which the LoS angles are derived from the specified focal length and detector geometry using the rectilinear relation given in Eq. 3. The entrance-pupil area is similarly derived from the specified pupil size. Even for this simplified configuration, the

pixel étendue varies across the FoV due to the field dependence of the object-space solid angle and the pupil projection factor. The pixel étendue is calculated according to Eq. 19:

$$G_p(\lambda) = A_{EP,p}(\lambda) \int_{\Omega_p} \cos \theta, d\Omega, \quad (19)$$

where $A_{EP,p}(\lambda)$ is the unprojected entrance-pupil area assigned to pixel p , Ω_p is the corresponding object-space solid angle, and θ is the angle between the LoS and the assumed pupil normal, aligned with the instrument optical axis.

For the configuration considered here, the increasing off-axis field angle results in a reduction in pixel étendue due to the variation of the pixel solid angle and the pupil projection factor. This reduces the detected signal and consequently the SNR towards the edge of the surface-viewing region. At the transition to limb-viewing observations, the limb radiance assigned to the corresponding LoS causes an additional reduction in the detected signal and SNR.

For more detailed instrument representations, the programme also allows the LoS angles to be provided directly as a function of detector pixel position rather than being derived from the rectilinear approximation. This enables the actual instrument LoS law, including field-dependent angular sampling, to be taken into account when determining the solid angle subtended by each pixel. In addition, field-dependent entrance-pupil areas and field dependent étendues can be provided. Together, these inputs enable the calculation of a more realistic pixel-dependent étendue and more realistic SNR distribution over the whole FoV for WFoV imagers.

5. CONCLUSION

This paper presented an L2L extension of the existing Instrument Performance Calculator developed within ESA's Future EO. The implemented framework enables the continuous representation of wide-field-of-view observations spanning from surface-viewing regions, across the Earth, to atmospheric limb-viewing and deep-space regions within a single instrument FoV.

The developed model determines the observation geometry for individual instrument lines of sight based on the orbital configuration, instrument characteristics, Earth model, and spacecraft attitude. Each LoS is subsequently classified as surface-viewing, limb-viewing, or deep-space viewing, providing the geometrical basis for assigning spatially dependent radiometric inputs. By combining the geometrical classification with radiance assignment, the L2L scene can be propagated through the existing instrument performance model. An SNR simulation demonstrated that surface-viewing, atmospheric limb-viewing, and deep-space regions can be treated consistently within a single FoV and that their different radiometric conditions are reflected in the resulting detector-level performance.

The developed extension therefore provides an instrument modelling capability for the performance assessment of WFoV optical instruments operating in L2L observation configurations. This capability is particularly relevant for observation concepts such as ECO, where measurements of the Earth's surface and atmospheric limb have to be considered simultaneously when assessing instrument performance and the measurement of TOR.

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