



Defence Research and  
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Recherche et développement  
pour la défense Canada



## Light scattering model for Karma

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The scientific or technical validity of this contract report is entirely the responsibility of the contractor and the contents do not necessarily have the approval or endorsement of the Department of National Defence of Canada.

**Defence Research and Development Canada – Valcartier**

Contract Report  
DRDC Valcartier CR 2012-185  
March 2012

**Canada**



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## **Defence Research and Development Canada – Valcartier**

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## Abstract

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Defence Research and Development Canada – Valcartier (DRDC Valcartier) studies threat warning imaging systems. The Karma engagement simulation framework was used to generate synthetic images as seen by these sensors. In order to provide a valid representation in the ultraviolet band for which the scattering phenomenon through aerosols present in the atmosphere is significant, a scattering model was integrated into Karma's scene generation module.

This contract report presents a scattering model able to reproduce the Modulation Transfer Function (MTF) of a source as seen through aerosols. This model was based on the classical Small Angle Approximation (SAA) scheme, which means that the backscattering contribution was neglected. The model was made to produce the MTF on field of views of up to 180°, which is far beyond the usual capacity of these models. Nevertheless, the model adequately reproduced the expected MTF. The frequency content was reproduced adequately. The results of the integration in Karma showed synthetic images including the scattering effect, which was validated against a higher fidelity Monte Carlo model.

## Résumé

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Recherche et développement pour la défense Canada – Valcartier (RDDC Valcartier) étudie les systèmes imageants de détection de menaces. L'environnement de simulation d'engagement Karma est utilisé pour générer des images synthétiques telles que vues par ces capteurs. Afin d'offrir une représentation valide dans la bande ultraviolette où le phénomène de diffusion dû à la présence d'aérosols dans l'atmosphère devient significatif, un modèle de diffusion a été intégré au module de génération de scène de Karma.

Ce rapport de contrat présente un modèle de diffusion capable de reproduire la fonction de transfert de modulation (MTF) d'une source lumineuse vue à travers un aérosol. Ce modèle est basé sur les modèles classiques d'approximation des petits angles, c'est-à-dire qu'il néglige les réflexions vers l'arrière. Le modèle est développé pour produire la MTF d'une source sur un champ de vue pouvant aller jusqu'à 180°, ce qui va bien au-delà de la capacité normale d'un tel modèle. Malgré cela, le modèle produit des résultats acceptables. Il est entre autres capable de reproduire adéquatement le contenu en fréquence du signal diffusé. Les résultats de l'intégration dans Karma montrent des images synthétiques incluant l'effet de diffusion qui a été validé par rapport à un modèle Monte Carlo de plus grande fidélité.

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# Executive summary

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## Light scattering model for Karma:

**Grégoire Tremblay; DRDC Valcartier CR 2012-185; Defence Research and Development Canada – Valcartier; March 2012.**

**Introduction or background:** In the context of Project 13nm, scientists from the Electro-Optical Warfare Section at Defence Research and Development Canada – Valcartier (DRDC Valcartier) are studying threat warning imaging systems. The Karma engagement simulation framework was used to generate synthetic images as seen by these sensors. In order to provide a valid representation in the ultraviolet band for which the scattering phenomenon through aerosols present in the atmosphere is significant, a scattering model was been integrated into Karma's scene generation module.

The scattering model was been developed by AEREX AVIONIQUE INC., under Task Authorization #4 of contract W7701-065363. This work reused the expertise developed by the Spectral and Geospatial Exploitation section, whose Monte Carlo model of the 3D information degradation of imaging systems in presence of multiple scattering on aerosols served as a reference for validation.

**Results:** This contract report presents a scattering model able to reproduce the Modulation Transfer Function (MTF) of a source seen through aerosols. This model was based on the classical Small Angle Approximation (SAA) scheme, which means that back scattering contribution was neglected. The model was made to produce the MTF on field of views (FOV) of up to 180°, which is far beyond the usual capacity of these models. Nevertheless, the model adequately reproduced the expected MTF and frequency content. The results of the integration in Karma showed synthetic images including the scattering effect, which was validated against the higher-fidelity Monte Carlo model.

**Significance:** The addition of the scattering modelling to DRDC Valcartier's Karma simulation framework augments its capacity (using the new imaging detection technologies) to advise the Canadian Forces about the acquisition and employment of equipment.

**Future plans:** The scattering model can now be used to execute imaging threat detection scenarios within the scope of Project 13nm. Additional work is planned under DTAES 8's Project 1203 in order to achieve a completely transparent usage of the scattering model in Karma, whatever the wavelength and environmental conditions. The model can be extended into the infrared band if the proportion of the absorbed and the scattered parts is taken into account. Furthermore, the integration with Karma's atmospheric model, namely the Suite Multi-resolution Atmospheric Radiative Transmission (SMART) developed by the Tactical and Surveillance Reconnaissance section, will allow automating pre computations. Finally, some adjustments will be done to also be able to use the scattering model with non-imaging sensors for which scattering is as significant.

# Sommaire

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## Light scattering model for Karma

**Grégoire Tremblay ; DRDC Valcartier CR 2012-185 ; Recherche et développement pour la défense Canada – Valcartier ; mars 2012.**

**Introduction ou contexte :** Dans le cadre du projet 13nm, des scientifiques de la section Guerre électro-optique du centre de Recherche et développement pour la défense Canada – Valcartier (RDDC Valcartier) étudient les systèmes imageants de détection de menaces. L'environnement de simulation d'engagement Karma est utilisé pour générer des images synthétiques telles que vues par ces capteurs. Afin d'offrir une représentation valide dans la bande ultraviolette où le phénomène de diffusion dû à la présence d'aérosols dans l'atmosphère devient significatif, un modèle de diffusion a été intégré au module de génération de scène de Karma.

Le modèle de diffusion a été développé par la firme AEREX AVIONIQUE INC., dans le cadre de l'autorisation de tâche 4 du contrat W7701-065363. Ces travaux réutilisent l'expertise développée par la section Exploitation spectrale et géospatiale dont un modèle Monte Carlo de la dégradation de l'information 3D de systèmes imageant en présence de diffusion multiple sur les aérosols sert de référence pour la validation.

**Résultats :** Ce rapport de contrat présente un modèle de diffusion capable de reproduire la fonction de transfert de modulation (MTF) d'une source lumineuse vue à travers un aérosol. Ce modèle est basé sur les modèles classiques d'approximation des petits angles, c'est-à-dire qu'il néglige les réflexions vers l'arrière. Le modèle est développé pour produire la MTF d'une source sur un champ de vue pouvant aller jusqu'à 180°, ce qui va bien au-delà de la capacité normale d'un tel modèle. Malgré cela, le modèle produit des résultats acceptables. Il est entre autres capable de reproduire adéquatement le contenu en fréquence du signal diffusé. Les résultats de l'intégration dans Karma montrent des images synthétiques incluant l'effet de diffusion qui a été validé par rapport au modèle Monte Carlo de plus grande fidélité.

**Importance :** L'ajout de la modélisation de la diffusion à l'environnement de simulation Karma de RDDC Valcartier augmente sa capacité à aviser les Forces Canadiennes lors de l'acquisition et l'emploi d'équipements utilisant les nouvelles technologies de détection à imagerie.

**Perspectives :** Le modèle de diffusion sera maintenant utilisé pour exécuter des scénarios de détection à imagerie de menaces dans le cadre du projet 13nm. Des travaux supplémentaires sont prévus dans le cadre du projet 1203 pour DTAES 8 afin de rendre l'utilisation du modèle de diffusion transparent dans Karma, peu importe la longueur d'onde et les conditions environnementales. Le modèle peut être étendu à la bande infrarouge en prenant en compte la proportion entre la partie qui est absorbée et celle qui est diffusée. De plus, une meilleure intégration avec le modèle d'environnement de Karma, appelé *Suite Multi-resolution Atmospheric Radiative Transmission* (SMART) et développé par la section Surveillance et reconnaissance tactique, permettra d'automatiser les pré-calculs. Enfin, des ajustements seront faits afin de pouvoir également utiliser le modèle de diffusion avec des capteurs non imageants tels les détecteur de menaces conventionnels pour lesquels la diffusion est toute aussi significative.





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***Light scattering model for Karma***

***Final Report***

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**In the framework of contract**

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# 1 Introduction

The SMART atmospheric calculation suite and its SMARTI interface can be used to emulate the effects of atmospheric absorption on the signal perceived by an observer. The calculations performed consider that the light that is either absorbed or scattered is lost to the observer. Only the unscattered light reaches him. In reality, we know that some of the light will reach the observer and this light will take the form of a halo around the source. We were asked to make a model capable of reproducing that halo knowing the basic parameters of the problem.

## 2 Proposed model

Reproducing the scattered light distribution through a turbid media can be done various ways. We can use Monte Carlo calculations or analytical models. Most of these calculations will provide excellent results on small angles (less than  $5^\circ$ ). For larger angles, analytical models will eventually drift. Monte Carlo can only provide adequate results if the entire system to model is under experimental control. No system extends to infinity in all directions. The aerosol will end eventually or its properties will change. The travelling light will meet the ground, or be absorbed or masked by some objects. The exact composition of the aerosol, relative concentration and location is never exactly known. Considering those facts, it is understood that a model cannot reproduce reality perfectly but can only produce an estimation of the effect. Considering that calculation time is an important issue in the problem, we have decided to develop a model based on the small angle approximation (SAA). This model is based on the following assumptions.

1. The backscattered light is lost. This will cause losses of precision in the model for aerosol having size parameter lower than 2. The size parameter is given by  $\pi D/\lambda$  where  $D$  is the diameter of the aerosol and  $\lambda$  is the source wavelength.
2. The light source is monochromatic. For polychromatic source, the phase function needs to be evaluated for each of the spectrum wavelengths.
3. The aerosol is made of monodispersed spherical particles. This means that we only need to calculate the phase function using the Mie calculation subroutine once. Otherwise this could increase considerably the calculation time.
4. The aerosol is made of water droplets. This simplifies the problem because we only need the water index database. Other aerosols could be used if the phase function is known.
5. The aerosol is infinite in all directions. It is uniform in density and optical depth in all directions.
6. The source is unpolarized.

### 2.1 The SAA scheme

The SAA scheme converts the aerosol in a multitude of thin layers (Tremblay & Roy, 2011). Each layer is considered infinitely thin and produces only first order scattering. The number of layers is chosen in part to respect that criterion. Figure 1 shows the geometry of the problem. We go from an aerosols system (top) to a layer system (bottom). These models are usually valid for small angular dimensions around the optical axis because backscattered light is neglected. The error caused by this neglected light is important for small aerosols. To produce a model of scattering valid for very large angles, we have to extend the layers to infinity.

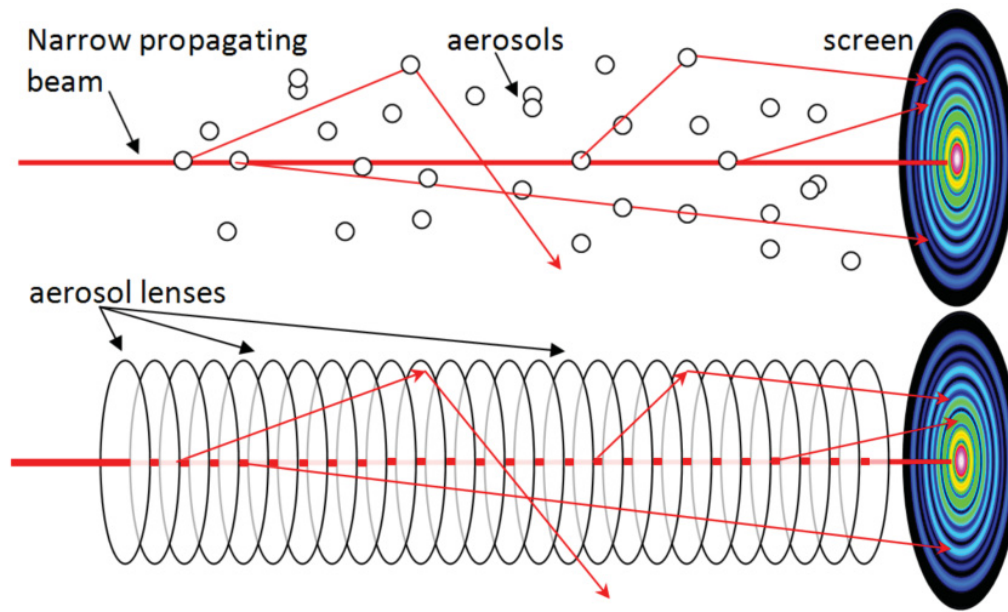


Figure 1. SAA scheme.

## 2.2 Large FOV issues

Large field of views (FOV) are always an issue for modulated transfer function (MTF) calculation. There is no way to reproduce a large FOV on a flat screen or a flat detector without introducing major aberrations in the system. The only way to produce a  $180^\circ$  FOV without aberration is on a dome. Even if the image is perfectly produced on a dome, we will need to produce some sort of rendering of that image on a flat surface thus causing some aberrations. The model considers that the detector of the system is a dome thus eliminating the aberrations from that part of the system. Then we suppose that the image produced on a 2D flat surface will be linear in angular dimension. Thus, on the 2D representation, the surface of a ring sustaining  $1^\circ$  will grow linearly with the distance to the optical axis. The physical surface represented by each ring will not grow linearly and this will create a bias in the representation. This representation gives too much weight to the large angle but this choice simplifies the model and avoids the use of spherical harmonics to estimate the frequency content of the image. On the other hand, the use of spherical harmonics could possibly allow the simulation of backscattered light but this hypothesis is purely speculative at this stage.

## 2.3 Required parameters

The parameters required by the model are listed below.

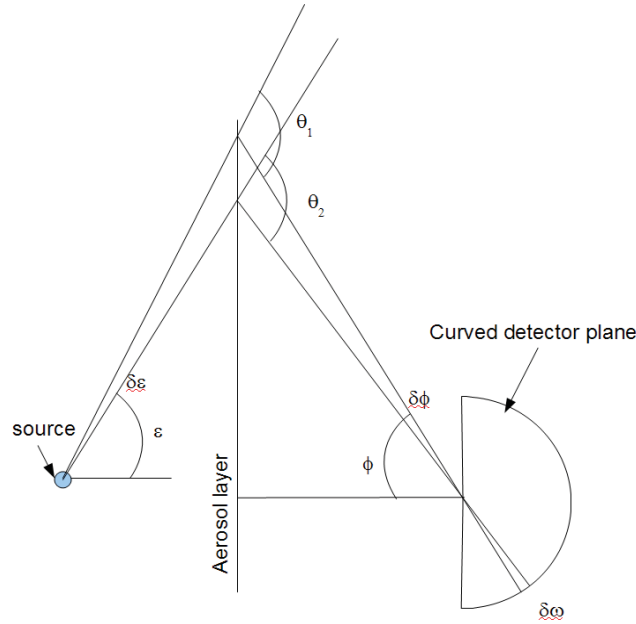
1. The source wavelength in nanometres. It will be used to calculate the aerosol phase function.
2. The source total divergence in radians. It will be used to calculate the contribution of the layer to the captured scattered light.
3. The source profile. The source can be lambertian or isotropic. This will be used to calculate the contribution of the layer to the captured scattered light.
4. The aperture diameter. It will be used to calculate the scattered light and direct illumination intensity on the detector. The MTF calculations are not sensitive to the aperture diameter if it is much smaller than the distance between the source and the receiver. The aperture will be hard coded for the time being.
5. The receiver FOV. It is used to determine the calculation border of the model.
6. The source–receiver distance. It is used to calculate the various angular dimensions of the model. A ratio aperture/distance would produce equivalent results. This distance is not critical for the MTF determination if the distance is much larger than the aperture of the receiver. It will be hard coded for the moment.

7. The number of layers used in the model. Since the aperture and the distance are hard coded, the number of layer is fixed to 100. The distance is fixed to 500 m. The first 40 layers are distributed uniformly between 500 and 100 m of the receiver. The remaining 60 layers are distributed following a geometric progression between 100 m and the receiver.
8. The number of resolution elements. It is the number of angles simulated on the detector. A larger number is more precise but takes more time to compute. For good results, this number should be about twice the number of resolution elements of the camera to simulate.
9. The aerosol optical depth. It determines the optical depth of individual layers. The optical depth is a combination of scattering and absorption. For the time being, the absorption contribution is neglected.
10. The medium index. It is usually air with an index close to 1 and it can be calculated from a database knowing the wavelength. Pressure and temperature are not considered.
11. The aerosol complex index. It is required to calculate the phase function of the aerosol. A water index database is included in the simulator.
12. The average diameter of the aerosols.

## 2.4 The model

The SAA model proposed is based on the model by Tremblay & Roy (2011), an evolution of the standard SAA models (Wells, 1968). Figure 2 shows a schematic view of the model. The receiver is on the right part of the figure and the detector is illustrated using a hemisphere. The model starts on the detector. Knowing the dimension  $\delta\omega$  of a detection element, the limits of this element are projected through the center of the lens. The projections go to the desired layer. Tracing lines from the source to the contact points of these limits, we define the angles  $\theta_1$  and  $\theta_2$ . The aerosol phase function tells us the amount of energy located between these angles. This is the maximum energy that can be scattered on the ring  $\delta\omega$ . This is divided by the square of the distance between the intersect point of the layer and the center of the receiver because intensity goes down with the square of the distance. This is multiplied by the surface of the receiver aperture and corrected for the receiver aperture projection at angle  $\phi$ . The amount of light actually on the layer at an angle  $\varepsilon$  from the source normal depends on the source profile. The intensity is multiplied by the amount of energy within the solid angle  $\delta\varepsilon$ . Finally, this is multiplied by the amount of first order interaction occurring within the layer. This will depend on the layer optical depth.

This last point raises a question: does the layer optical depth change with the value of angle  $\varepsilon$  ? In a physical system where we cut layers, the optical depth is larger. In fact, if we compare the model results with a Monte Carlo simulation, we need to change the optical depth with angle  $\varepsilon$ . This means that for  $\varepsilon$  close to  $\pi/2$ , the thin layer can be very thick violating one of the conditions of the model. Fortunately for us, the influence of these far regions is limited for most of the layers except for those located near the source.



**Figure 2. Schematic representation of the model.**

After all these calculations, we have the total amount of scattered light captured by the receiver on a ring corresponding to  $\delta\omega$ . Repeating the operation for all angles, we will have the total amount of scattered light on the detector. Normalizing each ring by its surface will provide the intensity profile on the detector. An Hankel transform of this distribution will give us the layer MTF. When we have all the layers MTF, they can be multiplied to provide the overall MTF.

From this point, using the equivalence principle, changing the distance between the source and the receiver is just a matter of changing the optical depth of individual layers. The Hankel transform does not need to be done several times to generate the MTF for other distances but we need only to change the amount of scattered light received from each layers.

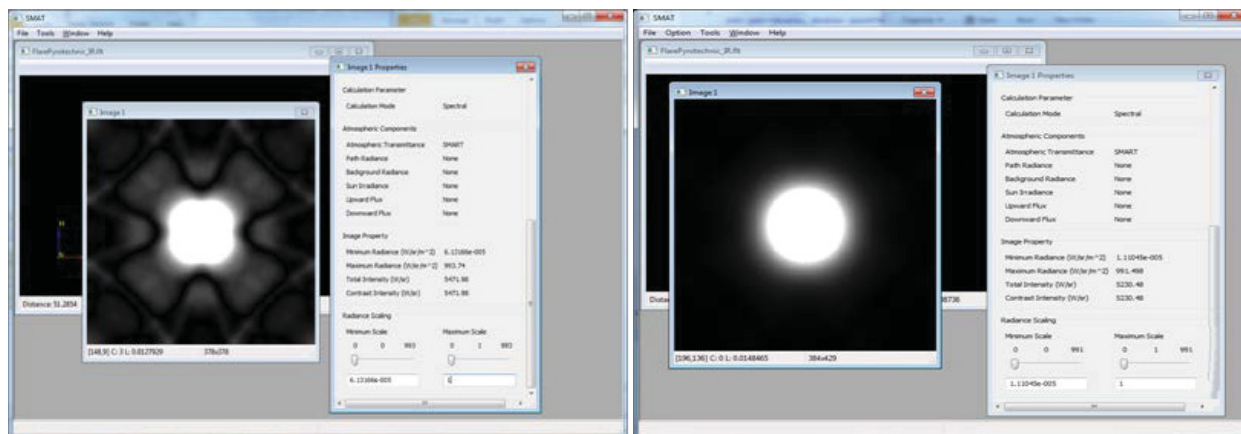
### 3 Implementation in Karma

The model produces a lookup table that contains the value of the MTF for the different spatial frequencies in the image. This MTF is provided for optical depth going from 0 to 5 in the default configuration. Within KARMA, the optical depth is obtained for a given source–receiver distance. The corresponding value of MTF is then taken from the lookup table and used to convolute the image produced by Karma.

A first important point is thus that the MTF cannot be normalized at a value of 1. Normalizing at 1 will take the energy within the image and spread it across the scene. This is not the expected result. We want to add the scattering contribution to the image. To do so, the unscattered contribution to the MTF must have an amplitude of 1 and the MTF must be normalized at a value that takes into account the scattering contribution. For large optical depths, the scattering contribution can dominate the MTF and the MTF can be normalized to high values. We have seen values of more than 30 for frequency 0.

A second point is the importance of interpolation in the MTF. To generate an adequate scene, the values of the MTF must be set properly around the 0 frequency. At this location, the changes in the MTF values are fast and bad interpolation can ruin the results. Figure 3 shows the impact of interpolation. The left figure shows the result of the convolution without interpolation; the right figure shows the results with interpolation.





**Figure 3. The influence of interpolation on the result of the convolution.**

A third point is to understand the convolution process adequately. Convolution of two images can be achieved by multiplying their Fourier transform. The MTF is already a Fourier transform, the Fourier transform of the point spread function (PSF). But the fast Fourier transform (FFT) of the image will place the zero frequency in the corner of the image while the zero frequency of the MTF is centered. The frequency content of the MTF must be properly shifted before the multiplication.

A last point concerns the dimensions of the images. FFT are performed on vector whose length is a power of 2 (2, 4, 8, 16, 32, 64, 128, etc.). If we are to use an image with another length, the FFT algorithm will make some padding and restore the original image after the operation. This works well in the case of an image made of an even number of pixels. We had some problems with images having an odd number of pixels. The cause is not clearly identified at this stage.

## 4 Validation of the results

A thorough validation process includes comparison with experimental measurements made in a controlled environment and independent calculation. We do not have experimental measurements on wide FOV acquisition of scattered system but we have a validated Monte Carlo simulator that can be used for validation. We first verify that the model gives results equivalent to the Monte Carlo simulation. Then we verify that the implementation of the model in Karma gives results equivalent to the Monte Carlo simulation.

### 4.1 Comparison between the model and the Undique Monte Carlo simulator

The model was validated using the Undique Monte Carlo simulator. The simulator is not capable of imaging over  $180^\circ$  and was modified to capture the photons on a dome structure similar to the structure used in the model. The MTF were calculated using the Undique standard process for MTF calculation. The results are presented here for an optical depth of 2 at a wavelength of 532 nm and a FOV of  $180^\circ$ . The results are shown for water droplet of 0.1  $\mu\text{m}$ , 1  $\mu\text{m}$ , 10  $\mu\text{m}$ , and 100  $\mu\text{m}$  in diameter. We see that in the 0.1  $\mu\text{m}$  case the scattered light contribution is underestimated. Nevertheless, the cut-off frequency of the curves are the same and the curves have the same profile showing that the frequency content is well represented but not the ratio of scattered to unscattered. We have a good agreement with the 1  $\mu\text{m}$  and the 10  $\mu\text{m}$  case for the ratios and for the frequency content. This is very good news since atmospheric aerosols are often located in this range. The 100  $\mu\text{m}$  case presents an odd behaviour. We see that the scattered light level is over estimated. This is not supposed to happen with a SAA approximation model. The difference is small and could come from the optimization criteria of the Monte Carlo simulator. We did not have time to investigate further.

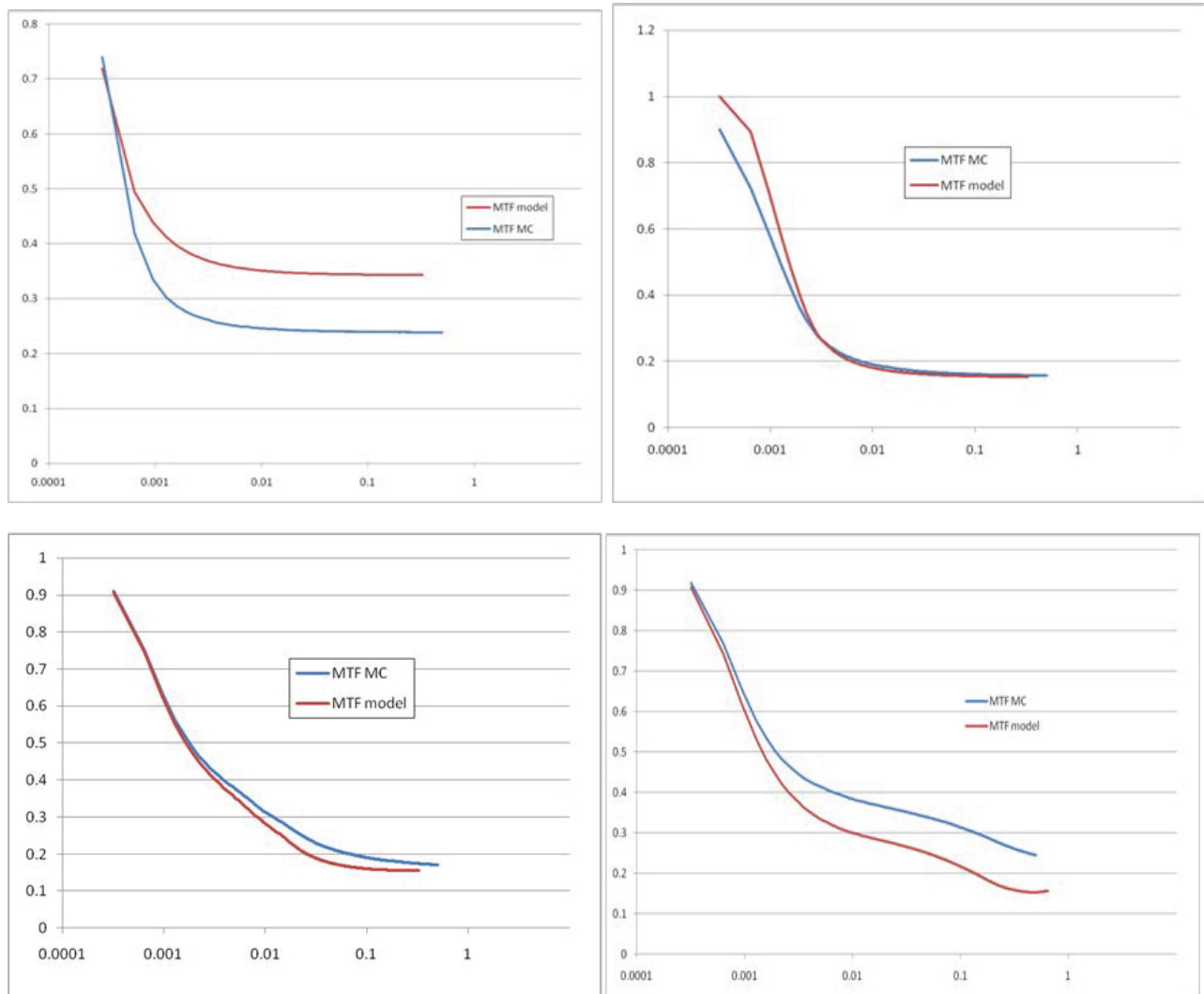


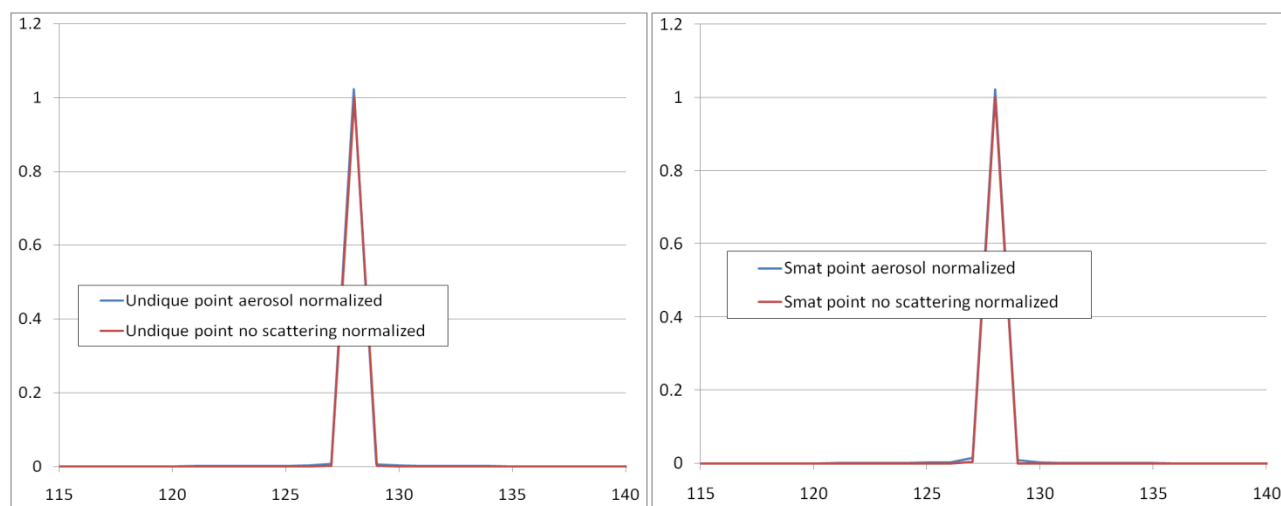
Figure 4. Validation of the model with the Undique Monte Carlo simulator (in the usual order:  $0.1 \mu\text{m}$ ,  $1 \mu\text{m}$ ,  $10 \mu\text{m}$ , and  $100 \mu\text{m}$ ).

## 4.2 Comparison between the Monte Carlo and the implementation of the model in Karma

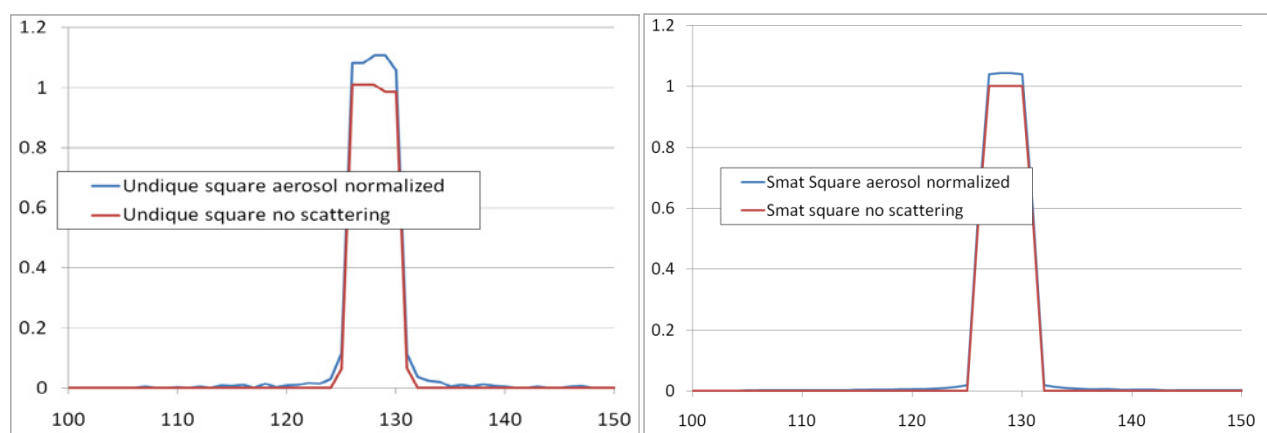
The model was implemented in Karma and we did a simple validation to verify that the convolution process works adequately. Figure 5 shows the comparison between the simulation made by the Undique Monte Carlo simulation and the image generated by the Signature Modeling and Analysis Tool (SMAT) using Karma's implementation of the model. The left image shows the Monte Carlo results. The red curve is the result without the scattering contribution and the blue curve is the result with the scattering contribution. We can see that the maximum of the curve is a little stronger when scattering is considered. The right figure shows the same thing but this time the calculations are done by SMAT and the lookup table generated by the model. We see the same behaviour.

Figure 6 presents the same results but this time a square source is used. Again we see the reproduction of similar behaviour although this time the intensity of the scattered signal with the model and SMAT is lower than the Monte Carlo results. Nevertheless, the model changes the image and makes it closer to the expected results. We have to note that both squares are not centered on the same amount of pixels but this should have no impact on the result.

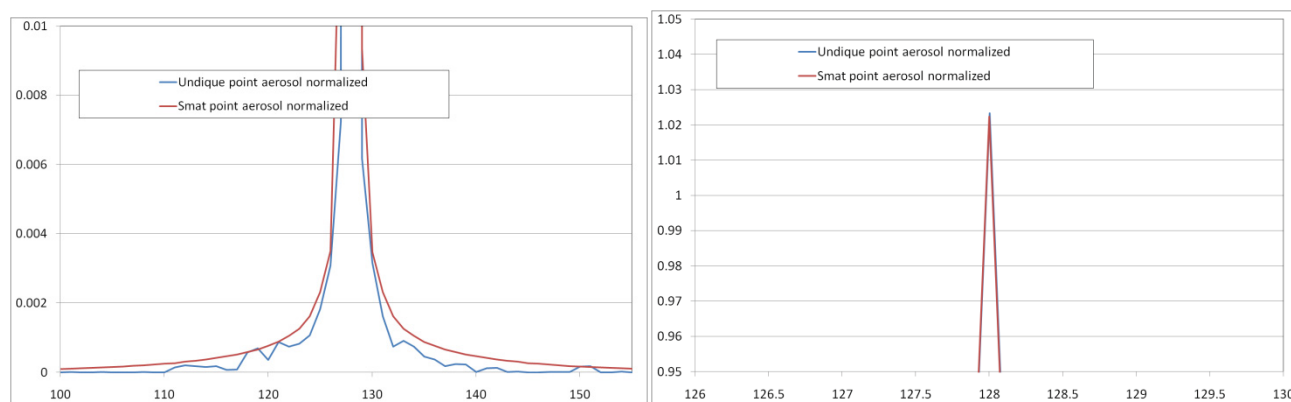
Figure 7 compares the SMAT and Undique scattered case. The left figure shows the details of the bottom of the curves and the right figure shows the tip of the curves. Both methods provide equivalent results.



**Figure 5. Comparison between SMAT and Undique: scattered versus unscattered point source case.**



**Figure 6. Comparison between SMAT and Undique: scattered versus unscattered square source case.**



**Figure 7. Comparison between SMAT and Undique: scattered superposition.**

## 5 Conclusion

We have presented the model used to calculate the MTF of a source propagating through an aerosol. Although this model has some limitations, it was shown to reproduce adequately the behaviour of scattered light in an optical system.

## 6 Reference

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Willard H. Wells, “**Loss of resolution in water as a result of multiple small-angle scattering**”, J. Opt. Soc. Am., 59, 686 (1969).

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Defence Research and Development Canada – Valcartier (DRDC Valcartier) studies threat warning imaging systems. The Karma engagement simulation framework was used to generate synthetic images as seen by these sensors. In order to provide a valid representation in the ultraviolet band for which the scattering phenomenon through aerosols present in the atmosphere is significant, a scattering model was integrated into Karma's scene generation module. This contract report presents a scattering model able to reproduce the Modulation Transfer Function (MTF) of a source as seen through aerosols. This model was based on the classical Small Angle Approximation (SAA) scheme, which means that the backscattering contribution was neglected. The model was made to produce the MTF on field of views of up to 180°, which is far beyond the usual capacity of these models. Nevertheless, the model adequately reproduced the expected MTF. The frequency content was reproduced adequately. The results of the integration in Karma showed synthetic images including the scattering effect, which was validated against a higher fidelity Monte Carlo model.

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Recherche et développement pour la défense Canada – Valcartier (RDDC Valcartier) étudie les systèmes imageants de détection de menaces. L'environnement de simulation d'engagement Karma est utilisé pour générer des images synthétiques telles que vues par ces capteurs. Afin d'offrir une représentation valide dans la bande ultraviolette où le phénomène de diffusion dû à la présence d'aérosols dans l'atmosphère devient significatif, un modèle de diffusion a été intégré au module de génération de scène de Karma. Ce rapport de contrat présente un modèle de diffusion capable de reproduire la fonction de transfert de modulation (MTF) d'une source lumineuse vue à travers un aérosol. Ce modèle est basé sur les modèles classiques d'approximation des petits angles, c'est-à-dire qu'il néglige les réflexions vers l'arrière. Le modèle est développé pour produire la MTF d'une source sur un champ de vue pouvant aller jusqu'à 180°, ce qui va bien au-delà de la capacité normale d'un tel modèle. Malgré cela, le modèle produit des résultats acceptables. Il est entre autres capable de reproduire adéquatement le contenu en fréquence du signal diffusé. Les résultats de l'intégration dans Karma montrent des images synthétiques incluant l'effet de diffusion qui a été validé par rapport à un modèle Monte Carlo de plus grande fidélité.

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scattering; light; modelling; simulation; scene generation; aerosol imaging sensor



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