# THE FRESCO+ CLOUD ALGORITHM FOR GOME AND SCIAMACHY: IMPROVEMENT AND VALIDATION

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## ABSTRACT

The FRESCO (Fast Retrieval Scheme for Clouds from the Oxygen A-band) algorithm simulates the measured TOA reflectance at 758, 761, and 765 nm, by considering $O_2$ absorption, cloud and surface reflections. In the new version FRESCO+, single Rayleigh scattering is added to the retrieval algorithm. The retrieved FRESCO(+) products are effective cloud fraction and cloud pressure. Here we show the principle of FRESCO+, the comparison with SGP/ARM cloud height data and the application in $O_3$ total column retrievals.

## 1. INTRODUCTION

FRESCO (Fast Retrieval Scheme for Clouds from the Oxygen A-band) is being used for GOME, SCIAMACHY and GOME-2. By using oxygen as a well-mixed gas, the cloud pressure can be retrieved in a straightforward way. In FRESCO the cloud pressure and the effective cloud fraction are retrieved from top-of-atmosphere reflectances in three 1-nm wide wavelength windows at 758-759, 760-761, and 765-766 nm. The cloud is assumed to be a Lambertian surface with albedo 0.8, and only absorption due to $O_2$ above the cloud or the ground surface and reflections from the surface and cloud have been taken into account [1]. In FRESCO+ single Rayleigh scattering is added to the transmission and reflectance databases (forward calculations) and the retrieval. Therefore FRESCO+ is an improvement of FRESCO in physics. FRESCO(+) is mainly used for cloud correction or cloud masking in retrieval of trace gases, such as $O_3$ and $NO_2$. For tropospheric trace gas retrievals the less cloudy pixels (with an effective cloud fraction below about 0.2) are most relevant [2].

## 2. PRINCIPLE OF FRESCO+

FRESCO+ retrieves cloud fraction from the continuum at 758 nm, and retrieves the cloud pressure from the strong and weak absorption bands at about 760 and 765 nm. Due to the presence of clouds, the reflectance at continuum is larger than the clear sky scene, and the depth of strong and weak absorption band varies according to the height of the cloud and the optical thickness. Typical GOME spectra with the high and low clouds are shown in Fig. 1. The principle of the FRESCO+ atmosphere model is shown in Fig. 2.

The reflectance ($R_{sim}$) at TOA is the sum of the reflectances from the cloud-free and cloudy parts of the pixel

$$R_{sim} = cT_cA_c + (1-c)T_sA_s + cR_c + (1-c)R_s, \qquad (1)$$

where $c$ is the effective cloud fraction, $R_c$, $R_s$, $T_c$, $T_s$ are the single Rayleigh scattering reflectances and transmittances of the cloud-free and cloudy parts of the pixel, respectively. $T_c$, $T_s$ also contain $O_2$ absorption, and are pre-calculated as a function of SZA, VZA, wavelength, and surface or cloud height. Cloud top albedo ($A_c$) is assumed to be 0.8. $A_s$ is the surface albedo from climatology [3, 4]. Rayleigh scattering is a small but significant contribution to $R_{sim}$ in the case of almost cloud-free pixels.

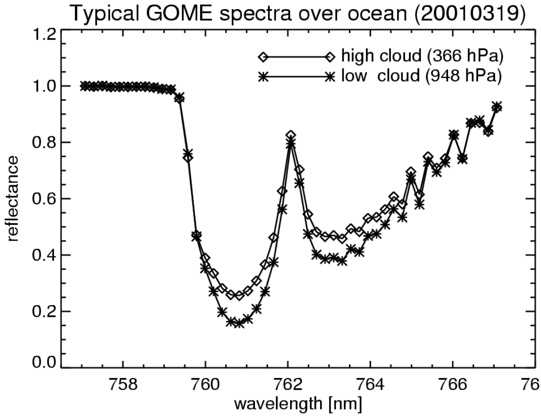

*Figure 1. Typical $O_2$ A-band spectra from GOME. The spectra are normalized at 758 nm to show the depth of the band for clouds of different heights.*

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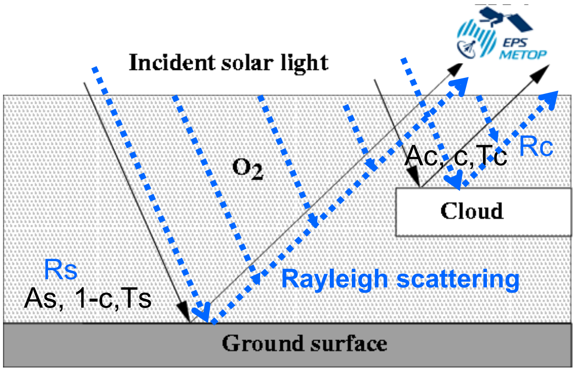

*Figure 2. FRESCO+ principle. The cloud and surface are both Lambertian reflectors. Two light paths are considered, from sun to surface to satellite and from sun to cloud to satellite. $O_2$ absorption and single Rayleigh scattering, of which the light paths are in blue, is included in the forward model simulation.*

## 3. RESULTS OF FRESCO+

When the effective cloud fraction is below 0.01, the FRESCO retrieved cloud pressures are often at 130 hPa, the upper limit of the FRESCO cloud pressure, which is not realistic. As shown in Fig. 3 it seems there is a gap between cloud fraction 0 and 0.01 in FRESCO cloud fraction. FRESCO+ retrieves more reasonable cloud pressures than FRESCO, even if the cloud fraction is less than 0.01. So, in Fig. 3 the FRESCO+ cloud pressures are reasonable values which fill the gap.

Due to the addition of single Rayleigh scattering in FRESCO+, the cloud pressure is higher than FRESCO, especially when cloud fraction is small, see Fig. 4. On average FRESCO+ cloud pressure is about 57 hPa higher than FRESCO. The difference in cloud pressure is larger for the less cloudy pixels than for the fully cloudy pixels, which depends on the relative amount of single Rayleigh scattering reflectance. The change in cloud fraction as compared to FRESCO is very small, about 0.01 [2], with FRESCO+ cloud fraction being larger.

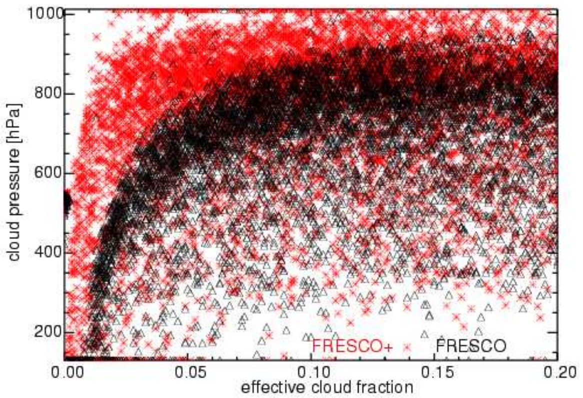

*Figure 3. Cloud pressure from FRESCO and FRESCO+ as a function of effective cloud fraction for GOME data on July 16, 1997.*

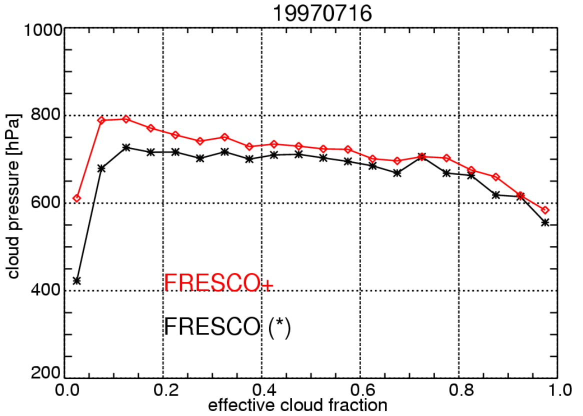

*Figure 4. Same as Fig. 3 but averaged over 0.05 cloud fraction bins.*

## 4. FRESCO+ CLOUD HEIGHT VALIDATION

$O_2$ A-band spectra have been simulated with the DAK model [5, 6], assuming a single layer and two-layer scattering clouds with different optical thickness and height, respectively. We also simulated the $O_2$ A-band spectrum without clouds to get the mixed spectra for the partly cloudy scene. The $O_2$ absorption cross sections are calculated line-by-line using HITRAN 2004 line parameters [7].

FRESCO+ and FRESCO cloud heights have been retrieved for simulated spectra. Cloud heights retrieved from the single layer, fully cloudy and partly cloudy scenes are shown in Fig. 5. For a single layer cloud, FRESCO(+) cloud height is close to the middle of the cloud rather than the cloud top, except for that at large SZA. FRESCO cloud height is a little higher than

FRESCO+ for both fully cloudy and partly cloudy scenes. The FRESCO cloud heights are the same for fully and partly cloudy scenes. However, FRESCO+ cloud height for partly cloudy scenes is lower than for fully cloudy scenes. This is because of the adding of single Rayleigh scattering in FRESCO+, so we see the difference of Rayleigh scattering in the clear part of the pixel. The cloud heights retrieved from the two-layer cloud scenes are shown in Fig. 6. They are both fully cloudy scenes but one is for optically thin cloud, another is for optically thick cloud. The FRESCO(+) cloud heights are between the two cloud layers, FRESCO+ cloud height is again lower than FRESCO. The cloud height retrieved from the optically thick cloud is higher than retrieved from the optically thin cloud. From the simulation we know that using a Lambertian reflector to approximate the reflectance from the real cloud will give a cloud height lower than the top of the cloud. The retrieved cloud height is in fact the height which produce a similar $O_2$ absorption as the scattering cloud in the scenes. There is also $O_2$ absorption inside the cloud, and $O_2$ absorption can be increased due to increase of the light path by multiple scattering, The Lambertian cloud cannot simulate $O_2$ absorption inside the cloud, so the retrieved cloud height has to be lower to produce more $O_2$ absorption. In fact, the retrieved cloud height depends on the cloud optical thickness, geometric height, SZA and the viewing geometry.

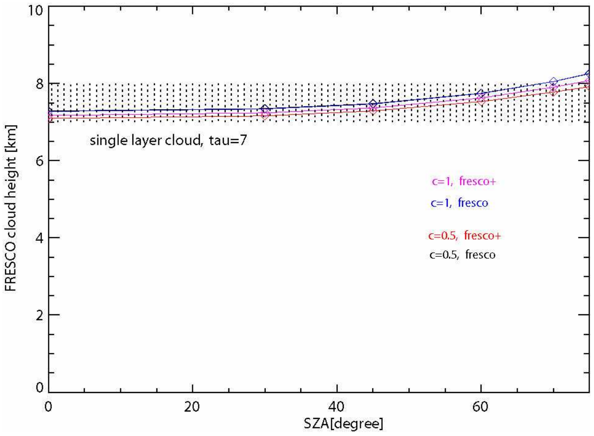

Figure 5. *Single layer cloud. FRESCO(+) cloud height retrieved from the DAK model simulated $O_2$ A-band spectra. The clouds are scattering clouds with H-G phase function, g=0.85.*

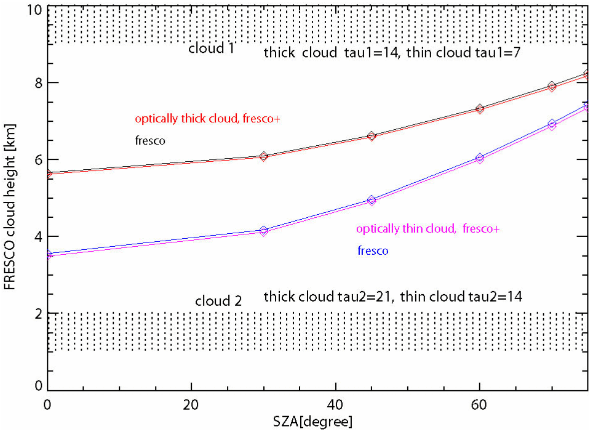

Figure 6. *Two-layer cloud. FRESCO(+) cloud height retrieved from the DAK model simulated $O_2$ A-band spectra. The clouds are scattering clouds with H-G phase function, g=0.85.*

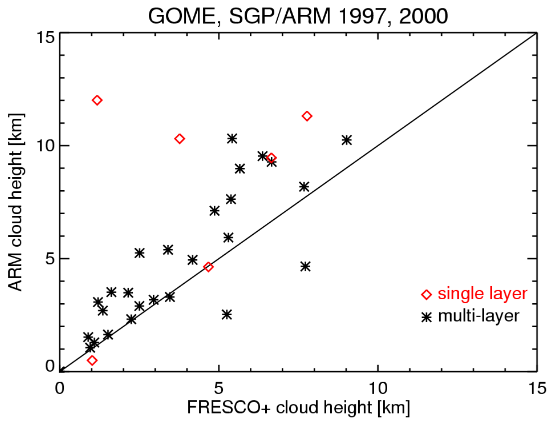

*Figure 7. Comparison between FRESCO+ cloud height and SGP/ARM site cloud height. Correlation coefficient is 0.8.*

FRESCO+ cloud heights are compared with SGP/ARM site Lidar/Radar cloud boundaries data in Fig. 7. ARM data within one hour of the GOME overpass and cloud cover longer than 0.5 hour are selected. The ARM cloud height is the weighted average cloud top height of all the clouds in the collocated pixel. The comparison with SGP/ARM cloud height confirmed our understanding of FRESCO(+) cloud height, namely that it is lower than the real cloud top height.

## 5. FRESCO(+) CLOUD HEIGHT IN $O_3$ RETRIEVAL

As we known FRESCO cloud height is close to the middle of the cloud, rather than the real cloud top. We simulated the impact of FRESCO cloud heights on $O_3$ total column ($N_t$) retrieval for fully cloudy scenes using:

$$N_t = \frac{N_s}{M} + N_g \qquad (2)$$

The real cloud scene is a Mie 'C1' type cloud at 1-8 km and optical thickness 70, optical depth is 10 per km. The $O_3$ airmass factors are calculated at 330 nm. The $O_3$ profile is from the mid-latitude summer atmosphere profile. The total $O_3$ vertical column is about 340 DU. Steps for simulation are the following:

1) calculate $O_2$ A-band spectra with scattering cloud, do FRESCO retrieval, get $P_c$, $c_{eff}$.
2) assume an $O_3$ profile, calculate $O_3$ AMFs for cloudy and clear scenes ($M_{sca}$, $M_{clear}$). The cloud is the same as in 1).
3) calculate AMFs with Lambertian cloud at several heights ($M$).
4) integral $O_3$ profile, get $N_v$ (total vertical column) and $N_g$ (ghost column). The $O_3$ slant column is $N_s = N_v M_{sca}$.
5) use Eq. 2 to calculate $N_t$.
6) compare $N_v$ and $N_t$.

The $O_3$ AMFs with a Lambertian cloud at several heights and a Mie scattering cloud are shown in Fig. 8. The $O_3$ AMFs with a Lambertian cloud decreases with the increase of the Lambertian cloud height.

The $O_3$ total column relative differences between the retrieved and real vertical columns of $O_3$ are shown in Fig. 9. For this cloud scene, the FRESCO cloud height (5.3 km) gives a smaller error than the real cloud top height (8 km). The difference is smaller for partly cloudy scenes because we assume that there is no error in the clear part of the pixel. For an optically thin cloud the FRESCO cloud height also gives a smaller error in $O_3$ total column than using the real cloud top height.

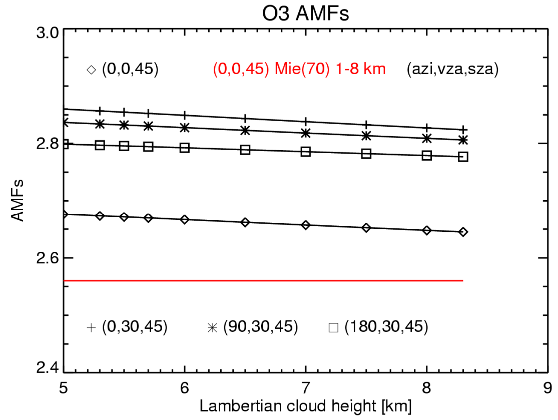

*Figure 8. The $O_3$ AMFs are calculated at 330 nm with Lambertian clouds and Mie clouds, SZA=45°, VZA=0° (nadir). For a Lambertian cloud scene, AMFs at three additional geometries are plotted, VZA=30°, AZI=0, 90, 180°.*

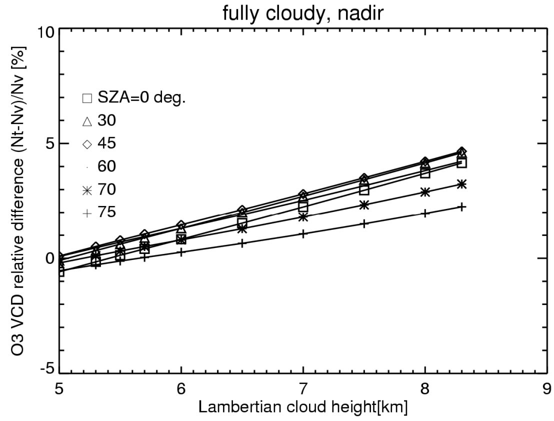

*Figure 9. $O_3$ total column relative difference between $N_t$ (retrieved column) and $N_v$ ( real column).*

## 6. CONCLUSIONS

Including single Rayleigh scattering improves the FRESCO+ cloud pressure for the less cloudy pixels, which are most relevant for the observation of tropospheric pollution, e.g. tropospheric $NO_2$.

Comparison of FRESCO(+) cloud height and Lidar/Radr cloud height at SGP/ARM site shows reasonable correlation. It confirmed that the FRESCO(+) cloud height is close to averaged cloud height or middle of the clouds.

Photons can penetrate a cloud until a certain altitude, which is similar in the UV and visible. The retrieved FRESCO(+) cloud height near the middle of the cloud compensates for the $O_3$ absorption in the cloud. Therefore, under the same Lambertian cloud assumption in FRESCO(+) and $O_3$ total column retrievals, the FRESCO(+) cloud height is better than the real cloud top height. Of course if one is using a scattering cloud in the $O_3$ AMF calculation, the cloud parameters should be retrieved using a scattering cloud model.

FRESCO and FRESCO+ data are freely available at the TEMIS website: www.temis.nl

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