UV Remote Sensing of Volcanic Ash

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The top-of-atmosphere radiance ($L_{TOA}$) can be separated into three different contributions for an aerosol laden atmosphere.

- **Radiance reflected from underlying surface**
- **Backscattered radiance by air molecules**: Rayleigh scattering + gas absorption
- **Radiance change due to aerosol scattering and absorption**

$$L_{TOA} = L_{atmo} + L_{surf} + L_{aer}$$
Spectral Dependence of Radiance contributions: Atmospheric Backscattering and Surface Reflection

- $L_{\text{atmo}}$: Atmosphere
- $L_{\text{surf}}$: Desert
- $L_{\text{surf}}$: Ocean
- $L_{\text{surf}}$: Vegetation

- Surface Albedo
- \( \lambda = 340 \text{ nm} \)
- \( \lambda = 440 \text{ nm} \)
- \( \lambda = 500 \text{ nm} \)
Spectral Dependence of Aerosol Effects: $L_{aer}$

$L_{aer}(\lambda) \approx AS + (L_{surf} + L'_{atmo})(1-\text{AA})$

where AS is aerosol scattering,

AA is aerosol absorption,

$L'_{atmo}$ is atmospheric radiance from under the aerosol layer.

- $L'_{atmo}$ is large in UV, small in VIS/NIR.
- In UV, aerosol measurement is accomplished by quantifying its scattering and absorption effects.
- In VIS/NIR, aerosol measurement is primarily relied on quantification of aerosol scattering, when surface is dark or when surface reflection is properly accounted for.
UV Aerosol Index (AI): Quantification of Radiance Change

Definition of Aerosol Index (AI):
Spectral slope of $R_{\lambda}$, proportional to AI value.

The spectral dependence of TOA radiance change is most pronounced for UV-absorbing aerosols, which cause $R_{\lambda}$ to increase with wavelength: $+AI$

Non-absorbing aerosols, under certain conditions, can cause $R_{\lambda}$ to decrease with wavelength: $-AI$
UV Aerosol Index (AI)

- AI is computed without any information about the aerosol particles (e.g., the refractive index and particle size distribution), and is determined by the deviation from Rayleigh atmosphere.
- AI can be used to determine their location and the relative amount of UV absorbing aerosols, even over bright surfaces, such as snow/ice or meteorological clouds.
Mapping of UV Absorbing Aerosols: Sample AI Data from SNPP/OMPS
Volcanic Ash Detection: Fresh Eruption Clouds

- Okmok; 7/12/2008
- Kasatochi; 8/8/2008
- Montserrat; 2/11/2010
Ash and SO$_2$: Grímsvötn, May 2011
Eyjafjallajökull Ash: Pixel Size Effect

April 15, 2010

GOME-2
80 km x 40 km

May 5, 2010

OMI
13 km x 24 km
SNPP/OMPS @ High Spatial Resolution Mode
Future JPSS-1&2 will have similar high resolution

12 km x 12 km

SO₂ VCD (DU)

UV Aerosol Index

Eruption of Sangeang Api (Indonesia) 05/31/2014

EPIC on NOAA/NASA DSCOVR at L-1 point, observes sunlit side of the Earth (UV/VIS discrete channels) at a spatial resolution of 24 km x 24 km, provides ash/\(\text{SO}_2\).

- TROPOMI on ESA polar orbiting Sentinel-5 Precursor, provides ash/SO$_2$ at a spatial resolution of 7 km x 7 km.
Quantification of Volcanic Ash

**Volcanic Cloud: Mixtures of Water/Ice Clouds and Ash Particles**
Micro-physical properties of each component:
- Particle shape (e.g., sphere/spheroid/irregular), mass density (e.g., $\rho_{ash} = 2.75 \text{ g/cm}^3$)
- Size distribution (e.g., Log-normal for ash particles, $r_{eff} = 2 \mu \text{m, } \sigma=1.6$)
- Refractive index (e.g., real = 1.5, imag = 0.005, independent of $\lambda$)

**Volcanic Cloud: Optical Properties**
Mass Coefficients: Scattering ($K_{sca}$), Absorption ($K_{abs}$),
Extinction ($K_{ext} = K_{sca} + K_{abs}$), Single Scattering Albedo ($\omega_0 = K_{sca}/K_{ext}$), and Scattering Phase Function

**Vertical Distribution of Particles:**
Layer height estimated from radiance measurements or trajectory analysis
**Surface Albedo**
Estimated from radiance measurements or based on climatology

**Extinction Optical Depths for Each Components:**
Estimated from satellite radiance spectra

**Ash Mass Concentration** ($\text{g/m}^2$)
Ash Concentration Estimation

Grimsvötn, 05/23/2011  OMI
Plume Height Retrieval

Kasatochi SO₂ Plume: August 9, 2008

SO₂

GOME-2 SO₂:
Total Mass: 1.5 Mt

OMI SO₂:
Total Mass: 1.6 Mt
August 2008 Kasatochi Eruption

Comparisons with CALIPSO

\[ \beta \times 10^3 \text{ (km}^{-1} \text{ sr}^{-1}) \]
Value of UV Data

UV spectra are highly sensitive to ash (absorbing aerosols) and SO$_2$ in the atmosphere.

Volcanic clouds under a wide range of conditions:

- Detectable independent of water/ice content or surface conditions
- Detectable for fresh (dense) plumes
- Detectable for aged (weak) SO$_2$ plumes: long-term tracking
- Detectable down to the lower troposphere, including SO$_2$ from degassing: volcanic unrest
- Plume height from SO$_2$ measurements
- Ash amount given ash cloud particle properties
Synergy of UV and IR

- Both UV and IR measurements are sensitive to ash particle size and composition, and its vertical location.
- Combining hyper-spectral UV (OMI, GOME2, OMPS) and IR (AIRS, IASI, CrIS) measurements provides greater constraints to a retrieval algorithm, and likely leads to more accurate estimates of volcanic ash particle size, plume height and loading.