UTILIZATION OF RADIATIVE TRANSFER CODE FOR SATELLITE IMAGE PROCESSING

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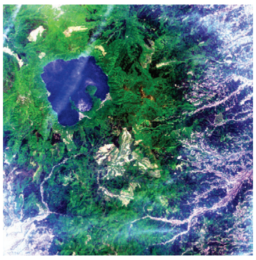

Before correction (DN)

After correction (Reflectance)

Landsat ETM+: 2003/5/25 Lake Towada

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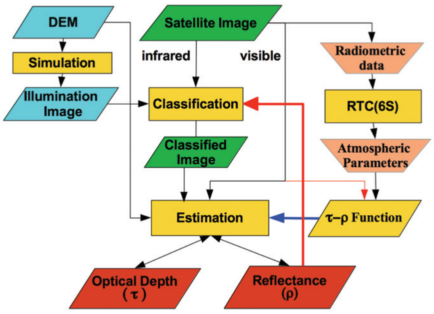
Simultaneous Estimation Method

$\rho = \rho(\overline{\tau}|\ L, \beta, ...)$ $\overline{\tau}$: averaged over neigboring pixels

$\tau = \tau(\overline{\rho}|\ L, \beta, ...)$ $\overline{\rho}$: averaged over homogeneous class



Pixels which look same
if there is no atmosphere
same reflectance (BRDF)
same illumination

Incident angle β
Emission angle γ
Infra-red images
Landcover class

Y.Iikura, M. Takeo, N. Manago, and H. Kuze, Surface reflectance estimation from satellite imagery with inhomogeneous atmospheric conditions, IGARSS2015

What is the purpose of the satellite image processing ?

* optical sensor with moderate spatial resolution
Landsat ETM+, ALOS AVNIR2, ASTER,

Extraction of Surface Information (Reflectance ρ)

quantitative, universal, comparable, ...

$$\rho = \rho(L, \tau, \beta, ...)$$

L : Radiance at Sensor calculated from Satellite Data
τ : Optical Depth (Atmospheric Conditions)
β : Solar Incident Angle (Topographical Conditions)

Extraction of optical depth (Atmospheric Conditions τ)

* Estimation of Surface Reflectance ρ from Satellite Imagery

Flat Terrain (based on 6S):

$$\rho = \frac{\pi(L_s - L_p - L_b)}{T_s(E_o T_\theta \cos\theta + E_d + E_e)}$$

Rugged terrain:

$$\rho = \frac{\pi(L_s - L_p - L_b)}{T_s(E_o T_\theta \cos\beta + E_d^* + E_e^* + E_t)}$$

Ed* = Ed * sky view factor
Ee* = Ee * sky view factor
Et : reflected irradiance from neigboring pixels
cos β : solar incident angle to the surface

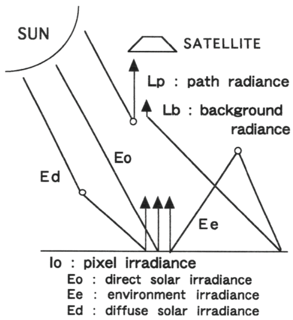
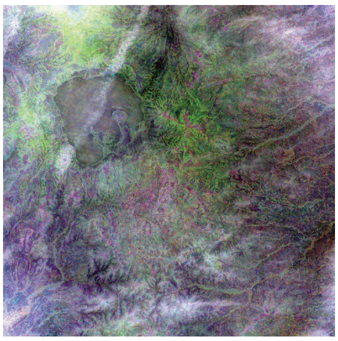


Fig.1 Physical Model of Satellite Data

Y.Iikura, Precise evaluation of topographic effects in satellite imagery for illumination correction, IGARSS2008

Estimation of Aerosol Distribution

Optical depth at 550nm



before spatial smoothing

after spatial smoothing

Explanatory Variables of the Correction Parameters

$$\rho = \frac{\pi(L_s - L_p - L_b)}{T_s(E_o T_\theta \cos\beta + E_d + E_e)}$$

Under the same solar position, atmospheric model, aerosol type

$$L_s = gain * DN + offset$$
$$L_p = L_p(\tau_o, h, \alpha)$$
$$L_b = L_b(\tau_o, h, \alpha, \overline{\rho}, S)$$
$$E_d = E_d(\tau_o, h)$$
$$E_e = E_e(\tau_o, h, \overline{\rho}, S)$$
$$S = S(\tau_o, h)$$: spherical albedo
$$T_s = e^{-\tau/\cos\alpha}$$
$$\tau = \tau(\tau_o, h)$$

h : surface elevation
τ_o : optical depth at 550nm and h=0m
α : sensor viewing angle

Calculation of correction Parameters by 6S

Input

```
0                                      (User Condition)
29.0 130.0  38.0 278.8  5 21           (Sun-Target Sensor Geometry)
2                 α                    (Mid Latitude Summer)
2                                      (AEROSOLS MODEL : Maritime)
0                                      (Optical thickness at 550nm )
0.2427 =>0.0524    τo
-0.0 => -3.0      h                    (TARGET ALTITUDE IN KM)
-1000                                  (SATELLITE CASE)
166                                    (ALOS AVNIR2 Band 1)
0                                      (HOMOGENEOUS CASE)
0                                      (no DIRECTIONAL EFFECTS)
0                                      (Reflectance)
0.12   ρ̄
-1                                     (No Atmospheric correction)
```

OUTPUT

```
*                 irr. at ground level (w/m2/mic)                  *
* direct solar irr.    atm. diffuse irr.    environment  irr       *
*         903.650             503.222              34.378          *
*                  rad at satel. level (w/m2/sr/mic)               *
* atm. intrin. rad.    background  rad.     pixel  radiance        *
*          45.930              17.940               28.483         *
```


6S

Input

```
0                          (User Condition)
60.0 0.0 0.0 0.0  6 30     (Sun-Target Sensor Geometry)
8                          (User-defined molecular atmospheric model)
0.00001 0.139              ( H2O g/cm2, O3 cm atm )
2                          (AEROSOLS MODEL : Maritime)
23                         (visibility)
-0.0                       (TARGET ALTITUDE IN KM)
-1000                      (SATELLITE CASE)
0                          (wave length is given)
0.4 0.405  =>(0.4~1.5)
0                          (HOMOGENEOUS CASE)
0                          (no DIRECTIONNAL EFFECTS)
0                          (Reflectance)
0.3
-1                         (No Atmospheric correction)
```

Output

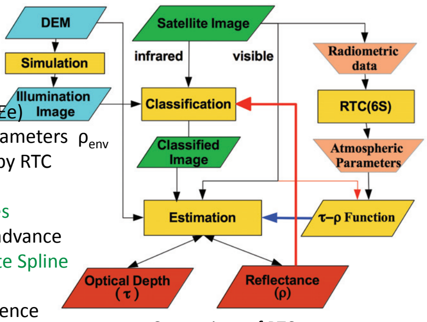
$$\rho = \frac{\pi(L_s - L_p - L_b)}{T_s(E_o T_\theta \cos\theta + E_d + E_e)}$$

$$T_s = e^{-\tau/\cos\alpha}$$
$$\tau = \tau(\tau_o, h)$$
$$S = S(\tau_o, h)$$

Problems and Solutions

* Programs are wrtten in Python

Classification by K-Mean Method
    scipy.cluster.vq.kmeans
Surface Elevation and optical depth
    scale height incorpolated
Treatment of Adjacent Effect (Lb & Ee)
    reduction of calculation for parameters ρ_{env}
Interpolation from Simulated Data by RTC
    10 x 10 x 10 for (τ_o、h、α)
    scipy.ndimage.map_coordinates
calculation of ρ-τ(ρ_{env}) function in advance
    speed ⇔ memory RectBivariate Spline



Iterative Estimation and It' Convergence
    scipy.interpolate.RectBivariate Spline
    np.polyfit & np.poly1d

Comparison of RTC:
    6S, Modtran, RSTAR
* Software made in Japan

Post Processing: interpretation of reflectance and optical depth

Modtran

Input : radiance mode (IEMSCT=2)   reflectance 0.0 0.1 0.2

```
MM  7   2   2   1   0   0   0   0   0   0   0   1   1   .000   0.30
tt  8f  0  330.000  g0.00001   a0.139 f t f f
DATA/B2001_01.BIN
   4   0USS 0   0   0   023.0000000.000000000.000000000.000000000.000000000
  36   0   2          Custom      0
.000000000.000000000.000000000.000000000.000000000.0000000002222222222222222 6
          .154081603          .000000000.000000000.000000000.000000000        US76
ibid.
100.000000.000000000.000000000.000000000.000000000.0000000002222222222222222 6
          .000000000          .000000000.000000000.000000000.000000000
  20   0   0   0
 0.000e+00                                                               title
.350001.13862.015725.73930.400001.09997.013486.73919.412001.09297.013051.73820
.443001.06973.011970.73850.470001.05181.011182.73820.488001.03780.010659.73984
.515001.02380.010555.73896.550001.00000.010974.74235.59000.982358.010053.74170
.63300.965276.010218.74271.67000.947914.009916.74382.69400.942033.009473.74396
.76000.917110.010815.74658.86000.888267.011646.750211.2400.819098.016168.76080
1.5360.760571.022546.775231.6500.744049.018751.777941.9500.716046.040828.78503
2.2500.653038.074506.809123.7500.550266.015630.74654
    20.000      .000   180.000      .000      .000      .000    0      0.00000
    2   2  180   0
      .000    60.000      .000      .000      .000      .000      .000      .000
       0.4       1.5    0.005    0.0010tm       m2aa  f  1
    0
```


Comparison of Radiative Transfer Codes (RTC)

Experimental Conditions

- Atmospheric Model : US Standard
- Aerosol : 6S Maritime (Visibility 23 km : τ_o=0.2347)
- Solar Zenith Angle : 60 degree
- Observation Date : July 30 (RSTAR unknown)
- Wave Length : 0.4～1.5μm (every 0.005μm)
- Surface Reflectance : 0.3 (mainly)
    - Modtran and RSTAR: 0, 0.1,0.2 (for estimation of L_b and E_e)

RTCs used in this study

6S : 6SV Ver.1.1, 2007.4
Modtran : Modtran4 Ver.3.1,2003.5
RSTAR : rstar6s1, 2015.8 with 6S aerosol model

rstar6b,2011.7 Original   rstar6s2,2015.8.24 with sensor response functions

OUTPUT:
***.flx**

```
SPECTRAL VERTICAL FLUX TABLE (W CM-2 / MICRON)
-----------------------------------------------
 1 LEVELS ( 4 TABLE COLUMNS)
TRIANGULAR  SLIT FULL-WIDTH-AT-HALF-MAXIMUM:  0.001000 MICRONS.
ALTITUDES:       0.00000 KM  Ed (ρ=0)
 --------------------------------Ed+Ee          Ex
 WAVLEN    UPWARD   DOWNWARD    DIRECT
(MICRON)   DIFFUSE   DIFFUSE     SOLAR
-------  ----------  ----------  ----------
1.50000 4.09312E-03 3.71693E-03 9.92680E-03
1.49500 4.10599E-03 3.73294E-03 9.95367E-03
ibid
0.40500 1.79602E-02 3.59498E-02 2.39177E-02
======= ========== ========== ==========
W CM-2: 1.36709E-02 1.68529E-02 2.87167E-02
```

OUTPUT:
***.7sc**

```
MM 7   2   2   1   0   0
  4   1   1   0   0   0 23.
 -99.000 -99.000 -99.000
 -99.00000 -99.00000 -99
  36          Custom
 20.00000   0.00000 180.
  0   2  180   0
 0.00000   0.00000   0.00
   6660    25035      1
  0   0   0.000  0   0.000  0   1.000                 Lp+Lb
 WAVLEN MCRN  TRANS  PTH THRML  THRML SCT  SURF EMIS  SOL SCAT  SING SCAT  GRND RFLT  DRCT RFLT  TOTAL RAD  REF SOL  SOL@OBS
DEPTH
  0.400000 0.5494 0.0000E+00      0.0000E+00 6.3010E-03 2.5159E-03 3.2630E-03 1.2717E-03 9.5640E-03 2.66E-02 1.60E-01
  0.405000 0.5593 0.0000E+00      0.0000E+00 5.7948E-03 2.3206E-03 3.1791E-03 1.2733E-03 8.9739E-03 2.67E-02 1.52E-01
  0.410000 0.5688 0.0000E+00      0.0000E+00 5.3528E-03 2.1480E-03 3.1007E-03 1.2735E-03 8.4536E-03 2.67E-02 1.44E-01
Ibid        T=exp(-τ)
 1.495000 0.8331 1.0444E-12      5.7769E-12 2.4689E-04 3.1609E-05 1.0907E-03 7.9352E-04 1.3376E-03 1.66E-02 2.87E-02
  1.500000 0.8337 1.1464E-12      6.3394E-12 2.4568E-04 3.1418E-05 1.0875E-03 7.9147E-04 1.3332E-03 1.66E-02 2.86E-02
 -9999.
```

RSTAR

Input

1 1 0 2 10 : ISOL INDA INDG IMTHD NDA
1 60.0 : NA0 TH0
1 180.0 : NA1 TH1
1 0.0 : NFI FI
1 : NW0
0.0 0.0 : RX
1.0 : RF
221 : NWL/ WL (Micron), DW (micron), GALB
0.4 0.405 0.41 0.415 0.42 0.425 0.43 0.435 0.44 0.445 0.45 …
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 …
0.3 0.3 0.3 0.3 0.3 0.3 0.3 0.3 0.3 0.3 0.3 0.3 0.3 0.3 0.3 0.3 …
6 45 : IATM NLN/ IPB (US Standard)
46 45 44 43 42 41 40 39 38 37 36 35 34 33 32 31 30 29 28 27 26 25 24
23 22 21 20 19 18 17 16 15 14 13 12 11 10 9 8 7 6 5 4 3 2 1
1 0 : IFRH TRH (relative humidity)
1 2 5.5e-05 : NPOLY ICN WLCN
1 0.2347 : NCOMP CNPT
2: MPTC (Maritime from 6S)
1.0 : VPTC

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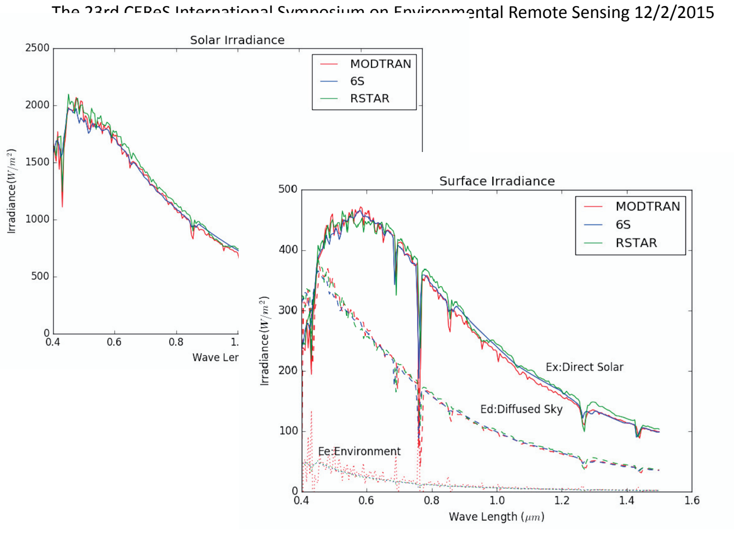

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0.4000 1.644E+03 : wl sol
l tau taua taur w g1 g2
1 2.199E-07 6.356E-08 1.564E-07 9.965E-01 6.370E-01 5.353E-01
2 4.473E-07 6.356E-08 3.838E-07 9.983E-01 5.326E-01 4.641E-01
ibid
44 9.883E-02 6.193E-02 3.688E-02 9.922E-01 7.073E-01 5.830E-01
45 1.427E-01 1.021E-01 4.058E-02 9.911E-01 7.153E-01 5.883E-01

$$\tau = \sum_{L=0}^{45} TAU_L$$

l flxd flxdd flxu
1 8.218E+02 8.218E+02 3.466E+02
2 8.217E+02 8.217E+02 3.466E+02
ibid
45 6.985E+02 3.175E+02 2.278E+02
46 6.688E+02 2.386E+02 2.006E+02
FLXD= Ed+Ee & Ed (FLXD with ρ=O)

Estimation of L_b
$L_b = L - L_p$ - FLXU*tt/π
Transmittance tt=exp(-tau)

: l / radiance (th1->fi->th0)
1
8.4967E+001
2
ibid. *Lp* (L with ρ=O)
46
6.3864E+001

$$\rho = \frac{\pi(L_s - L_p - L_b)}{T_s(E_o T_\theta \cos\theta + E_d + E_e)}$$

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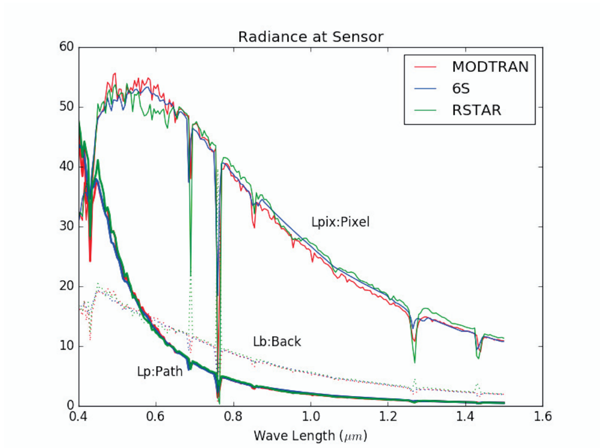

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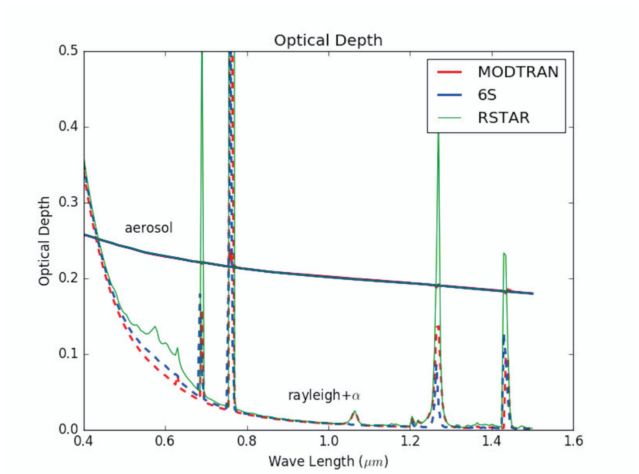

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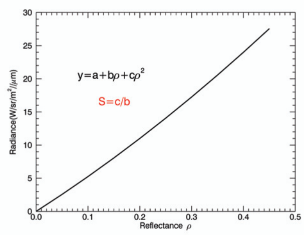
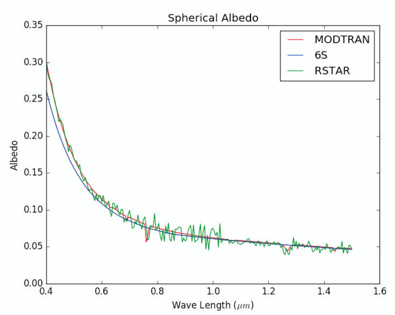
Estimation of Spherical Albedo

$$L_b = \frac{\overline{\rho} t_s (T_\theta + t_\theta)\mu_s E_s}{(1 - \overline{\rho} S)\pi} \sim (1 + \rho S)\rho$$





Conclusion

Improvement on the simultaneous estimation method

Utilization of Python with Scientific Modules for Progamming
numpy and scipy etc.
Reduction of Explanetory Variables for Correction Parameter
averaged reflectance for adjacent effect
Calculation of ρ-τ (ρ_{env}) function in advance
efficient t but memory required
Iterative Estimation and It' Convergence
outlier removing and deccelaration coeeficients
Comparison of Radiative Transfer Code
utilization of RSTAR for satellite image processing

Issues to be considered: many but challenging

Post Processing:
interpretation of reflectance and optical depth
Initial value setting
for optical depth and averaged reflectance
Utilization of MODIS products
Accurate calculation of reflected irradiance
from neighbor pixels
Viewshed Calculation
Validation by ground measurements
Application to other sensors such as MODIS, Himawari ....