Hyperspectral Remote Sensing

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Dr. J. SARAVANAVEL
Assistant Professor
Department of Remote Sensing
Bharathidasan University
Tiurchirappalli, Tamil Nadu
Email : saravanavel@bdu.ac.in

Hyperspectral Sensors

Airborne

1. CASI (Canadian technology)
2. AVIRIS (American NASA technology)

Other airborne:

1. HYDICE
2. DAIS

Spaceborne

1. Hyperion
2. Modis
3. CHRIS
4. MERIS

Ground Based

1. Spectroradiometer

AVIRIS: Airborne Visible Infrared Imaging Spectrometer

Airborne Visible Sensor/Infrared Imaging Spectrometer (AVIRIS) are new in terms of hyperspectral systems attached to planes. The AVIRIS sensor, developed by NASA/Jet Propulsion Laboratory (JPL), is working in bands of 224, with a spectral resolution of about 10 nm and covering the spectral range from 0.40 to 2.50 µm. The sensor is a Whiskbroom system that uses a scanning system for acquiring data on the transverse direction of advancement.

Four off-axis double-pass Schmidt spectrometers capture light from oreoptics using optical fiber and send it to four linear panels, one for each spectrometer, which have a strong sensitivity in the range 0.4…0.7 µm, 0.7…1.2 µm, 1.2…1.8 µm and 1.8…2.5 µm.

AVIRIS sensor takes images from an altitude of 20 km with a spatial resolution of 20 meters, from a band whose width is of 10.5 kilometers. Starting with 1998, the sensor is mounted on a Twin Otter aircraft flying at low altitude, taking pictures with a spatial resolution ranging between 2 and 4 meters

AVIRIS: Airborne Visible Infrared Imaging Spectrometer

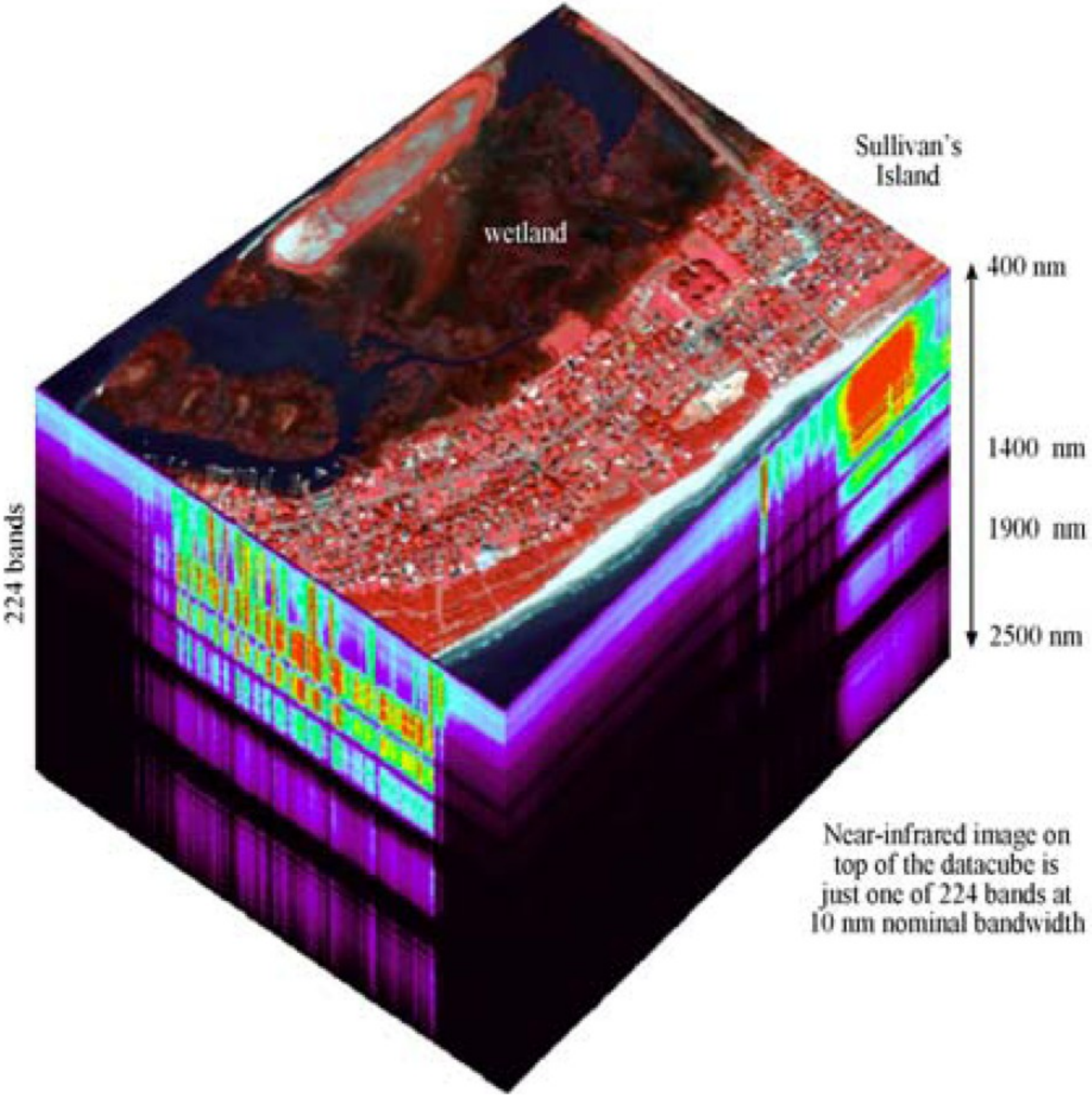
- CCD array for spectral bands
- across-track scanning.
- 224 spectral bands
- Wavelength range: 0.38 to 2.50 µm.
- Bandwidth: 10 nm
- 30° field of view
- 614 pixels per scan
- Usually flown on the NASA/ARCER-2 aircraft at an altitude of 20 km
  - Swath width 11 km
  - Pixel size 20 m x 20 m

Can be flown lower (under clouds)

  - Pixel size reduced to ~ 5 m

- 12 bit data

Airborne Visible Infrared Imaging Spectrometer (AVIRIS) Datacube of Sullivan's Island Obtained on October 26, 1998



HyMAP: the hyperspectral mapper

Typical:

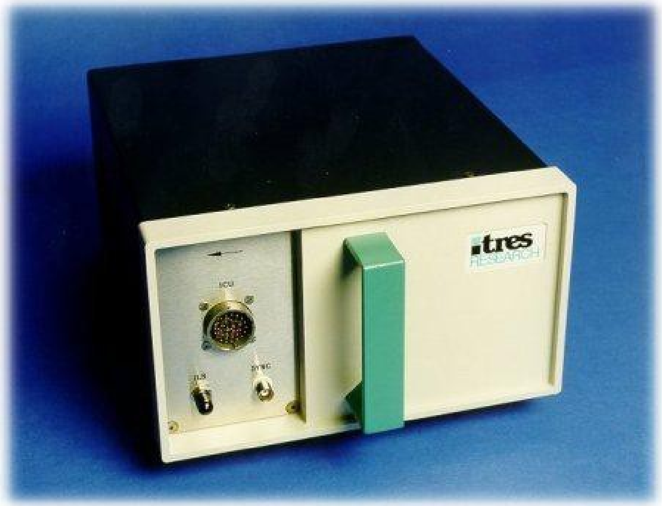
- 128 band
- 400 – 2500 nm.
- 4-5 m. on the ground

- General
  - 100 - 200 bands
  - bandwidths of 10 – 20 nm
  - high signal to noise, > 500:1
  - 2 -10 m spatial resolution
  - 60 -70 degrees swath width

Integrated Spectronics, Sydney, Australia, has been developing field spectrometers for several years. Its field portable spectrometer, the PIMA-II has brought fundamental changes to the way many field and mine geologists work. With the introduction of the HyMap™ hyperspectral airborne system, the potential exists to start routine commercial use of airborne imaging spectrometry. HyMap is the first commercially available sensor to provide combined high spatial resolution (2 to 10-m), high spectral resolution (12 to 16nm), and high signal-to-noise (>500:1) performance.

CASI Sensor: Compact Airborne Spectrographic Imager

- Manufactured by Itres Research Ltd. of Calgary
- 288 selectable spectral bands ranging from 390-900 nm
- 512 spatial pixels across a 35 degree swath
- spatial resolution 1 to 10m depending on altitude
- radiometric resolution is 12 bit



Other Airborne Sensors

HYDICE

- developed by the US Navy
- 210 channels, spectral resolution ~ 10 nm
- Wavelengths: 413 to 2,504 nm.
- spatial dimension - 320 pixels.
- Spatial resolution dependent on altitude (1 – 10 m)

DAIS (Digital Airborne Imaging Spectrometer)

- European
- spectral coverage between 450 and 2,500 nm
- 72 channels, three spectral intervals:
  - 400-1200 nm (bandwidth 15-30 nm);
  - 1,500-1,800 nm (bandwidth 45 nm);
  - 2,000-2,500 nm (bandwidth 20 nm).
  - The gaps coincide with atmospheric absorption bands

Satellite Sensors

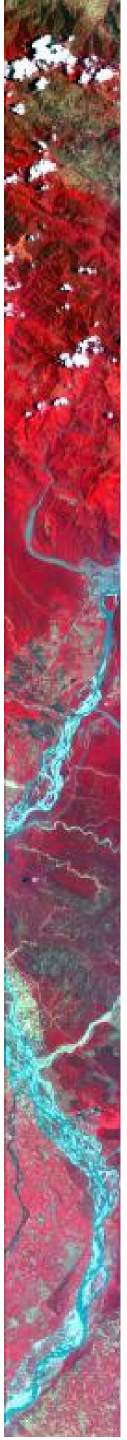
Moderate Resolution Imaging Spectrometer

- Near-polar, 705 km sun-synchronous orbit
- Whiskbroom scanner
- 36 bands
    - 20 bands from 400 to 3000 nm
    - 16 bands from 300 to 15,000 nm
- Spatial resolution
    - 250 m x 250 m (bands 1-2)
    - 500 m x 500 m (bands 3-8)
    - 1 km x 1 km (bands 8-36)

Hyperion

The Hyperion EO-1 sensor was launched in November 2000 by NASA with the purpose of taking hyperspectral images from space in order to create mineralogical mapping. Hyperion is a hyperspectral satellite sensor which works in the spectral range 0.40…2.50 µm with 242 bands which have a spectral resolution of about 10 nm and a spatial resolution of 30 meters, the data is taken from an altitude of 705 km. Hyperion is a push-broom instrument that takes pictures with a radiometric resolution of 8 bits, the band having a width of 7.5 km and being perpendicular on the movement of the satellite. The system used for taking images is formed of two spectrometers: one working in the visible/near infrared (VNIR) (0.4…1.0 µm) and one in shortwave infrared (SWIR) (0.9…2.5 µm). The data are calibrated using both the radiation measured before the mission and when the images are taken

- 220 spectral bands
- from 0.4 to 2.5 µm
- 30 meter spatial resolution.
- images a 7.5 km by 100 km imaged



CHRIS Compact High Resolution Imaging Spectrometer

- ☐ Part of the Proba satellite, launched 2001, European Space Agency
- ☐ 18 km x 18 km images
- ☐ 18 meter resolution
- ☐ 200 spectral bands

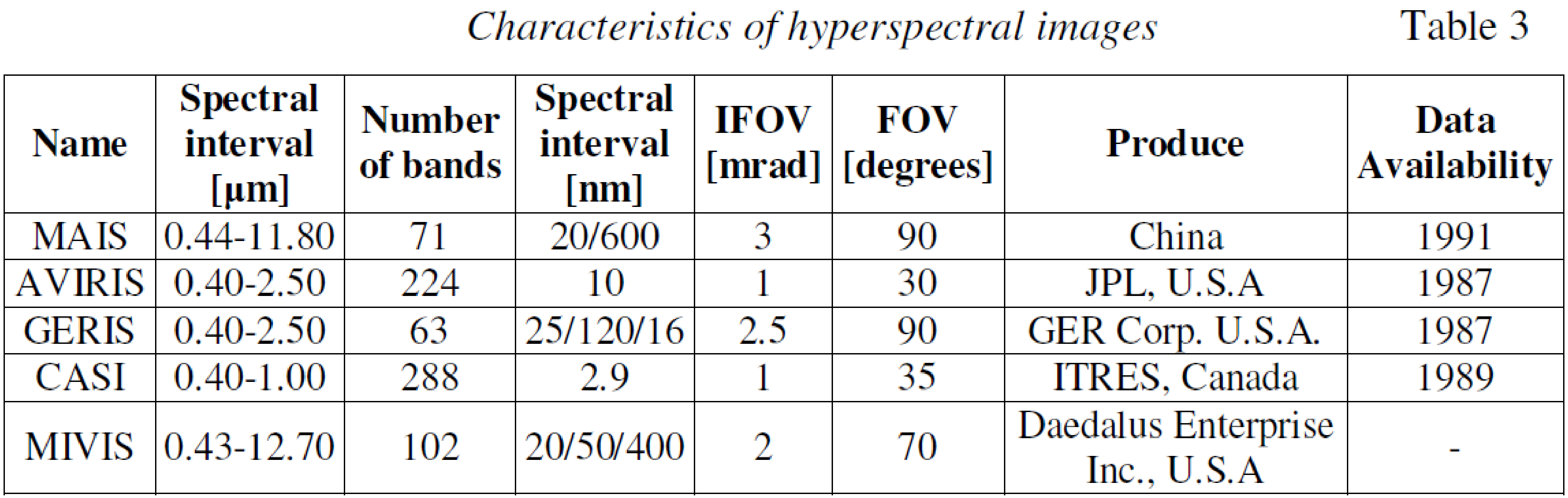
IMS-1 - HYSI
Indian Mini Satellite- 1 : Hyperspectral Imager

Launched April 2008

Swath (km)	130
Spatial resolution (m)	505.6
Number of bands	64
Spectral separation (nm)	8
Spectral range (microns)	0.4 - 0.95
Quantization (bits)	11
CCD array size	256 X 512
Data rate (Mbps)	4.0
Repetivity (days)	24 days

Chandrayan - HYSI

- 64 contiguous bands in the VNIR, Spectral range - 0.4-0.95 µm region
- Spectral resolution of better than 15 nm
- Spatial resolution of 80 m,
- swath coverage of 20 km.



Characteristics of hyperspectral images Table 3

Name	Spectral interval [µm]	Number of bands	Spectral interval [nm]	IFOV [mrad]	FOV [degrees]	Produce	Data Availability
MAIS	0.44-11.80	71	20/600	3	90	China	1991
AVIRIS	0.40-2.50	224	10	1	30	JPL, U.S.A	1987
GERIS	0.40-2.50	63	25/120/16	2.5	90	GER Corp. U.S.A.	1987
CASI	0.40-1.00	288	2.9	1	35	ITRES, Canada	1989
MIVIS	0.43-12.70	102	20/50/400	2	70	Daedalus Enterprise Inc., U.S.A	-

Main hyperspectral sensors on aircraft and satellites Table 1

<table>
<tr><th colspan="4">Hyperspectral sensors on satellites</th></tr>
<tr><th>Types of sensors</th><th>Producer</th><th>Number of bands</th><th>Spectral range [µm]</th></tr>
<tr><td>FTHSI on MightySat II</td><td>Air Force Research</td><td>256</td><td>0.35-1.05</td></tr>
<tr><td>Hyperion on EO-1</td><td>NASA Guddard Space Flight Center</td><td>242</td><td>0.40-2.50</td></tr>
<tr><th colspan="4">Hyperspectral sensors on aircrafts</th></tr>
<tr><td>AVIRIS (Airborne Visible Infrared Imaging Spectrometer)</td><td>NASA Jet Propulsion Lab.</td><td>224</td><td>0.40-2.50</td></tr>
<tr><td>HYDICE (Hyperspectral Digital Imagery Collection Experiment)</td><td>Naval Research Lab.</td><td>210</td><td>0.40-2.50</td></tr>
<tr><td>PROBE-1</td><td>Earth Search Sciences Inc.</td><td>128</td><td>0.40-2.50</td></tr>
<tr><td>CASI (Compact Airborne Spectrographic Imager)</td><td>ITRES Research Limited</td><td>Over 228</td><td>0.40-1.00</td></tr>
<tr><td>HyMap</td><td>Integrated Spectronics</td><td>100 la 200</td><td>Visible to termal infrared</td></tr>
<tr><td>EPS-H (Environmental Protection System)</td><td>GER Corporation</td><td>VIS/NIR (76),
SWIR1 (32),
SWIR2 (32),
TIR (12)</td><td>VIS/NIR (0.43-1.05)
SWIR1 (1.50-1.80)
SWIR2 (2.00-2.50)
TIR (8-12.50)</td></tr>
<tr><td>DAIS 7915 (Digital Airborne Imaging Spectrometer)</td><td>GER Corporation (Geophysical and Environmental Research Imaging Spectrometer)</td><td>VIS/NIR (32),
SWIR1 (8),
SWIR2 (32),
MIR (1),
TIR (12)</td><td>VIS/NIR (0.43-1.05)
SWIR1 (1.50-1.80)
SWIR2 (2.00-2.50)
MIR (3.00-5.00)
TIR (8.70-12.30)</td></tr>
<tr><td>DAIS 21115 (Digital Airborne Imaging Spectrometer)</td><td>GER Corporation</td><td>VIS/NIR (76),
SWIR1 (64),
SWIR2 (64),
MIR (1),
TIR (6)</td><td>VIS/NIR (0.40-1.00)
SWIR1 (1.00-1.80)
SWIR2 (2.00-2.50)
MIR (3.00-5.00)
TIR (8.00-12.00)</td></tr>
<tr><td>AISA (Airborne Imaging Spectrometer)</td><td>Spectral Imaging</td><td>Over 288</td><td>0.43-1.00</td></tr>
</table>

Future hyperspectral sensors

- **Environmental Mapping and Analysis Programme (ENMAP) of DLR Germany**

Spectral range from 0.430 to 0.950 m (VNIR) and from 0.950 to 2.400 m (SWIR) with 184 channels, a swath width of 30 km at high spatial resolution of 30 m and off-nadir (30◦) pointing feature for fast target revisit (<3 days).

- **PRISMA mission by Italian space agency**

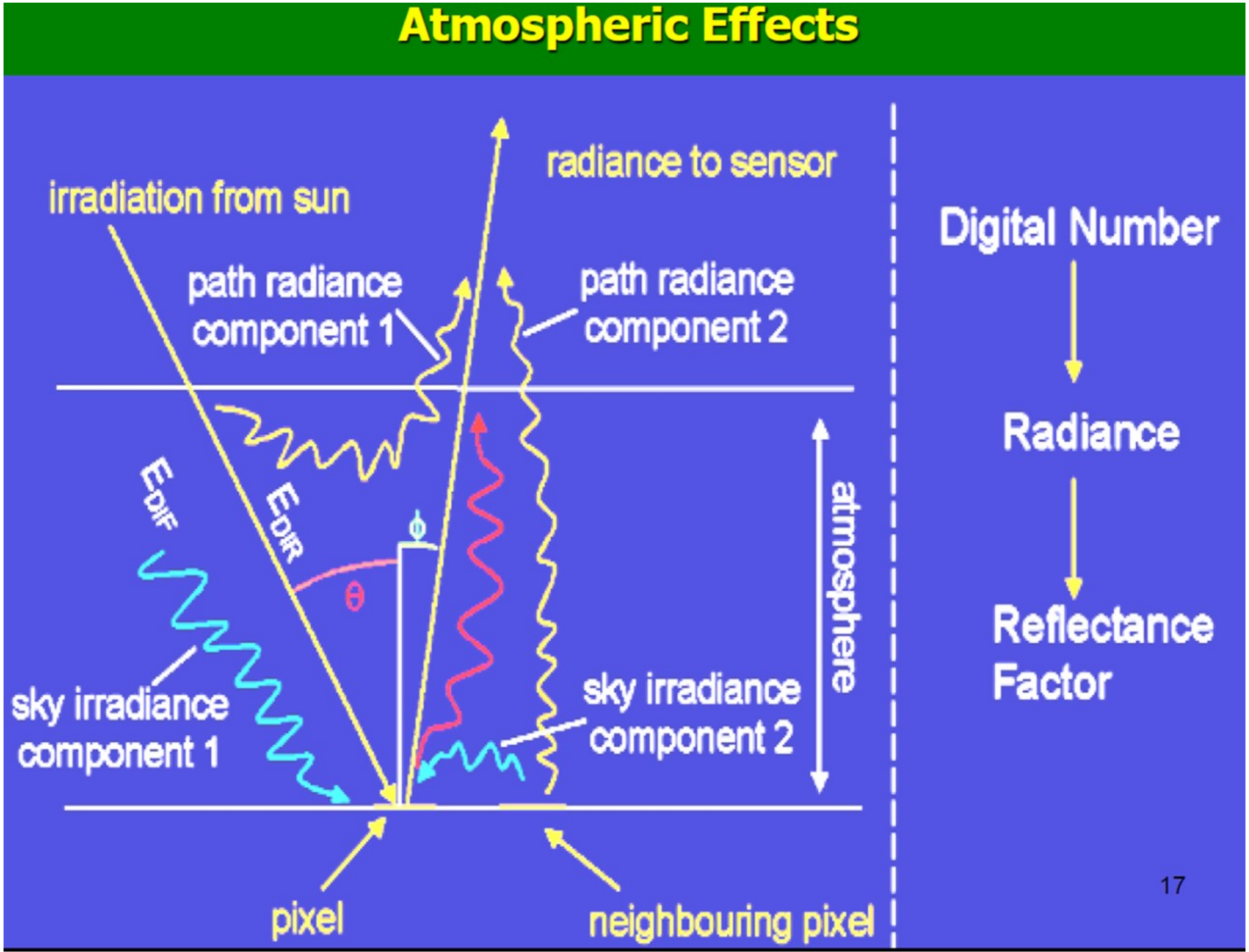
(700 km orbit, 20–30 m resolution, swath width of30–60 km, 0.4–2.5 m continuous coverage with 10 nm bands) to be launched in 2012 by the Italian Space Agency

Hyper–multi spectral mission named HISUI (HyperspectralImager SUIte), Japanese hyperspectral mission

57 VNIR bands (0.4–0.97 micometer at 10 nm resolution) and 128 SWIR bands (0.9–2.5 microm. at 12.5 nm resolution) at a 30 m spatial resolution and 30 km swath

Preprocessing Hyperspectral Data

1. **Atmosphere correction**
2. **Noise removal and dimensionality reduction**



INTERACTION WITH THE ATMOSPHERE

Because hyperspectral data is collected some distance above the target on the ground, the reflected solar illumination must travel through the atmosphere.

Characteristics of the atmosphere can have a profound effect on the incoming solar energy recorded by the hyperspectral sensor.

The way light interacts with the atmosphere depends on many factors: the types of particulates and gases, the amount of atmospheric reflection, atmospheric absorption, and atmospheric scattering. The atmosphere is a complex mixture of particulates and gases. Particulates are small particles usually less than 20 µm in diameter. Particulates greater than 20 µm are not likely to stay in the atmosphere for long durations and tend to settle to the ground rather quickly

Amount of Atmospheric Absorption

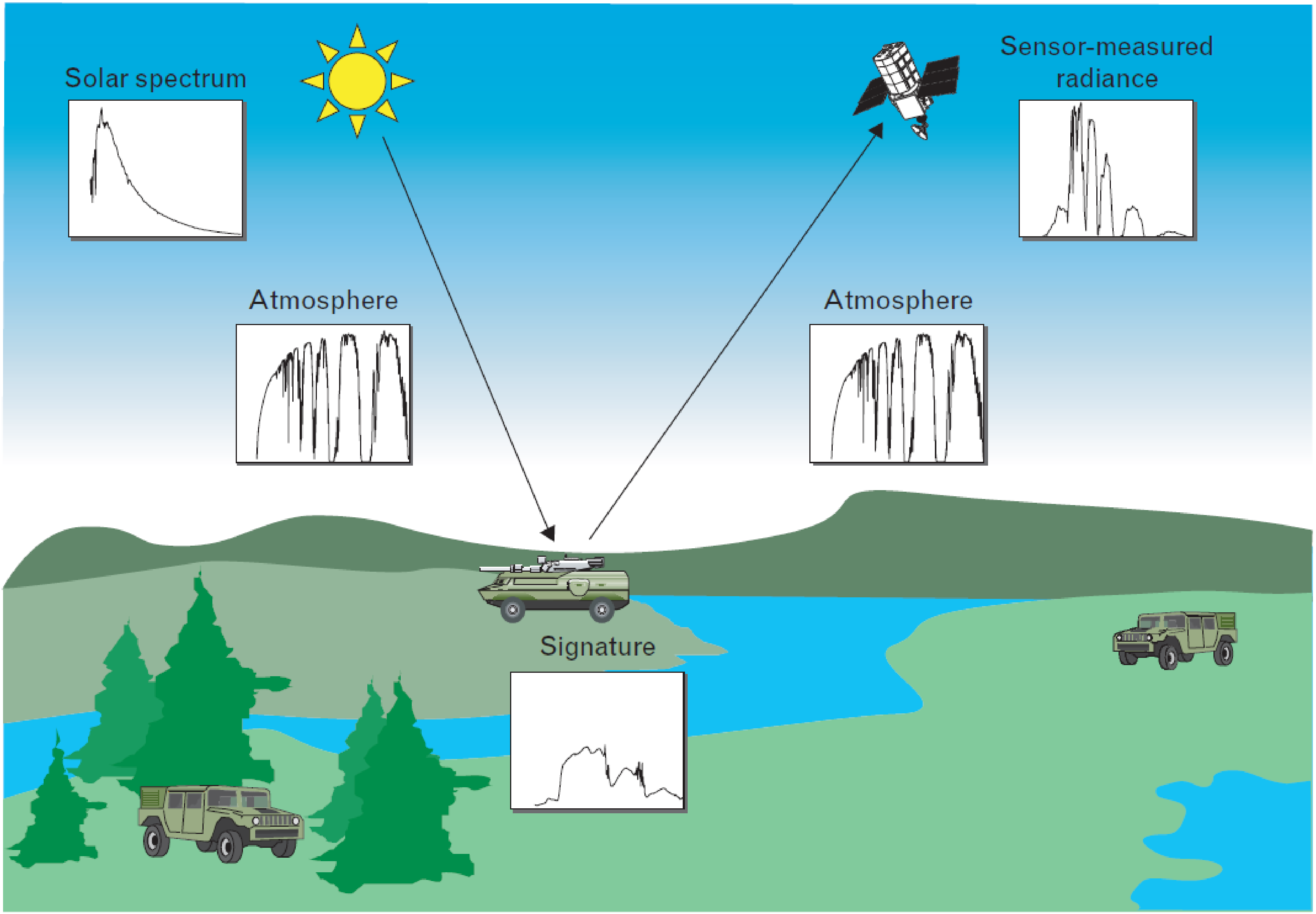
Atmospheric absorption is the removal of energy from solar irradiance by conversion of the electromagnetic energy to another form, usually thermal energy. Atmospheric absorption occurs when a photon induces a molecular vibration, rotation, or electron orbital transition to an alternate energy state.

The photon is absorbed by the constituent molecules of the atmosphere, and only photons with specific energy levels can be absorbed.

Table 4.1 Principal Molecular Absorption Lines in the Earth Atmosphere

Wavelength (μm)	Molecule	Wavelength (μm)	Molecule
0.26	O_3	3.9	N_2O
0.60	O_3	4.3	CO_2
0.69	O_2	4.5	N_2O
0.72	H_2O	4.8	O_3
0.76	O_2	4.9	CO_2
0.82	H_2O	6.0	H_2O
0.93	H_2O	6.6	H_2O
1.12	H_2O	7.7	N_2O
1.25	O_2	7.7	CH_4
1.37	H_2O	9.4	CO_2
1.85	H_2O	9.6	O3
1.95	CO_2	10.4	CO_2
2.0	CO_2	13.7	O_3
2.1	CO_2	14.3	O_3
2.6	H_2O	15	CO_2
2.7	CO_2		

Source: Rees, W.G., *Physical Principles of Remote Sensing*, 2nd ed., Cambridge University Press, 2001. With permission.


Solar spectrum
Sensor-measured radiance
Atmosphere
Atmosphere
Signature

Molecular Absorption

Molecules can absorb electromagnetic radiation in three ways: electronic transitions, vibration, and rotation. Electronic transition requires the greatest amount of energy and involves the promotion of electrons to higher energy levels. Vibration involves the molecular bond between atoms and models it as a spring. Rotation can be considered in the context of a simple diatomic molecule of two atoms. The two atoms can rotate about their center of mass.

Molecular absorption can be complicated by a combination of mechanisms occurring simultaneously. For example, the energy level of a molecule can be described by both rotation and vibration.

Amount of Atmospheric Scattering

The surface area of the particulate and gases interacts with the light and creates scattering or a redirection of the electromagnetic radiation (EMR), which can cause a change in the distribution of the EMR.

The three basic types of scattering are classified as Rayleigh, Mie, and non-selective scattering. Rayleigh scattering occurs when the EMR interacts with the minute particles or molecules that are the components of the atmosphere, primarily when the particles are much smaller than the wavelength of the incident flux. Mie scattering results when the wavelength of the incident EMR is approximately equal to the size of atmospheric particles, such as aerosols, dust particles, fossil fuel combustion products, and suspended sea salts. Nonselective scattering occurs when the suspended atmospheric particles are very large with respect to the incident EMR; particles such as water droplets and ice crystals can cause nonselective scattering

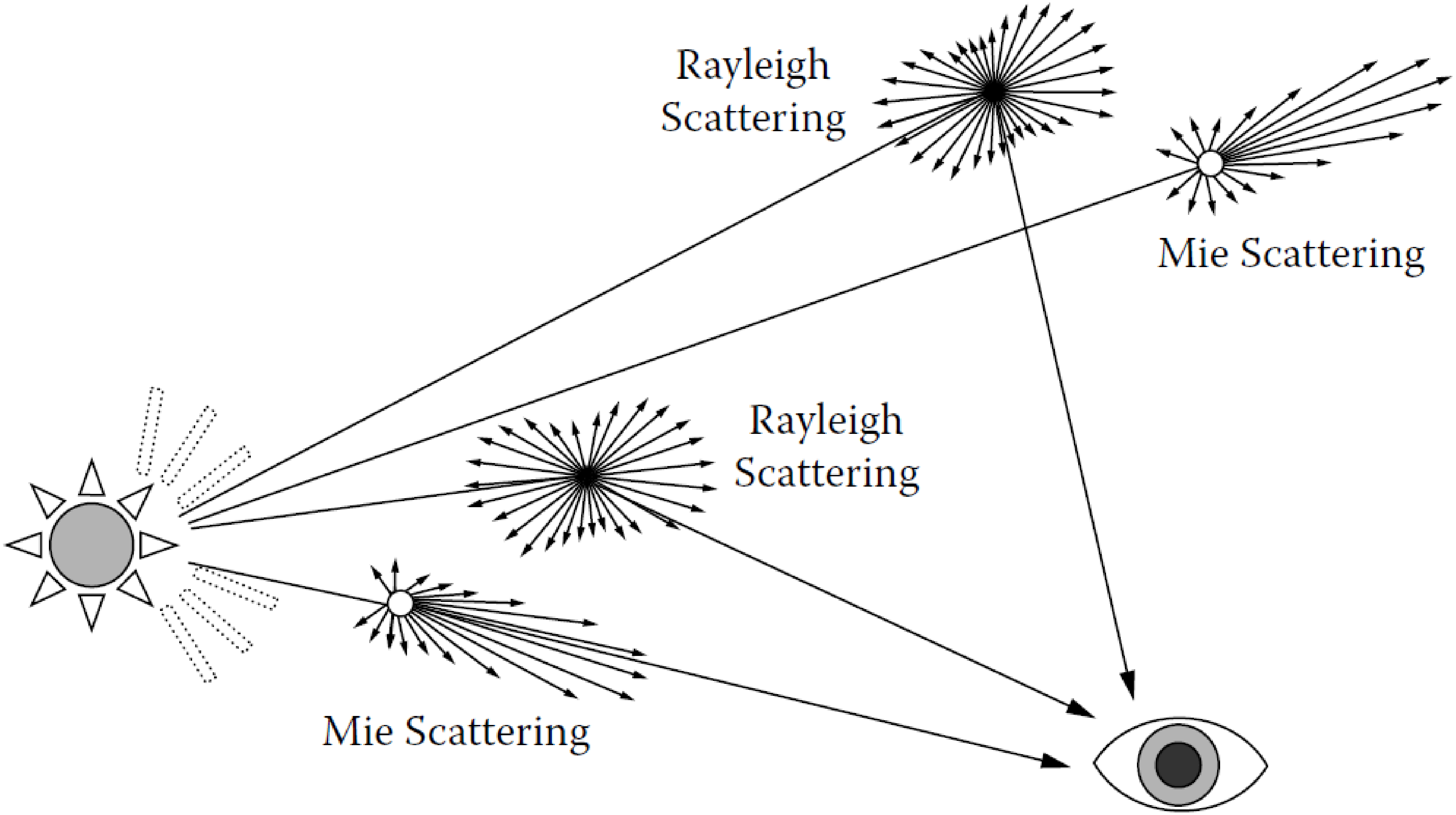


Figure 4.2 Basic principles of Rayleigh and Mie scattering.

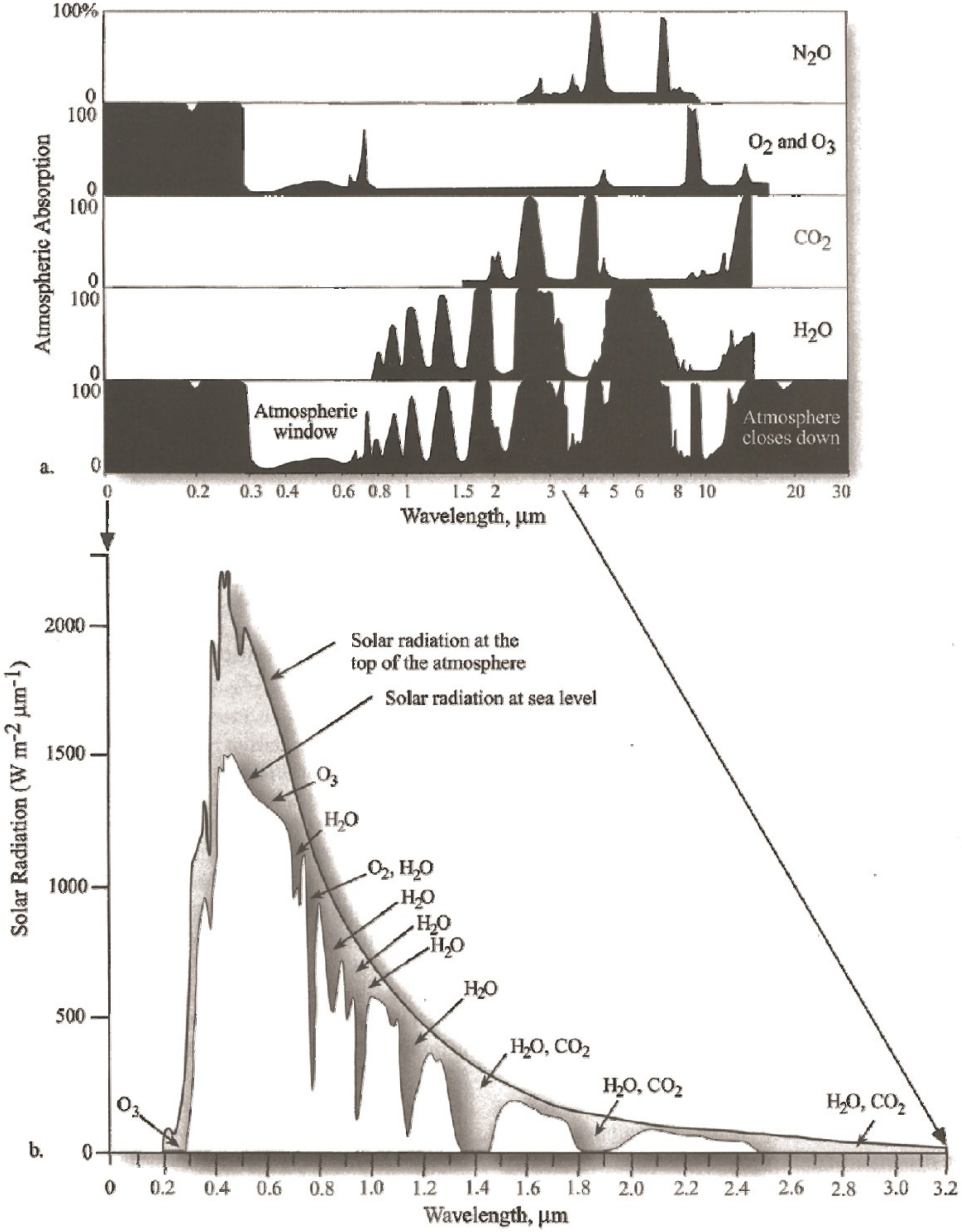
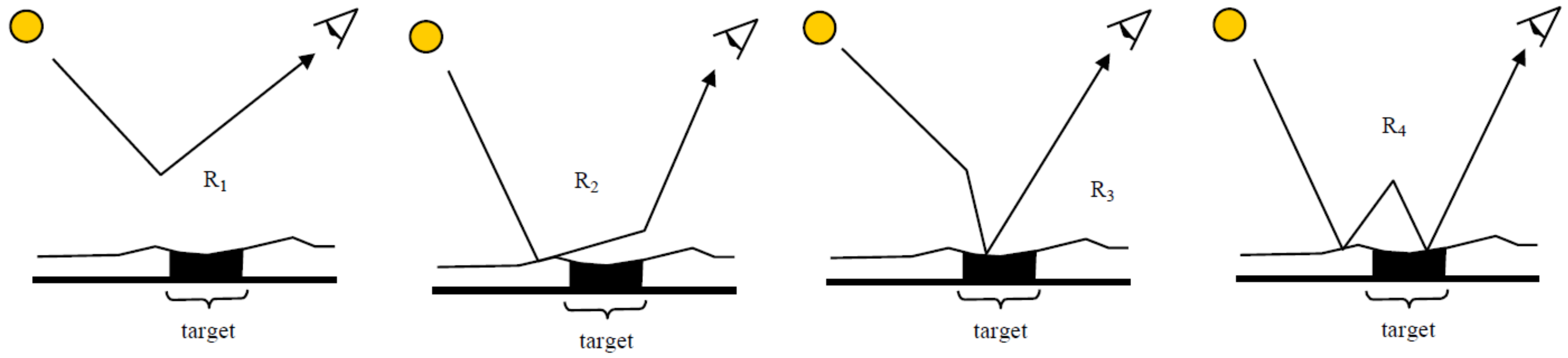


Fig 6 Solar radiation at the top of the atmosphere and at sea level, with absorption by various atmospheric gases (from Jensen, 2007).

Target reflectance is a function of:



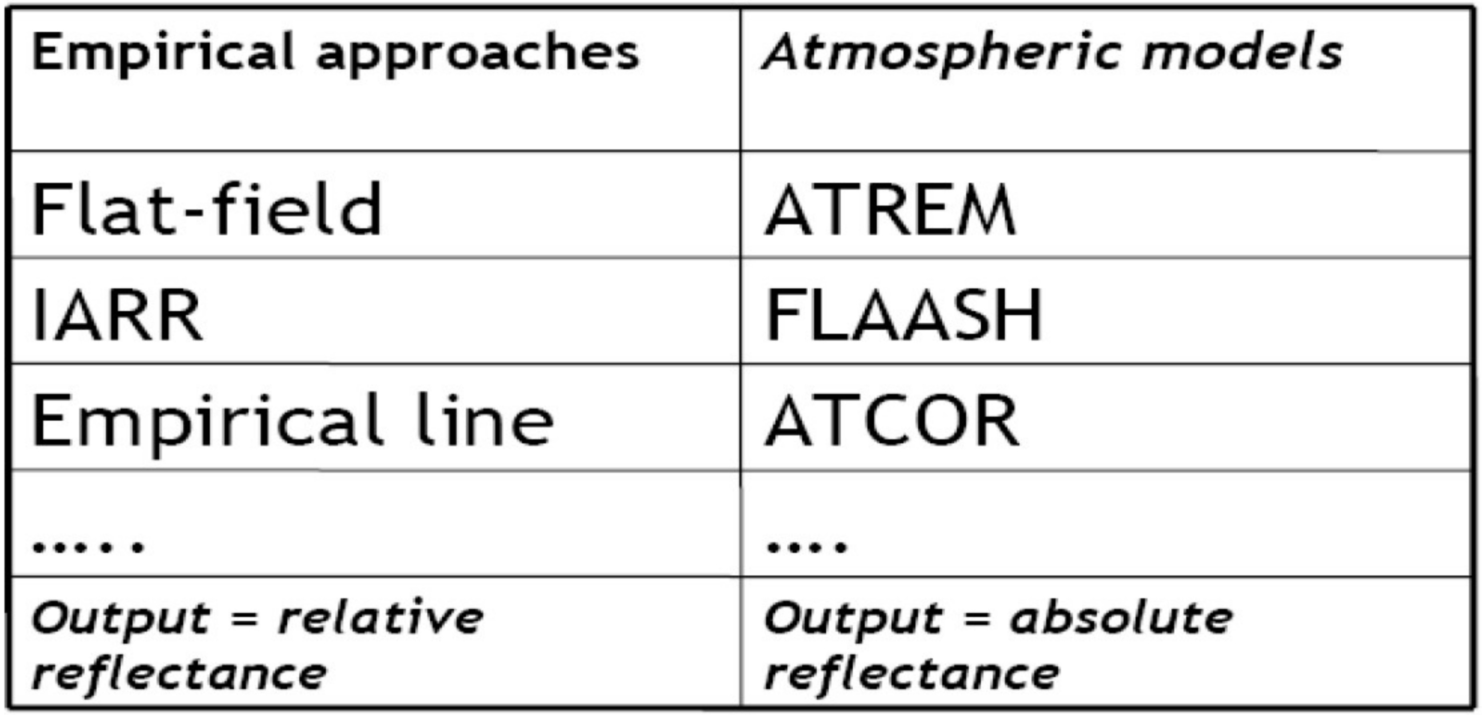
- Atmospheric irradiance (path radiance: R1)
- Reflectance outside target scattered into path (R2)
- Diffuse atmospheric irradiance (scattered onto target: R3)
- Multiple-scattered surface-atmosphere interactions (R4)

Atmospheric Correction Models

Physics based Models

- Atmospheric REMoval (ATREM)
- Atmospheric Correction Now (ACORN)
- Fast Line-of-sight Atmospheric Analysis of Spectral Hypercubes (FLAASH)

Semi-Empirical/Empirical Models



Empirical approaches	*Atmospheric models*
Flat-field	ATREM
IARR	FLAASH
Empirical line	ATCOR
…..	….
Output = relative reflectance	*Output = absolute reflectance*

Atmospheric correction is the process of converting satellite signals (at-sensor radiance) to ground reflectance

- Removes atmospheric and solar illumination effects
- Improves change detection
- Used with spectral library based classifiers
- Simplifies satellite data inter-comparisons

Different levels of atmospheric correction yield different approximations of scene reflectance

- Planetary reflectance –no knowledge of atmosphere
- Ground reflectance using knowledge of atmosphere
- Ground reflectance using knowledge of atmosphere and adjacency effects

Atmospheric Correction Measures

Compensation for the shape of the solar spectrum.

> **The measured radiances are divided by solar irradiances above the atmosphere to obtain the apparent reflectance of the surface.**

Compensation for atmospheric gaseous transmission and molecular and aerosol scattering enable apparent reflectances to be converted to scaled surface reflectances

Scaled surface reflectance can be converted to real surface reflectance after accounting for topographic effects or by assuming that surfaces are lambertian

Flat Field Correction

Flat Field Correction (FFC) technique is used to normalize images to an area of known uniform “flat” reflectance (Kruse et al., 2003b).

The method requires locating a large, spectrally flat, spectrally uniform area in the data, usually defined as a Region of Interest (ROI). The radiance spectrum from this area is assumed to be composed of primarily atmospheric effects and the solar spectrum.

The average radiance spectrum from the ROI is used as the reference spectrum, which is then divided into the spectrum at each pixel of the image.

FFC normalizes the hyperspectral data to an area of known flat reflectance, and derives relative reflectance from hyperspectral data. The resultant apparent reflectance is comparable with laboratory spectra.

Internal Average Relative Reflectance (IARR) calibration technique is used to normalize images to a scene average spectrum.

This is particularly effective for reducing imaging spectrometer data to relative reflectance in an area where no ground measurements exist and little is known about the scene (Kruse et al., 2003b).

It works best for arid areas with no vegetation. The IARR calibration is performed by calculating an average spectrum for the entire scene and using this as the reference spectrum. Apparent reflectance is calculated for each pixel of the image by dividing the reference spectrum into the spectrum for each pixel.

Empirical Line Calibration

- ❑ **Empirical Line Calibration technique is used to force image data to match selected field reflectance spectra (Kruse et al., 1990).**
- ❑ **This method requires ground measurements and/or knowledge. Two or more ground targets are identified and reflectance is measured in the field.**
- ❑ **Usually the targets consist of at least one bright and one dark area. The same two targets are identified in images and average spectra are extracted for Regions of Interest.**
- ❑ **A linear regression is calculated between the field reflectance spectra and the image radiance spectra to determine a linear transform from radiance to reflectance for each band of the data set.**
- ❑ **Gains and offsets calculated in the regression are applied to the radiance spectra for each pixel to produce apparent reflectance on a pixel-by-pixel basis.**
- ❑ **In this method, linearly transform the hyperspectral imaging radiance values to ground reflectance**

- **This process is equivalent to removing the solar radiance and the atmospheric path radiance from the measured signal**

$$R_{\Box}= G_{\Box}\, L_{\Box} +O_{\Box}\ (+\Box_{\Box}\ )$$

$R_{\Box}$ calculated reflectance for band$_{\Box}$, $O_{\Box}$ is the offset for band$_{\Box}$, $L_{\Box}$ is the at sensor radiance for band$_{\Box}$, $\Box_{\Box}$ is the error term from the regression for band$_{\Box}$

- **The relative methods are computationally fast, but the information pertaining to the intervening atmosphere is not derived in these approaches. These techniques are considered more of a calibration tool than an atmospheric correction model.**

Absolute Atmospheric Correction

Ideally, researchers would like to be able to calibrate their data to absolute reflectance rather than relative reflectance without actually having to make ground measurements.

Absolute atmospheric correction methods require a description of the components in the atmospheric profile. The output of these methods is an image that matches the reflectance of the ground pixels with a maximum estimated error of 10 %, if atmospheric profiling is adequate enough.

The advantage of these methods is that ground reflectance can be evaluated under any atmospheric condition, altitude and relative geometry between sun and satellite.

The disadvantage is that the atmospheric profiling required for these methods is rarely available.

Most of the atmospheric correction models like ATREM, ACORN, FLAASH, etc. basically follow the radiative transfer model shown below. though each model uses a slightly different version and the FLAASH algorithm adds a term to account for adjacency effects.

$$L_0(\lambda)=L_{sun}(\lambda)\, T(\lambda)\, R(\lambda)\, \cos(\theta) + L_{path}(\lambda)$$

Where

(λ)= wavelength
$L_0(\lambda)$=observed radiance at sensor
$L_{sun}(\lambda)$ = Solar radiance above atmosphere
$T(\lambda)$ = total atmospheric transmittance
$R(\lambda)$ = surface reflectance
θ =incidence angle
$L_{path}(\lambda)$ = path scattered radiance

Current atmospheric correction programs assume that the surface is horizontal and has a Lambertian reflectance. This is because for real data we typically don't have enough information to make the topographic [cos(θ)] correction. The end result is called "scaled surface reflectance" or "apparent reflectance". The scaled surface reflectance can be converted to surface reflectance if the surface topography is known.

MODTRAN radioactive transfer model

MODTRAN (MODerate spectral resolution atmospheric TRANSsmittance algorithm and computer model) is developed by AFRL/VSBT in collaboration with Spectral Sciences, Inc. The MODTRAN Code calculates atmospheric transmittance and radiance for frequencies from 0 to 50,000 cm-1 (wavelength: 200nm to +∞) at moderate spectral resolution.

Except for its molecular band model parameterization, MODTRAN adopts all the LOWTRAN 7 capabilities, including spherical refractive geometry, solar and lunar source functions, and scattering (Rayleigh, Mie, single and multiple), and default profiles (gases, aerosols, clouds, fogs, and rain).

The optical interaction effect between sun-atmosphere-surface and surface-atmosphere- sensor is constituted three sets . It is showed that the radiance at the sensor is composed of three different contributions: (1) radiation scattered by the atmosphere into the viewing direction. (2) radiation reflected from the target and directly transmitted in the viewing direction. (3) radiation reflected from the background (surroundings) and diffusely transmitted to the sensor, which is called the adjacency effect

Assumed that the surface is uniform and has a Lambertian reflectance, the radiance at a downward looking aircraft sensor can be written in a simplified form as follow

$$L = G_t \frac{\rho}{1-\rho_e S} + G_b \frac{\rho_e}{1-\rho_e S} + L_o \qquad (1)$$

Where ρ is target region reflectance, ρ_e is surrounding region reflectance, S is atmospheric spherical albedo, L is the radiance at the sensor, L_o is the radiance of atmosphere backscattering, G_b surrounding pixel coefficient(depend on atmospheric and geometric condition), G_t target pixel coefficient(depend on atmospheric and geometric condition).

The retrieval of target region reflectance ρ involves computing a spatially averaged radiance image $\overline{L}$ from which the spatially averaged reflectance , and the spatially averaged reflectance ρ_e is estimated using the approximate equation.

The spatial averaging is performed using Gaussian function that describes the relative contributions to the pixel radiance.

$$\rho = \frac{L - L_o + \frac{G_b}{G_t}(L - \overline{L})}{G_b + G_t + (\overline{L} - L_o)S} \qquad (2)$$

Where L , L_o , S , G_b , G_t are same as them in Equation (1),and $\overline{L}$ is spatial averaging .

In order to be able to determine all five effective parameters for a given atmospheric state and geometry, three MODTRAN4 runs should be carried, with spectrally flat surface albedos of 0%, 50%, and 100%, respectively, and all of three runs are set for a uniform Lambertian surface reflectance[7][8]. MODTRAN outputs corresponding each wavelength to Hyperion are PATH (total path radiance), GRFL (radiance contribution due to ground-reflected sunlight), and TOT (total ground-reflected radiance contribution), as well as the extraterrestrial spectral solar irradiance. For PATH, the results obtained for 0% and 100% albedo are used, which are respectively called PATH_0 and PATH_{100} . For GRFL, only the output for 100% albedo is required (GRFL_{100}), and for GTOT one needs the outputs for 50% and 100% albedo, The spatial averaging is performed using Gaussian function that describes the relative contributions to the pixel radiance.

$$\rho = \frac{L - L_o + \frac{G_b}{G_t}(L - \overline{L})}{G_b + G_t + (\overline{L} - L_o)S} \qquad (2)$$

Where L , L_o , S , G_b , G_t are same as them in Equation (1),and $\overline{L}$ is spatial averaging .

ATREM – ATmospheric REMoval Program

ATREM is software developed by the University of Colorado for retrieving scaled surface reflectance from hyperspectral data using a radiative transfer model (Gao and Goetz, 1990; Gao et al., 1993; CSES, 1999).

First the solar zenith angle is derived based on the AVIRIS acquisition time, date, and geographic location.

Atmospheric transmittance spectra are derived for each of seven atmospheric gases [water vapor (H2O), carbon dioxide (CO2), ozone (O3), nitrous oxide (N2O), carbon monoxide (CO), methane (CH4), and oxygen (O2)] using the Malkmus narrow band model (Malkmus, 1967).

A water vapor "lookup table" is created by generating modeled spectra for various water vapor concentrations, again using the Malkmus narrow band model and estimating the 0.94 and/or 1.13 micrometer water vapor band depths for each spectrum.

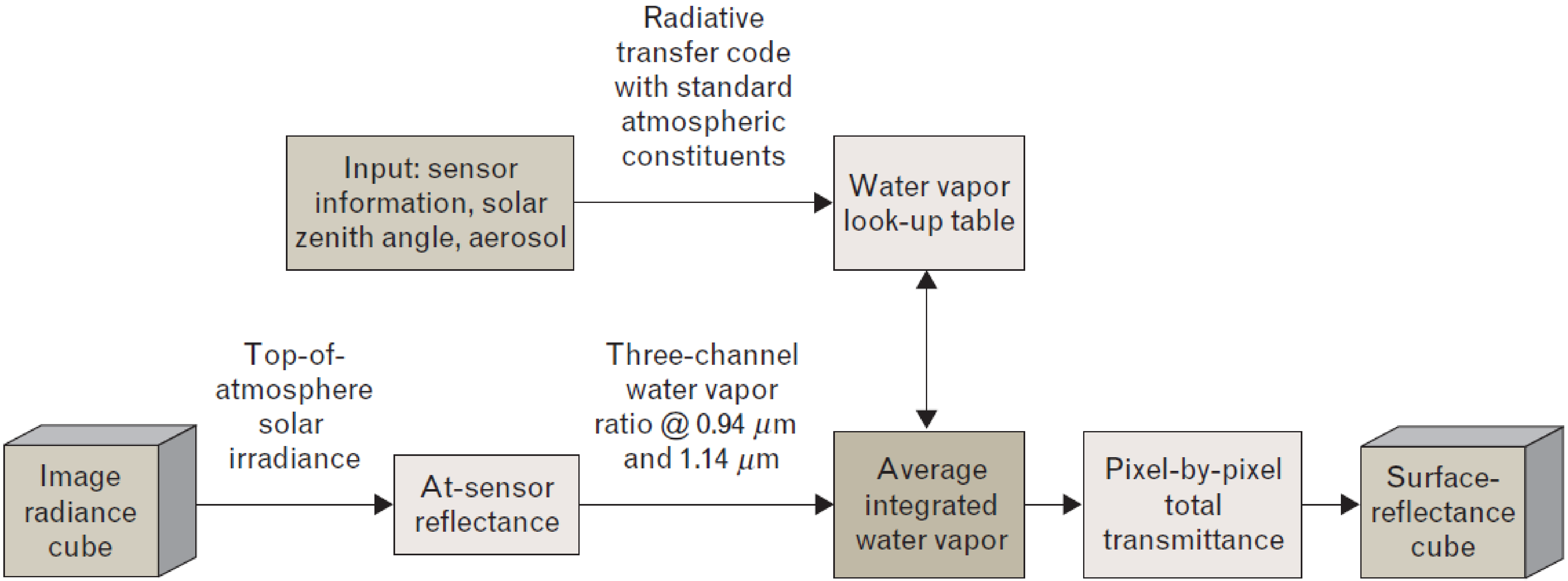


FIGURE 4. Schematic flow of the physics-based Atmospheric Removal (ATREM) program. The diagram shows the various steps used to convert the radiance data to surface-reflectance data.

Band depths are determined using a ratio of the band center to the two band shoulders. Water vapor is then estimated for each AVIRIS pixel by determining the band depth and comparing to the modeled band depths in the lookup table. The output of this procedure is an image showing the spatial distribution of various water vapor concentrations for each pixel of the AVIRIS data.

Atmospheric scattering is modeled using the "6S" radiative transfer code, (Tanre et al., 1986). Apparent reflectance spectra are obtained by dividing each AVIRIS spectrum by the solar irradiance curve above the atmosphere (Kneizyx et al., 1983) and using the water vapor image along with the other atmospheric parameters in the radiative transfer model of Tiellet (1989).

The final results are a water vapor image and reflectance-corrected AVIRIS data without use of ground spectral measurements. While the ATREM software package is no longer supported and is not available to new users, many HSI data users have and use ATREM. It demonstrates baseline atmospheric correction capabilities. ATREM Version 3.1 was the last publicly released software and was used for this research (CSES, 1999).

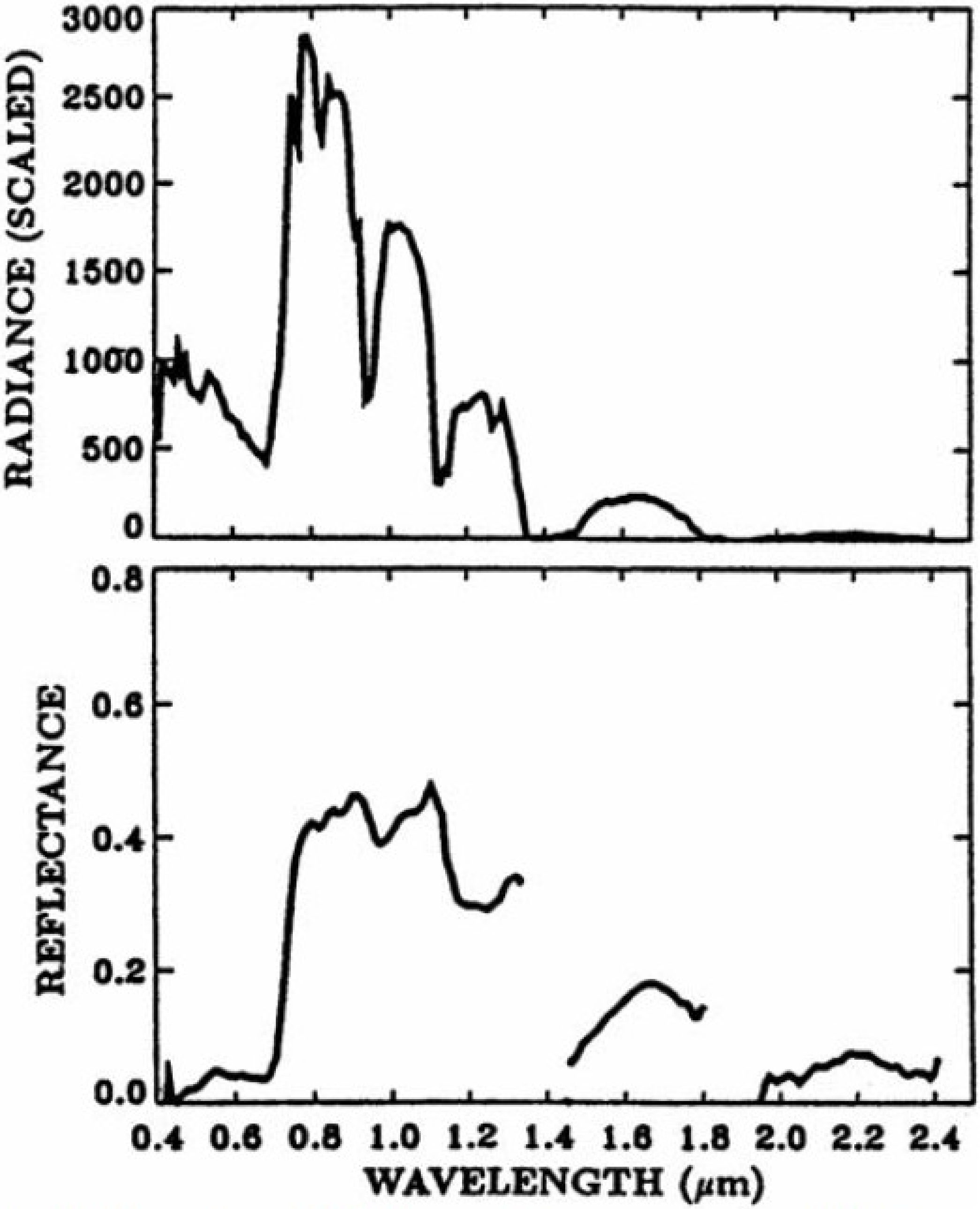


Fig. 13.7. **a** Raw AVIRIS vegetation spectrum and **b** its correction based on ATREM. (Reprinted from Gao et al., 1993 with permission from Elsevier Science)

ATREM - EFFORT

Even though the ATREM correction is adequate for most analysis purposes, the spectra usually still contain residual atmospheric and instrument effects, which is difficult to direct comparison with spectral libraries. To remove such effect, empirical models can be used effectively like EFFORT (Empirical Flat Field Optimized Reflectance Transformation).

The EFFORT correction takes advantage of the fact that a typical hyperpsectral scene contains a number of featureless spectra because these spectra still contain the noise effects, they can be used to characterize the nature of noise.

Feature less spectra are identified by calculating a Legendre Polynomial Fit to each spectrum in the image and then determining which spectra are well modelled by their corresponding polynomial.

Once the well modelled spectra are determined, then the gains and offset required to explain the difference between modelled spectra and actual spectra. A linear regression is used to calculate the gain and offset for each band that will make ATREM featureless spectra look like the modeled spectra

These gains and offset are then applied to every spectrum in the hypserspectral dataset. The resulting spectrum contain all of the fine absorption features.

ACORN: ATMOSPHERIC CORRECTION NOW

ACORN is a commercially-available, enhanced atmospheric model-based software that uses licensed MODTRAN4 technology (Berk et al, 1999) to produce high quality surface reflectance without ground measurements. The package provides an atmospheric correction of Hyperspectral and Multispectral data measured in the 0.4 - 2.5 micrometer spectral range (AIG, 2001).

ACORN uses look-up-tables calculated with the MODTRAN4 radiative transfer code to model atmospheric gas absorption as well as molecular and aerosol scattering effects, converting the calibrated sensor radiance measurements to apparent surface reflectance (AIG, 2001). The well mixed gases are constrained by the elevation and the observation geometry.

Water vapor is estimated from the data on a pixel-by-pixel basis using the water vapor absorption bands at 0.94 and/or 1.150 micrometers. A lookup table for a range of water column vapor densities is generated using MODTRAN4 and then fitted in a least-squares sense against the imaging spectrometer data.

A key feature of ACORN is full spectral fitting to solve for the overlap of absorptions between water vapor and liquid water in surface vegetation. Visibility is estimated from the AVIRIS data using nonlinear least-squares spectral fitting between the AVIRIS radiance spectra and MODTRAN modeled radiance with the aerosol optical depth as the primary fitting parameter.

The two-way transmitted radiance and atmospheric reflectance are calculated for each pixel using MODTRAN and the derived water vapor, pressure elevation, and aerosol optical depth estimations.

Apparent surface reflectance is derived from the total upwelling spectral radiance for a given atmosphere using a variant of the radiative transfer equation

The principal outputs of ACORN are a water vapor image and a scaled surface reflectance cube. An image showing an estimate of leaf-water is also optionally produced. ACORN artifact suppression options include automated wavelength correction, removal of noisy channels, and “polishing” of residual errors. The latest version, ACORN 4.15 was used for this research.

FLAASH - Fast Line-of-sight Atmospheric Analysis of Spectral Hypercubes

FLAASH is a MODTRAN4-based atmospheric correction software package developed by the Air Force Phillips Laboratory, Hanscom AFB and Spectral Sciences, Inc (SSI) (Adler-Golden et al., 1999).

It provides accurate, physics-based derivation of apparent surface reflectance through derivation of atmospheric properties such as surface albedo, surface altitude, water vapor column, aerosol and cloud optical depths, surface and atmospheric temperatures from HSI data.

FLAASH operates in the 0.4 – 2.5 micrometer spectral range. First, MODTRAN simulations of spectral radiance are performed for various atmospheric, water vapor, and viewing conditions (solar angles) over a range of surface reflectances to establish lookup tables for the atmospheric parameters of column water vapor, aerosol type, and visibility for subsequent use.

Typically, the 1.13 micrometer water band is used to estimate water vapor, and a ratio of in-band and out-of-band radiance values allows estimation of absorption band depths for a range of water vapor column densities.

FLAASH also derives pressure altitudes by applying the same method to the oxygen 0.762 micrometer absorption band. The radiance spectra are extracted from the data and compared against the MODTRAN lookup tables on a pixel-by-pixel basis to determine scaled surface reflectance.

FLAASH offers the additional option of correcting for light scattered from adjacent pixels. Spatially averaged reflectance is used to account for the “adjacency effect’’

FLAASH provides additional flexibility when compared to the other two atmospheric correction programs in that it allows custom radiative transfer calculations for a wider range of conditions including off-nadir viewing and all MODTRAN standard aerosol models.

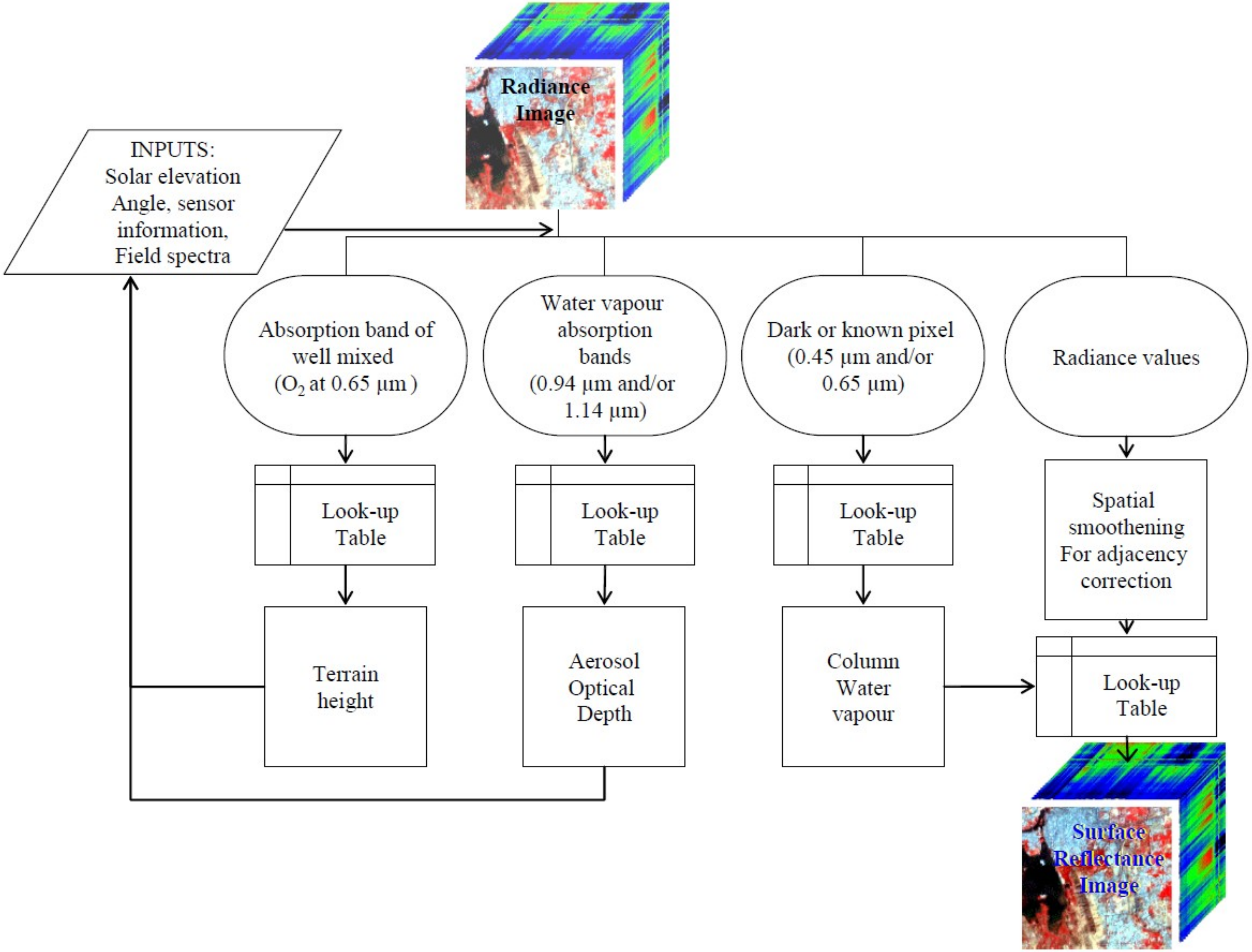


Figure 2-4 Schematic process flow for FLAASH showing basic steps involved in radiance to reflectance conversion (Griffin and Hsiao-hua, 2003)

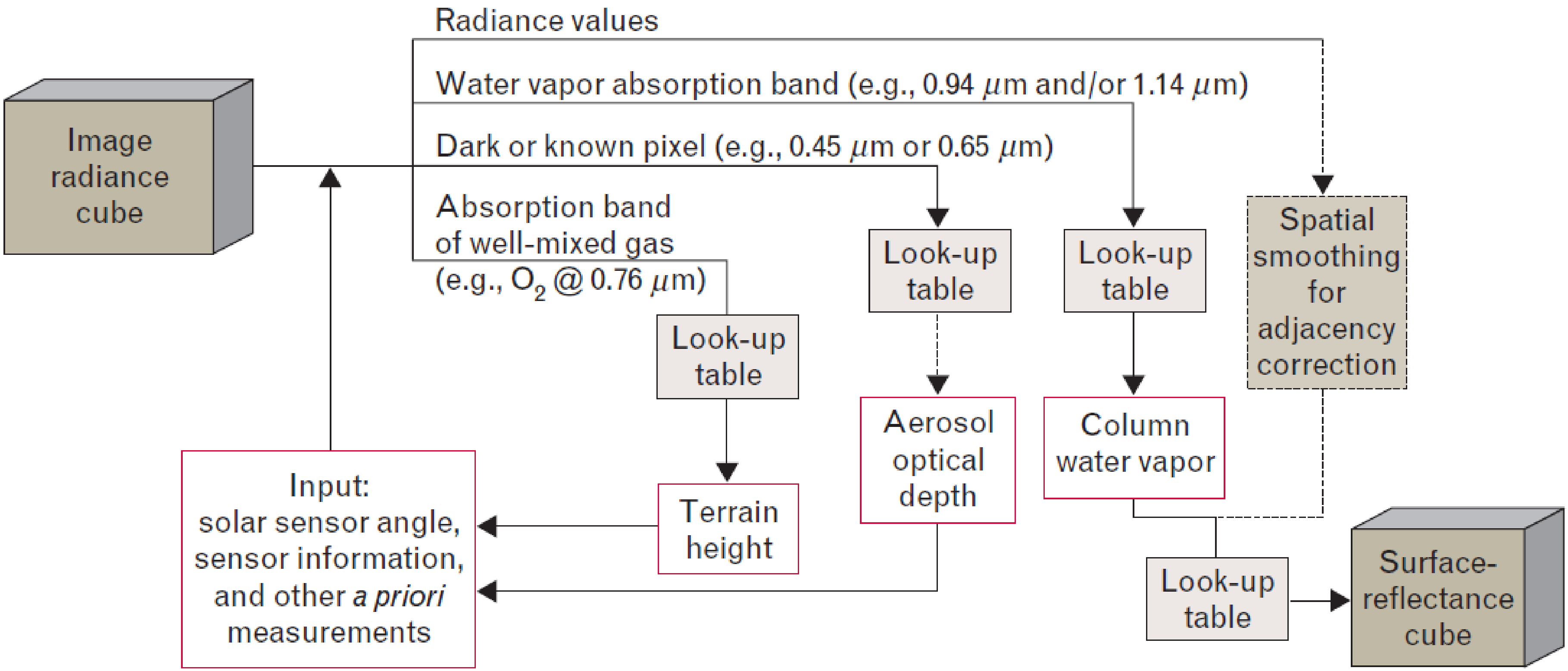
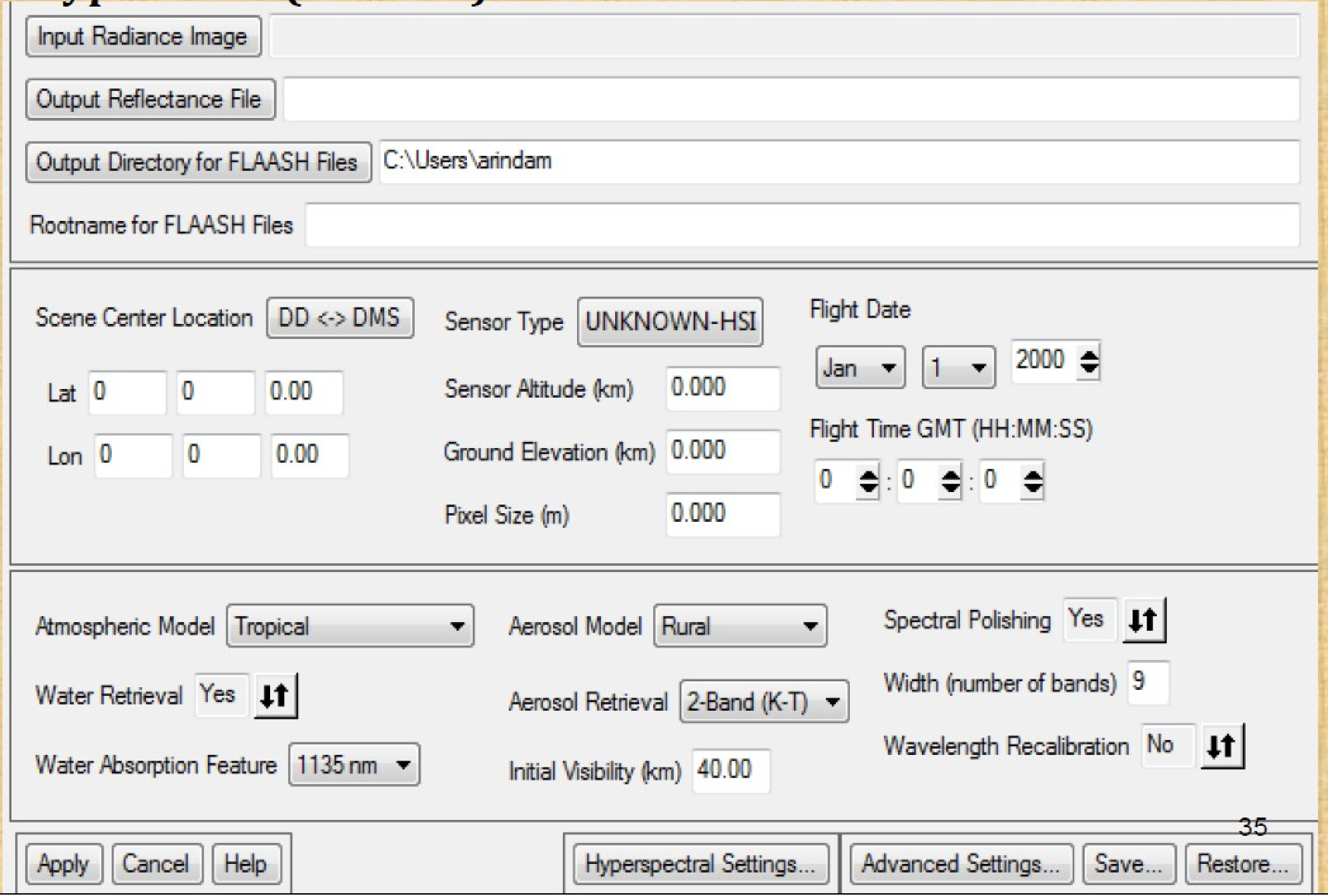


FIGURE 5. Schematic flow of the Fast Line-of-Sight Atmospheric Analysis of Spectral Hypercubes (FLAASH) code. The diagram defines the basic steps used to convert the sensor measured radiance to surface reflectance. Secondary products such as the column water vapor and the aerosol optical depth can also be obtained. The dotted connection lines indicate an optional selection in FLAASH.

Fast Line-of-sight Atmospheric Analysis of Spectral Hypercubes(FLAASH)



Output Directory for FLAASH Files: C:\Users\arindam

Rootname for FLAASH Files:

Scene Center Location

Lat 0 0 0.00

Lon 0 0 0.00

Sensor Type: UNKNOWN-HSI

Sensor Altitude (km): 0.000

Ground Elevation (km): 0.000

Pixel Size (m): 0.000

Flight Date: Jan 1 2000

Flight Time GMT (HH:MM:SS): 0 : 0 : 0

Atmospheric Model: Tropical

Water Retrieval: Yes

Water Absorption Feature: 1135 nm

Aerosol Model: Rural

Aerosol Retrieval: 2-Band (K-T)

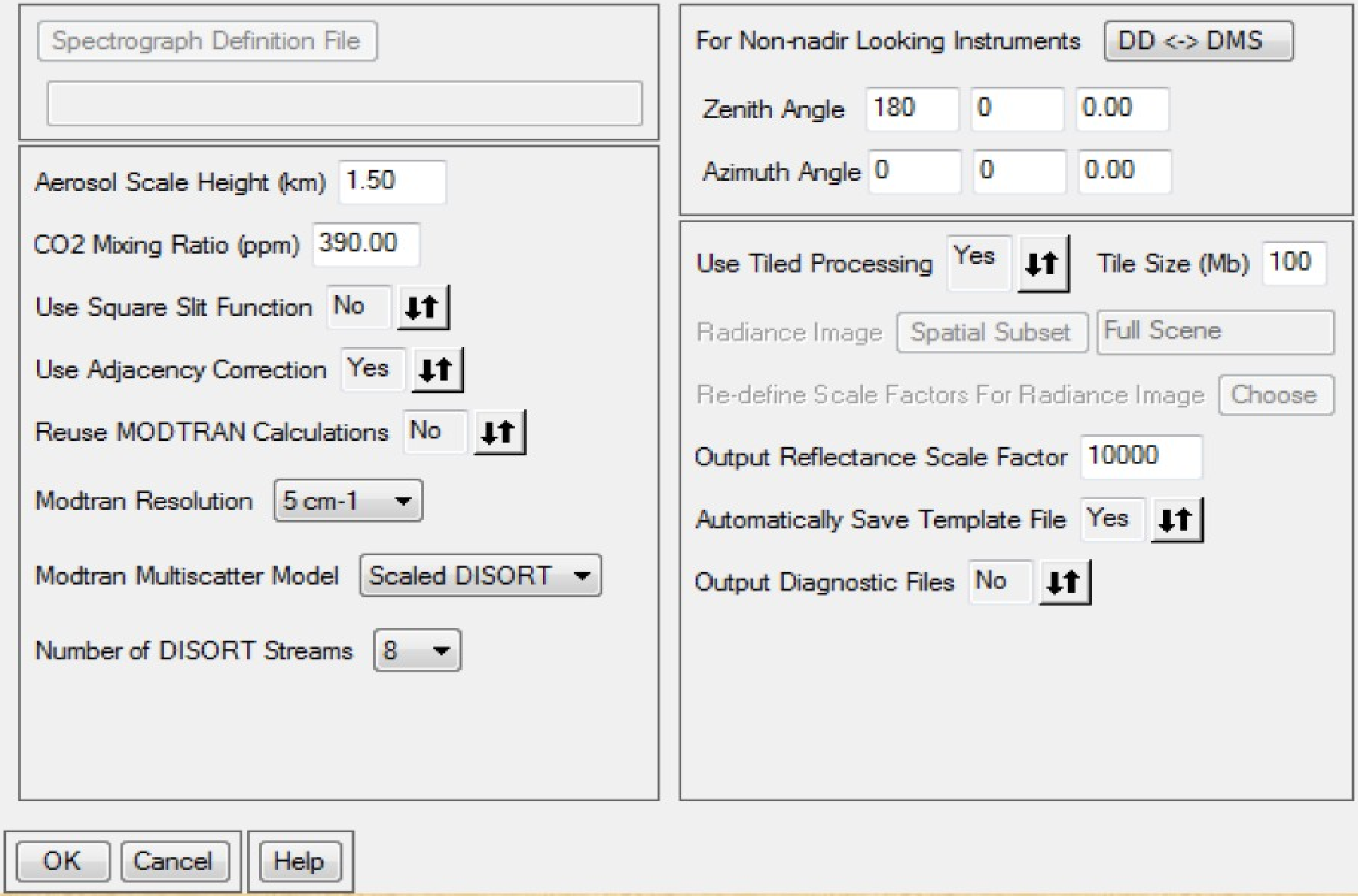
Initial Visibility (km): 40.00

Spectral Polishing: Yes

Width (number of bands): 9

Wavelength Recalibration: No

Fast Line-of-sight Atmospheric Analysis of Spectral Hypercubes(FLAASH)



Aerosol Scale Height (km) 1.50

CO2 Mixing Ratio (ppm) 390.00

Use Square Slit Function No

Use Adjacency Correction Yes

Reuse MODTRAN Calculations No

Modtran Resolution 5 cm-1

Modtran Multiscatter Model Scaled DISORT

Number of DISORT Streams 8

For Non-nadir Looking Instruments

Zenith Angle 180 0 0.00

Azimuth Angle 0 0 0.00

Use Tiled Processing Yes

Tile Size (Mb) 100

Radiance Image Full Scene

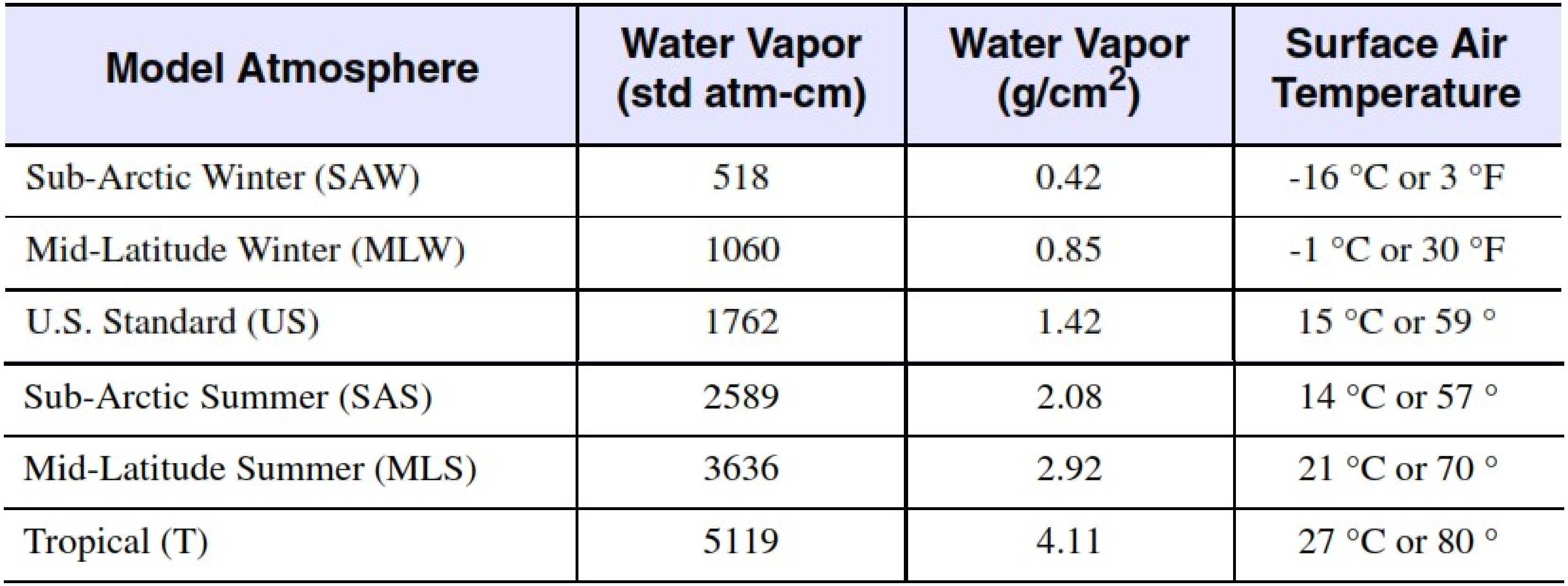
Re-define Scale Factors For Radiance Image

Output Reflectance Scale Factor 10000

Automatically Save Template File Yes

Output Diagnostic Files No

Column Water Vapor Amounts and Surface Temperatures for the MODTRAN Model Atmospheres



Model Atmosphere	Water Vapor (std atm-cm)	Water Vapor (g/cm^2)	Surface Air Temperature
Sub-Arctic Winter (SAW)	518	0.42	-16 °C or 3 °F
Mid-Latitude Winter (MLW)	1060	0.85	-1 °C or 30 °F
U.S. Standard (US)	1762	1.42	15 °C or 59 °
Sub-Arctic Summer (SAS)	2589	2.08	14 °C or 57 °
Mid-Latitude Summer (MLS)	3636	2.92	21 °C or 70 °
Tropical (T)	5119	4.11	27 °C or 80 °

Latitude (°N)	Jan.	March	May	July	Sept.	Nov.
80	SAW	SAW	SAW	MLW	MLW	SAW
70	SAW	SAW	MLW	MLW	MLW	SAW
60	MLW	MLW	MLW	SAS	SAS	MLW
50	MLW	MLW	SAS	SAS	SAS	SAS
40	SAS	SAS	SAS	MLS	MLS	SAS
30	MLS	MLS	MLS	T	T	MLS
20	T	T	T	T	T	T
10	T	T	T	T	T	T
0	T	T	T	T	T	T
-10	T	T	T	T	T	T
-20	T	T	T	MLS	MLS	T
-30	MLS	MLS	MLS	MLS	MLS	MLS
-40	SAS	SAS	SAS	SAS	SAS	SAS
-50	SAS	SAS	SAS	MLW	MLW	SAS
-60	MLW	MLW	MLW	MLW	MLW	MLW
-70	MLW	MLW	MLW	MLW	MLW	MLW
-80	MLW	MLW	MLW	SAW	MLW	MLW

Table 2-2: Selection of MODTRAN Model Atmospheres Based on Latitudinal/Seasonal Dependence of Surface Temperature

Using Water Retrieval

To solve the radiative transfer equations that allow apparent surface reflectance to be computed, the column water vapor amount for each pixel in the image must be determined. FLAASH includes a method for retrieving the water amount for each pixel. This technique produces a more accurate correction than using a constant water amount for the entire scene. To use this water retrieval method, the image must have bands that span at least one of the following ranges at a spectral resolution of 15 nm or better:

- 1050-1210 nm (for the 1135 nm water feature)
- 870-1020 nm (for the 940 nm water feature)
- 770-870 nm (for the 820 nm water feature)

For most of the multispectral sensor types, the **Water Retrieval** setting is **No** because these sensors do not have the appropriate bands to perform the retrieval.

The **Water Retrieval** options are as follows:

- **Yes**: Perform water retrieval. From the **Water Absorption Feature** drop-down list, select the water feature you wish to use. The 1135 nm feature is recommended if the appropriate bands are available. If you select 1135 nm or 940 nm, and the feature is saturated due to an extremely wet atmosphere, then the 820 nm feature is automatically used in its place if bands spanning this region are available.

Selecting an Aerosol Model

- **Rural:** Represents aerosols in areas not strongly affected by urban or industrial sources. The particle sizes are a blend of two distributions, one large and one small.

- **Urban:** A mixture of 80% rural aerosol with 20% soot-like aerosols, appropriate for high-density urban/industrial areas.

- **Maritime:** Represents the boundary layer over oceans, or continents under a prevailing wind from the ocean. It is composed of two components, one from sea spray and another from rural continental aerosol (that omits the largest particles).

- **Tropospheri c:** Applies to calm, clear (visibility greater than 40 km) conditions over land and consists of the small-particle component of the rural model.

For more details on MODTRAN aerosol models, see Abreu and Anderson (1996).

FLAASH includes a method for retrieving the aerosol amount and estimating a scene average visibility using a dark pixel reflectance ratio method based on work by Kaufman et al. (1997).

The dark-land pixel-retrieval method requires the presence of sensor channels around 660 nm and 2100 nm. A dark-land pixel is defined to be one with a 2100 nm reflectance of 0.1 or less
and a 660:2100 reflectance ratio of approximately 0.45.

If the input image contains bands near 800 nm and 420 nm, an additional check is performed, requiring the 800:420 radiance ratio to be 1 or less, which eliminates pixels likely to be shadows and water bodies.

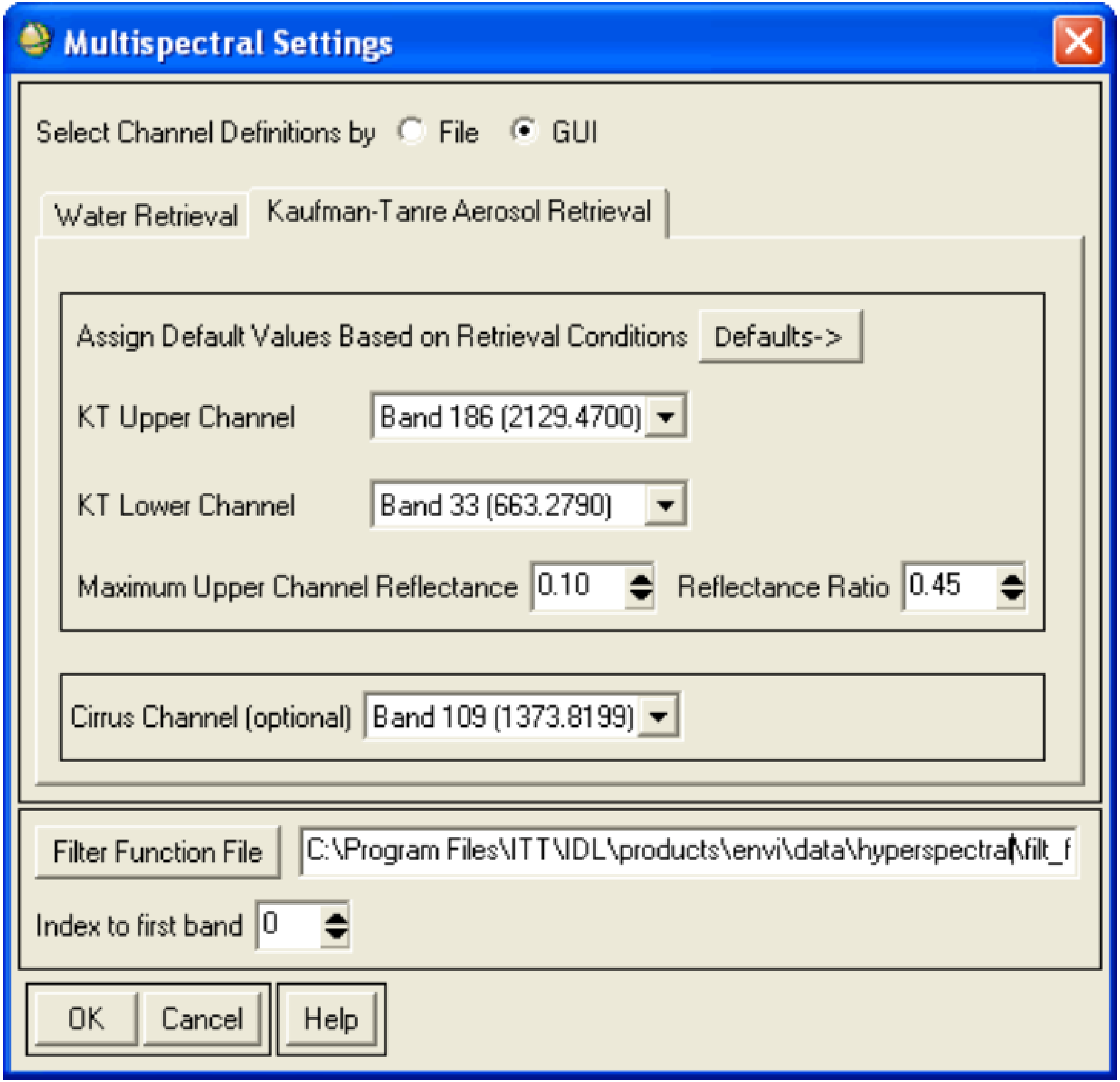
Entering an Initial Visibility Value

In the **Initial Visibility** field, enter an estimate of the scene visibility in kilometers. The initial visibility value is assumed for the atmospheric correction if the aerosol is not being retrieved.

Table 2-3 lists approximate values based on weather conditions.

Weather Condition	Scene Visibility
Clear	40 to 100 km
Moderate Haze	20 to 30 km
Thick Haze	15 km or less

Table 2-3: Approximate Scene Visibility Values



Multispectral Settings

Select Channel Definitions by ○ File ● GUI

Assign Default Values Based on Retrieval Conditions

KT Upper Channel: Band 186 (2129.4700)

KT Lower Channel: Band 33 (663.2790)

Maximum Upper Channel Reflectance: 0.10

Reflectance Ratio: 0.45

Cirrus Channel (optional): Band 109 (1373.8199)

Filter Function File: C:\Program Files\ITT\IDL\products\envi\data\hyperspectral\filt_f

Index to first band: 0

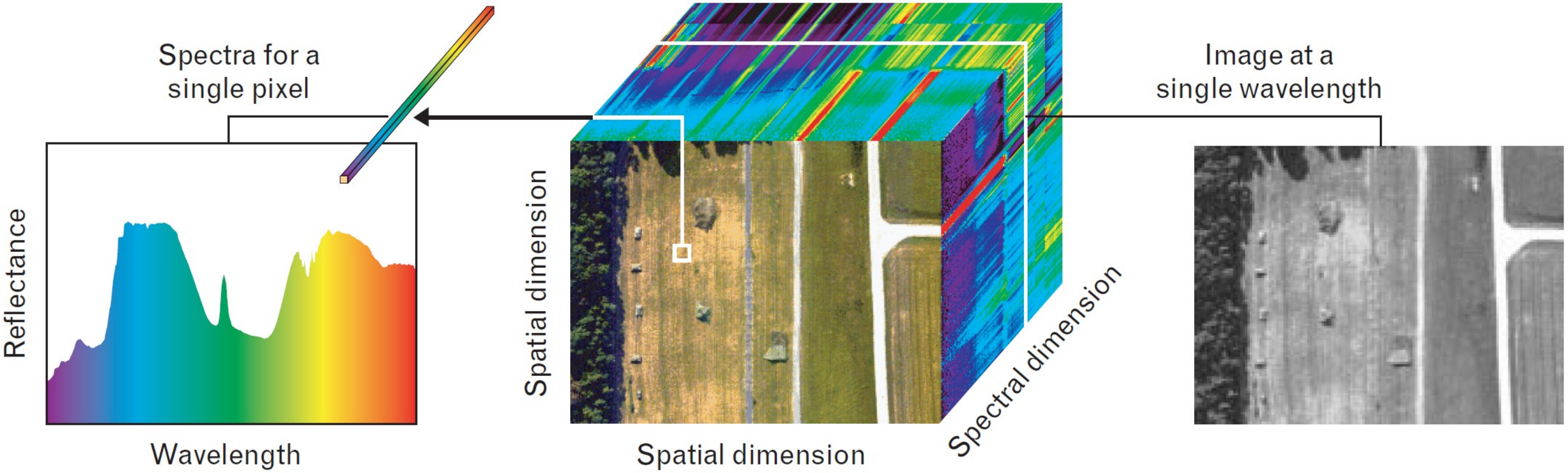
Data Cubes and Spectral Vectors

As a result of spatial and spectral sampling, airborne hyperspectral imaging (HSI) sensors produce a three dimensional (3D) data structure (with spatial-spatialspectral components), referred to as a data cube.

The 3D Hypercube Display emphasizes the high spectral content of the hyperspectral image while allowing you to quickly examine any of the individual wavelength bands. The 3D Hypercube Display window portrays the hyperspectral image as a three-dimensional "image cube".

If we extract all pixels in the same spatial location and plot their spectral values as a function of wavelength, the result is the average spectrum of all the materials in the corresponding ground resolution cell

The values of all pixels in the same spectral band, plotted in spatial coordinates, result in a grayscale image depicting the spatial distribution of the reflectance of the scene in the corresponding spectral wavelength.



Basic data-cube structure (center) in hyperspectral imaging, illustrating the simultaneous spatial and spectral character of the data. The data cube can be visualized as a set of spectra (left), each for a single pixel, or as a stack of images (right), each for a single spectral channel

The top and right panels of the cube show the corresponding edge cells of each wavelength band, with wavelength increasing toward the back of the cube.

The observed spectral radiance data, or derived apparent surface reflectance data, can be viewed as a scattering of points in an *K*-dimensional Euclidean space, denoted by $\Re$ *K*, where *K* is the number of spectral bands. Each spectral band is assigned to one axis of the space, all axes being mutually orthogonal.

Therefore, the spectrum of each pixel can be viewed as a vector x = $[x_1, x_2, \ldots, x_K]^T$, where *T* denotes matrix transposition.

The tip of this vector corresponds to an *K*-dimensional point whose Cartesian coordinates x_i are the radiance or reflectance values at each spectral band. Since each component $x_i \geq 0$, spectral vectors lie inside the positive cone of $\Re^K$. Notice that changes in the level of illumination can change the length of a spectral vector but not its orientation, which is related to the shape of the spectrum. If each material is characterized by a unique deterministic spectrum, which can serve as a spectral fingerprint.

Noise Estimation and dimensionality reduction in Hyperspectral Data

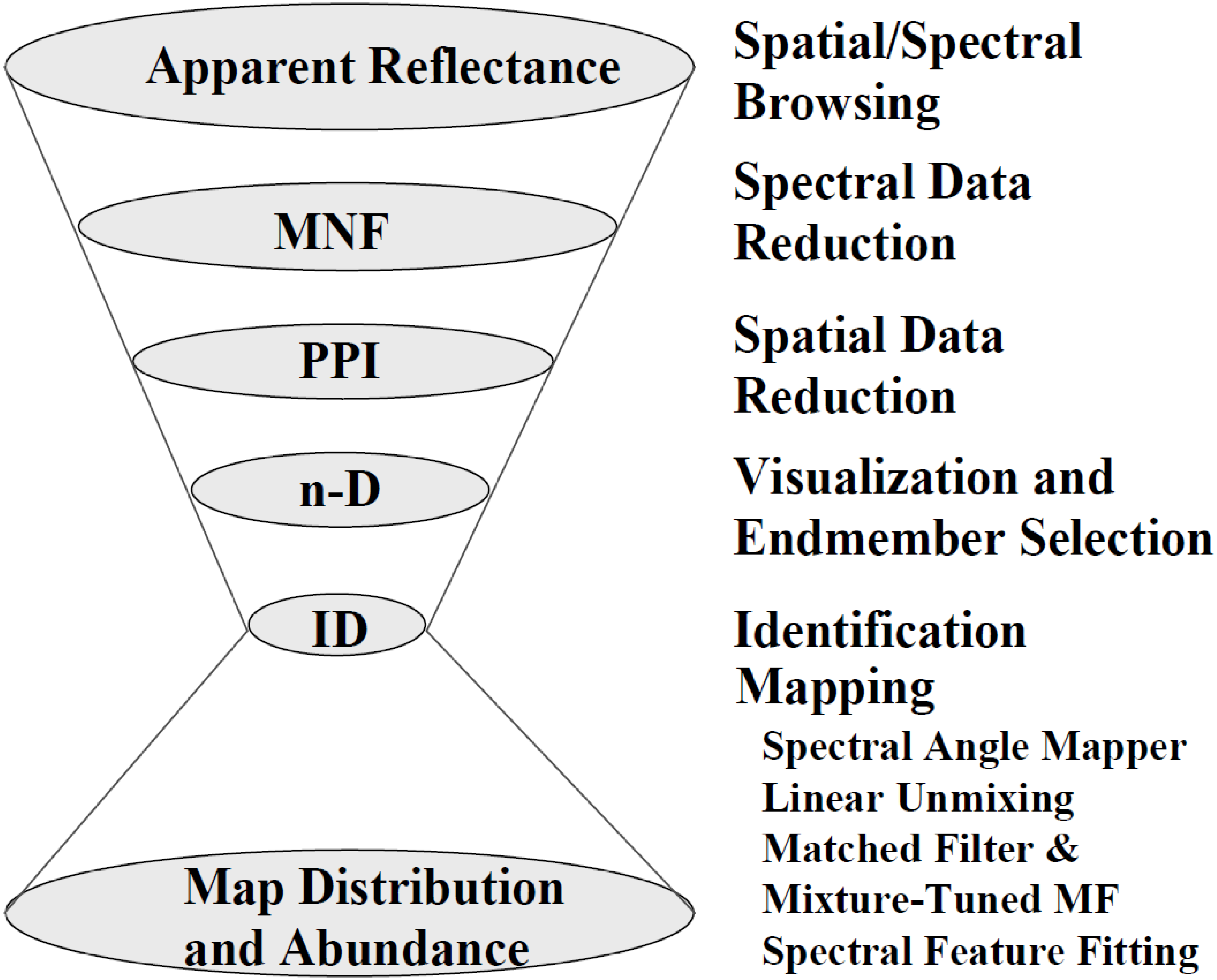


Figure 5. Standardized Processing methods for hyperspectral data analysis.

Principal Components Transform

Adjacent hyperspectral image bands are visually and numerically similar, and therefore contain much redundant information. The Principal Components transform is a standard method for deriving a new set of images with reduced spectral redundancy.

The process is a linear transformation that projects each image cell's spectrum to a new set of orthogonal coordinate axes. These axes are chosen so that the output images are uncorrelated and ordered by decreasing variance, with the first principal component axis corresponding to the direction of maximum variance in spectral space.

Important image information is generally concentrated in the low-order components, while noise increases with increasing component number. Use of low-order PC rasters in place of original image bands can speed visual analysis and classification of the hyperspectral image.

Minimum Noise Fraction Transform

MNF is used determine the inherent dimensionality of image data, to segregate noise in the data, and to reduce the computational requirements for subsequent processing.

If bands in a hyperspectral image have differing amounts of noise, standard principal components derived from them may not show the usual trend of steadily increasing noise with increasing component number.

A minimum noise fraction (MNF) transformation is used to reduce the dimensionality of the hyperspectral data by segregating the noise in the data.

The Minimum Noise Fraction transform (MNF) is a modified version of the Principal Components transform that orders the output components by decreasing signal to noise ratio.

The MNF procedure first estimates the noise in each image band using the spatial variations in brightness values. It then applies two successive principal component transforms.

The first uses the noise estimates to transform the dataset to a coordinate system in which the noise is uncorrelated and is equal in each component.

Then a standard principal components transform is applied to the noise-adjusted data, with output components ordered by decreasing variance.

This procedure produces a component set in which noise levels increase uniformly with increasing component number.

The low-order components should contain most of the image information and little image noise.

Often hyperspectral imagery is reduced in dimensionality to simplify analysis. The technique of principal components analysis (PCA) is used to reduce dimensionality in a manner that rotates the majority of information content (variance) into fewer bands. Specifically it transforms redundant information by de-correlation of the data via linear transforms . This is done by finding a new coordinate system in hyper-dimensional vector space where the data exhibits no correlation.

Basically, the covariance matrix in the new coordinate system is diagonal or uncorrelated. A linear transformation, U, that transforms the original hyperspectral data, X, into the new coordinate system Y must then be calculated. The original covariance matrix, Σx, becomes the diagonalized covariance matrix, Σy. The solution to this problem becomes a generalized eigenvalue problem of the form