Radiometric Verification Using Ground Truth Measurements

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Course Objective

- Describe and Review a method for verifying radiometric on-orbit performance of commercial imaging satellites
- Emphasis on visible and NIR sensors such as Landsat, SPOT, Ikonos 1, QuickBird, and Orbview 3.

Course Outline

- High level ground truth verification considerations
- Possible methodologies
- The recommended methodology
  - Procedures
  - Software and hardware components
  - Data requirements
  - Atmosphere characterization
  - Target characterization
  - Accuracy and errors
- Operational considerations
- Test and verification
- Recommended future upgrades and improvements

Ground Truth Verification Considerations

- Verification is only as good as your knowledge of the truth
  - You never really know the truth
  - You're knowledge of the truth is never better than the weakest link in your verification of the truth source

- Objective is to estimate accuracy of sensor radiance measurements, not to characterize the atmosphere

Entrance Aperture Radiance vs. Reflectivity as a Verification Parameter

- Verification of sensor performance should be based upon the parameter measured by the sensor, not on the parameters derived from that measurement.

$R_{TOA}=R_T\tau+h=\rho R_D\tau+h$

$\Delta R_{TOA}/ R_{TOA}=\Delta h/(\rho R_D\tau+h)$

$\rho=(R_{TOA}-h)/\tau R_D$

$\Delta\rho/\rho=(\Delta R_{TOA}-\Delta h)/(R_{TOA}-h)$

h = haze

R_{TOA}= radiance at top of atm

τ = transmission

R_D = radiance of target

- If $h\approx R_{TOA}$ then $\Delta\rho/\rho$ is very large, while $\Delta R_{TOA}/ R_{TOA}$ is relatively unaffected.
- Errors in ρ are leveraged heavily by the accuracy of R
- $\Delta\rho/\rho$ should really only be used for sensitivity analyses of reflectivity relative to atmospheric errors

How Good Does Your Collection System Have to Be?

- That depends upon the user requirements and the sensor capabilities.
  - What is the actual product metric?
    - Ag analysts generally want average, band-dependent reflectivity
    - Global warming analysts usually want absolute radiance and temperature
- Difficult to get users to quantify their requirements
  - Always want better accuracy than they get now
  - Usually unsure of their current accuracy
  - Rarely know the relationship between measurement accuracy and improvement in results
- Measurement uncertainties with historic systems drove the development of less sensitive metrics
  - Metrics were developed that were insensitive to absolute radiometric errors
    - Normalized Differential Vegetative Index {NDVI =(NIR-red)/(NIR+red)}
    - Band ratios

Historical Perspective

- Landsat TM had errors estimated as high as 20%
  - Still considered a useful, productive sensor
  - Atmospheric correction of images has been crude
    - Difficult to correct for atmospheric interference when there is little direct data of the atmospheric conditions at the image site
- Similar problems with AVHRR and SPOT

Radiometric Calibration of Remote Sensors

- Different Types and different potential accuracies
  - Ground truth (2%-10% under excellent conditions)
  - Reflective solar diffusers (3%-4%)
  - Small solar apertures (3%-8%)
  - Integrating spheres (?)
  - Lamps (?)
  - Lunar calibration (?)
  - Combination techniques (3%-5%)
- By Program
  - Landsat 4 TM (10% spec 15%-20% estimated)
  - Landsat 7 TM (5% spec ? estimated)
  - SPOT
  - Modis (5% vis/3% IR spec)
  - MISR
  - ASTER (4% spec)

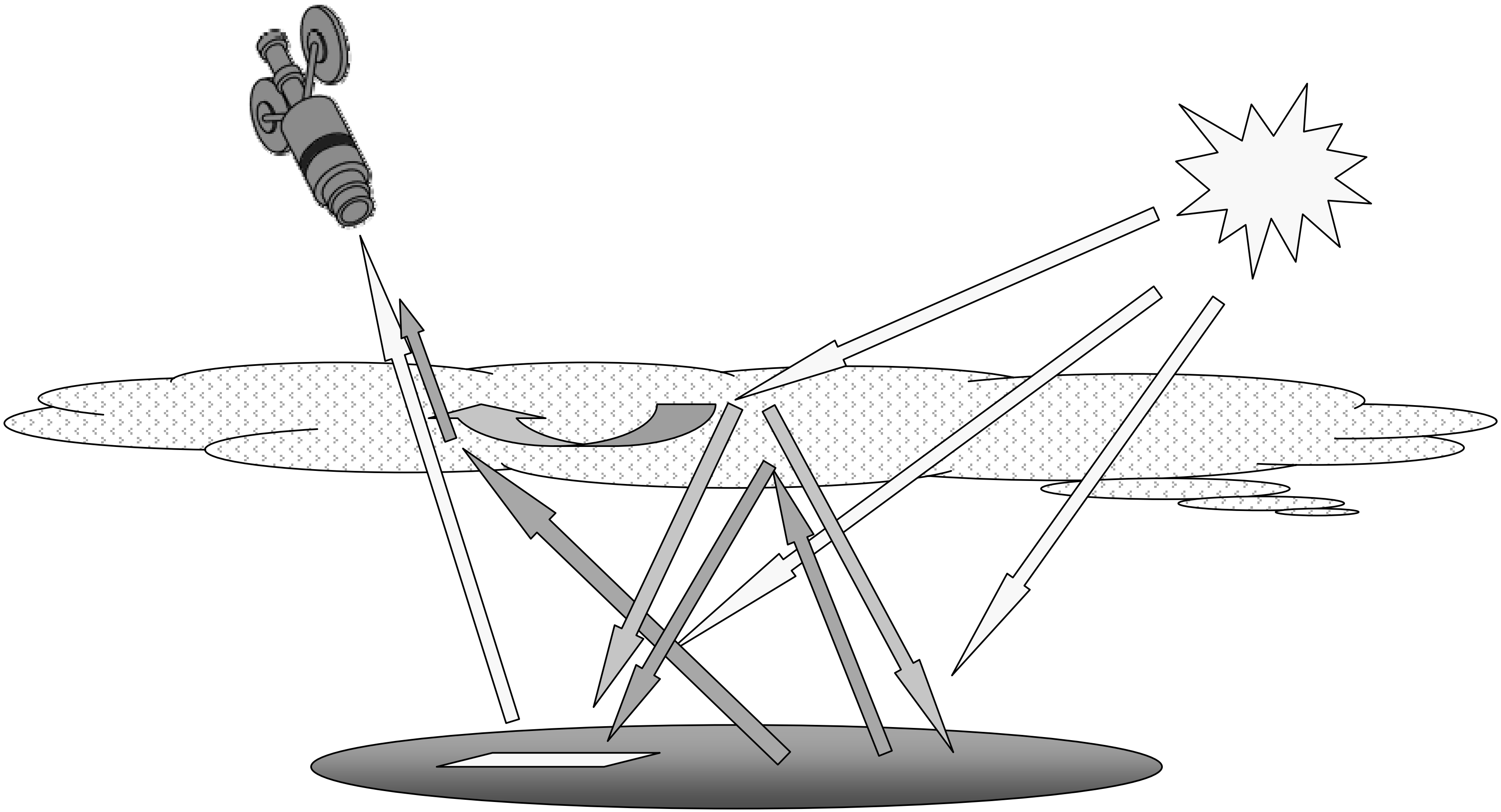
Other Ground Truth Programs

- University of Arizona (Dr. Phillip Slater)
  - Attempted to radiometrically calibrate Landsat and SPOT from ground truth measurements in southwest US (Lunar Lake, Railroad Valley, White Sands)
  - Believed to be able to estimate TOA radiance to 2%-5%.
    - Partially verified.
- JPL
  - Setting up a ground truth program for MISR
- South Dakota State University (Dr. Steven Schiller)
  - Independent attempt to match U of A data using different techniques in southwest
    - Matched within 3%-5%
  - Other tests at Huntsville, Alabama
- FIFE and OTTER
  - Common overflight by multiple sensors for experimental purposes
  - Not primarily geared toward calibration/verification

So How Accurate Does Ground Truth Have to Be?

- As good as you can afford.
- Sensors are typically designed to be more accurate than ground truth (though they rarely are).
- Ground Truth will never be good enough to <u>directly</u> verify a good on-orbit radiometer in the visible bands.
- Ground truth can be used to increase confidence
- Need to verify ground truth accuracy as much as possible
- Need to "look below the noise" using statistical analyses over several collections to separate sensor errors from ground truth errors
  - Watch for bias errors vs. random errors
  - Errors correlated across spectral bands
    - "Typically," sensor calibration errors tend to be strongly correlated across bands
    - Check correlation of errors across multiple sensors
    - Will probably require design information on sensors

Radiative Transfer Scenario



Pieces of the Puzzle That Must Be Assembled

- The Illumination of the Target
- The Target
- The Atmosphere Between the Target and the Sensor
  - The atmosphere is not the same between the sun and target and the target and sensor

Driving Requirements for the Test

- Cost
- What are you trying to measure/verify?
- The Sensor Characteristics and Physical Relationships
  - For today: VNIR with 1 meter / 4 meter GSD
  - SWIR? MWIR? LWIR?
- Operational Constraints
  - Location (Stennis and Northern Arizona)
  - Weather (High humidity, low altitude, low humidity, high altitude)
  - Available manpower
- Instrumentation Constraints
  - What Instruments Exist?
  - What Instruments are available?
- Known Methodologies, Concepts of Operation, Algorithms and Processing

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Possible Methodologies

1) Vicarious calibration

- Fly a high altitude aircraft or a satellite with a well-calibrated sensor over the targets coincident with the sensor to be evaluated
- Make small corrections for any residual atmosphere

2) Model the atmosphere based upon available ground measurements and measure the target separately.

- Use the model to estimate both downwelling and upwelling effects.
- Recommended technique

Atmospheric Characterization Techniques

- Radiative Transfer Models (RTM)
  - Utilize (generally passive) measurements, assumptions about the aerosol characteristics, and physical models to estimate state of atmosphere
    - Measurements generally of spectral radiance
    - Typical Assumptions
      - Spherical scatters
      - Junge size distribution
      - Constant index of refraction
      - Langley Plots
    - Typical Physical Models
      - Mie scattering equations
      - Rayleigh scattering equations

Atmospheric Characterization Techniques (cont'd)

- Phenomenological Modeling
  - In weather forecasting, this is called the Variational Assimilation Method (VAM)
  - Utilizes similar measurements, some physical models, and empirically derived formulae to estimate the impact of atmospheric interference.
    - More generalized assumptions about overall characteristics
    - Often uses small perturbations about a standardized model
    - More concentration on impact and less on details of causality
  - Conceptually, the equivalent of a polynomial fit of a complex function over a limited range.

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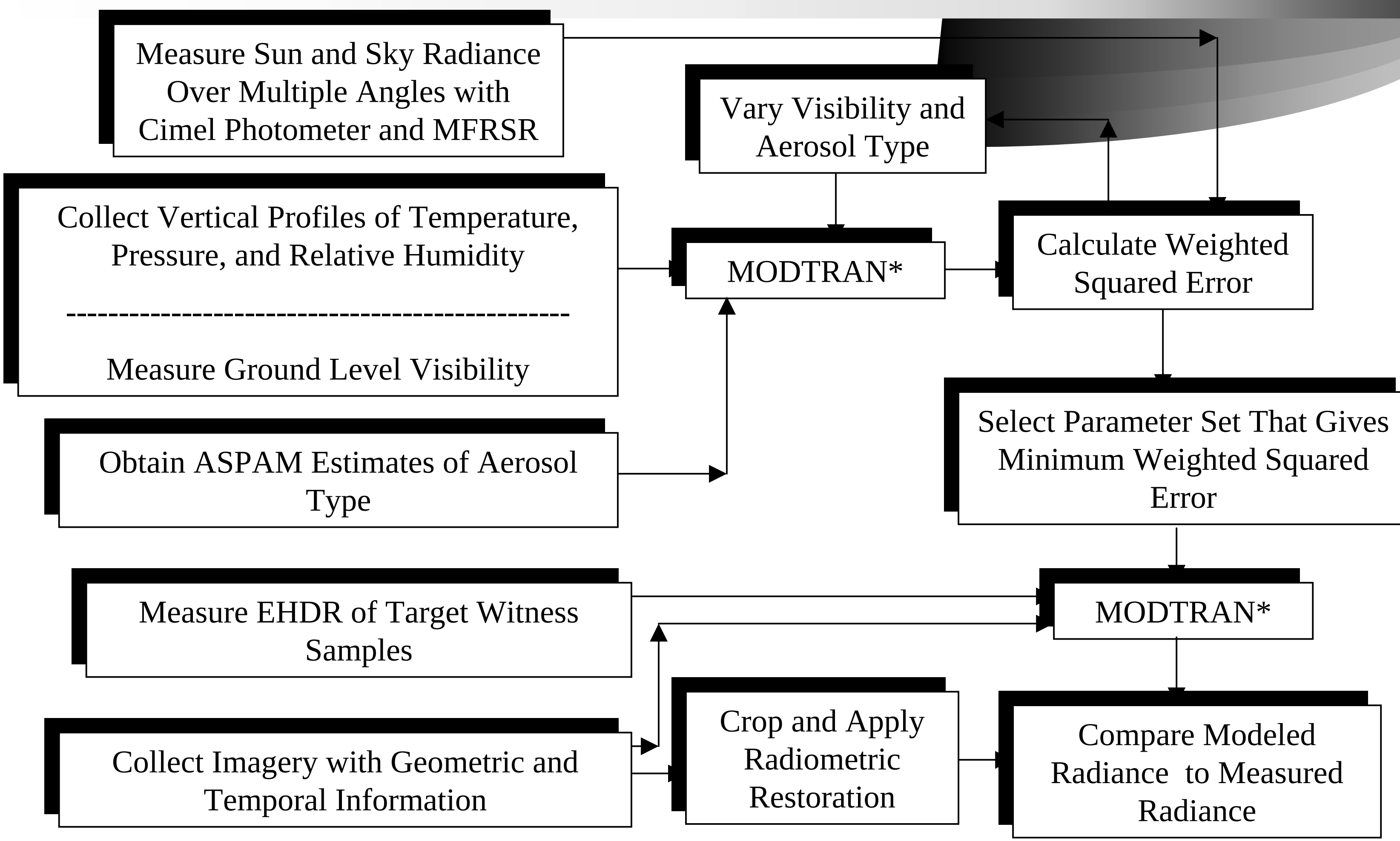
Radiometric Verification Initial Operational Concept



* May require custom modifications

The Recommended Atmospheric Effects Model is MODTRAN

- MODerate resolution TRANsmission model
- Originally developed at the AFGL. Now maintained by Phillips Labs.
- Based upon a combination of physical models and empirical data.
- Contains several "standard" atmospheric models

  Midlatitude summer and winter   Subarctic winter

  Moist Tropic   US Standard
- and several "standard" aerosol models
  - urban   spring/summer   stratospheric dust (IVULCN)
  - rural   fall/winter
  - Navy maritime
  - maritime   coastal impacts (fetch)
  - desert

  all of which can be overridden.

MODTRAN Inputs and Outputs

- Inputs
  - Extremely user configurable
  - Simplest configuration
    - Lat, long, altitude, date, time, model atmosphere, background albedo type, wavenumber range and interval, aerosol type ...
  - Too many complex configurations to list
    - Examples of selectable inputs
      - Vertical profiles of temperature, pressure and relative humidity
      - Four atmospheric layers, each with its own extinction profile
- Outputs
  - Several output files with desired and diagnostic data
  - File TAPE7 contains path transmission and spectral radiance of:
    - single and multiple solar scattered light
    - direct atmospheric and background scattered thermal energy in LOS
    - target thermal emissions
    - reflected direct solar and total reflected energy

Assumed Ground Instrumentation

- For atmospheric characterization
  - Cimel Photometer
    - Provides radiance in 5 spectral bands along almucanter scan and principal plane scan
  - Multifilter Rotating Shadowband Radiometer
    - Provides whole sky irradiance and direct solar irradiance in 6 spectral bands
  - Balloon Launched Radiosondes
    - Measures temperature, pressure, and relative humidity as a function of altitude
    - **Note**: Only Vaisalla radiosondes should be used
      - Other radiosondes display excessive error in relative humidity
  - Visibility Meter
  - Whole Sky Camera
- Other
  - Downlooking spectroradiometer with accurate positioning (Sandmeier Goniometer)

Estimating Other Required Inputs to the Model

- Initial estimate of aerosol type comes from the Air Force ASPAM report
  - ASPAM (Advanced Slant Path Atmospheric Model)
    - A tremendous amount of data regarding weather and atmospheric conditions
    - Provides data interpolated to time and location based upon > 6000 radiosonde launches and innumerable synoptic and other reports worldwide
    - A special subset is available to qualified subscribers that is perfectly suited to this project
- Background survey
  - Materials different from, and surrounding the target, cause additional colored energy to enter the field of view of the target
    - Sometimes called an adjacency effect
    - Not an MTF effect
  - An estimate of the average spectral reflectivity of the background is necessary for MODTRAN to account for adjacency effects
    - Inserted in the bkgrd file
    - Approximate readings are good enough

ASPAM Data

Number of altitude levels in provided vertical profile
Aerosol Extinction Selection Code (IHAZE)
Continental Influence for Boundary Layer Aerosol (ICSTL)
Seasonal Aerosol Profile Code (ISEASN)
Stratospheric Aerosol Selection Code (IVULCN)
Surface Level Visibility (VOBS) (km)
Ozone Density Profile (M3)
Aerosol Type Quality Index (QIHAZE)
Alternative Surface Level Visibility (VOBS) (Nominal minus 1 error) (km)
Alternative Aerosol Extinction Selection Code
Alternative Continental Influence for Boundary Layer Aerosol
For each altitude level
Height (x100) (0.01 km MSL)
Pressure (x100) (0.1 mb)
Temperature (x10) (0.1°C)
Water Vapor Density (x100) (0.01 g/m3)
AHAZE (x1000) (0.001 km-1)
Alternative Temperature (x10) (Nominal plus 1σ error) (0.1°C)
Alternative Water Vapor Density (x100) (Nominal minus 1σ error) (0.01 g/m3)
Alternative AHAZE (x1000) (0.001 km-1)

24 Hour Surface Weather History
Best RAOB Data Description
Distance to best RAOB (nmi)
Bearing to best RAOB (degrees)
RAOB site elevation used (meters)
Target site elevation used (meters)
RAOB time (UTC)

Repeat the following for every 3 hours over the last 24 hours (9 entries)

Date
- Year
- Julian Day
- Hour and Minute (GMT)

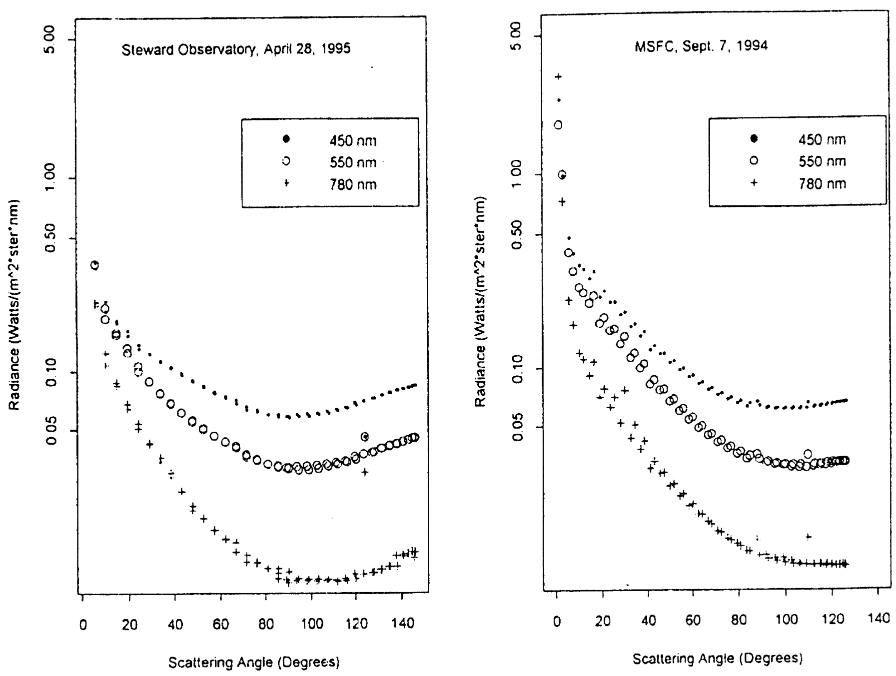
Cloud Cover
- Level 1
- Level 2
- Level 3
- Level 4
- Total % Cloud Cover

Visibility (km)
Precipitation Type
Obstruction to Visibility
Pressure (x10) (0.1 mb)
Temperature (°C)
Dewpoint Temperature (°C)
Wind Direction (x0.1) (10 degrees)
Wind Speed (m/s)
Alternative Wind Speed (Nominal plus 1σ error) (m/s)
Max 24 hour temperature (°C)
Min 24 hour Temperature (°C)
Daily Snow Depth

Calculation of Sky Radiance

- For each azimuth/elevation combination of angles between ground instrument and sky
  - Use MODTRAN to calculate radiance of each portion of sky
    - Angles should match those collected by Cimel Photometer
  - Special provision for point source sun in MODTRAN
- Use one MODTRAN run with zenith angle to calculate global diffuse hemispheric radiance, with and without the sun
  - Used for a comparison to the output of the MFRSR

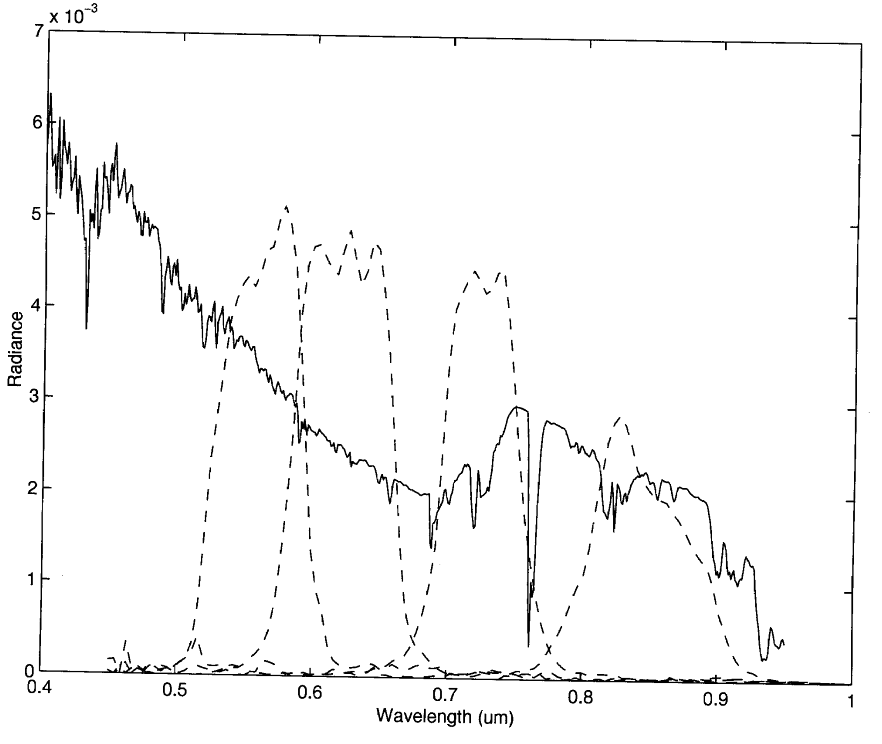
Sample Sky Radiances vs. Scattering Angle



. Almucantar scans recorded at Steward Observatory, Arizona and Marshall Space Flight Center, Huntsville, Alabama. The scans were made at the sun's altitude of 15° and 27° respectively. Only the data for 3 of the 512 PGAMS channels are shown.

Conversion of Modeled Spectral Radiance to Modeled Ground Instrumentation Measurements

- Spectral estimates from MODTRAN must be integrated across spectrum weighted by the spectral responses of each of the ground instrument channels



Calculation of the Figure of Merit

- Determine how closely the modeled atmosphere matches the ground measurements by calculating the Squared Weighted Normalized Difference

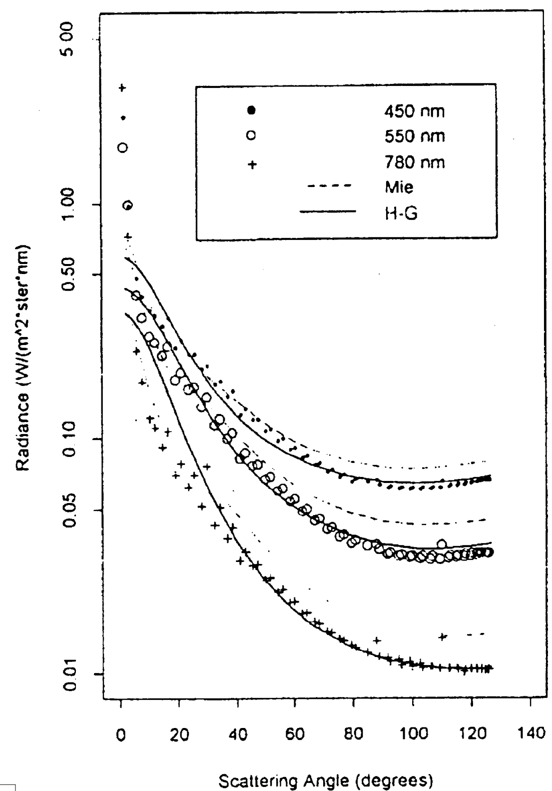
$$M(s)=\sum_{b}\left\{\sum_{\theta}W_{R(b)}\left[\frac{R_P(b,\theta)}{R_M(b,\theta,s)}-1\right]^2+W_{I(b)}\left[\frac{\left(I_D(b)/I_G(b)\right)_{MFRSR}}{\left(I_D(s,b)/I_G(s,b)\right)_{MODTRAN}}-1\right]^2\right\}$$

$M(s)$	=	*figure of merit*
s	=	*MODTRAN input settings of visibility and aerosol type*
b	=	*spectral band index*
θ	=	*angular position of the reading*
R_P	=	*radiance estimate from photometer*
R_M	=	*radiance estimate from MODTRAN*
I_D	=	*diffuse sky irradiance*
I_G	=	*global sky irradiance (sky + sun)*
$W_{R(b)}$	=	*weighting factor for band b of the photometer*
$W_{I(b)}$	=	*weighting factor for band b of the MFRSR*

Search for the Best Combination of Values That Minimizes the Figure of Merit

- Vary the visibility and aerosol type inputs about the nominals from the meter and the ASPAM
- The model inputs which yield the minimum FOM most accurately describes the effects of the atmosphere

Measured and Modeled Radiance vs. Scattering Angle for Three Wavelengths



PGAMS observed "atmospheric" scattering phase function compared to MODTRAN3 path radiance calculations for Mie and adjusted Henyey-Greenstein phase functions.

You've Got the Sky, Now What Do You Do With It?

- So far, we only have the target illumination. Now we need to:
  - Calculate target radiance
  - Determine atmospheric effects between the target and the sensor
  - Calculate TOA radiance

Calculating Target Radiance

- Must turn irradiance from all sources, at all angles, at all wavelengths to target radiance as seen by the sensor
- Irradiance Sources (show world diagram)
  - Direct solar illumination
  - Scattered solar energy
    - Single scattered
      - Sun to aerosol to target
    - Multiple scattered
      - Sun to background to aerosol to target
        - Sun to aerosol to background to aerosol to target
- If the irradiance varies with angle, does that mean that radiance must be calculated differently for each source angle?

Target Characterization

- The most accurate representation of target reflectance is the Bidirectional Reflectance Distribution Function (BRDF) $\rho'(\theta_i,\varphi_i,\theta_r,\phi_r,\lambda)$
  - Ratio of spectral radiance to spectral irradiance
  - Function of
    - Illumination source azimuth
    - Illumination source elevation
    - Sensor azimuth
    - Sensor elevation
    - Wavelength
  - (Note: The 2 azimuth angles indicate a possible orientation preference.)
- Directional Hemispheric Reflectance $\rho_D(\theta_r,\phi_r,\lambda)$
  - BRDF assuming an isotropically distributed source
- Lambertian Targets $\rho_D(\lambda)$
  - Targets whose BRDF is independent of source and sensor position

Calculating Target Radiance (cont'd)

- If the targets are Lambertian, then one only needs the total irradiance from all sources and the cosine of the zenith angle. (EQUATION)
  - The biggest assumption and the easiest technique
- If the targets can be represented by the EHDR ______ (EQUATION)
- If the targets are not close to Lambertian, then the irradiance due to each portion of the sky and the sun must be multiplied by the BRDF individually, and integrated together. (EQUATION)
- Obviously, the more Lambertian the target, the better

Additional Target Selection and Characterization Considerations

- Can generally be broken down into two categories
  - Environment
    - Selected to minimize atmospheric interference
      - High altitude
      - Low humidity
      - Isolated (to reduce variable aerosols)
  - Target
    - Selected to minimize errors in measured and model radiance
      - Very large (to minimize MTF and adjacency effects)
      - Uniform (to minimize the random variations in radiance across the target)
      - Bright (to maximize the signal in hazy bands)
      - Very Lambertian (to minimize errors due to varying solar and sensor angles in visible bands)

Types of Targets

- Natural Targets
  - Until now the targets of choice
    - Visible bands
      - Salt flats, dry lake beds, etc.
        - Examples: White Sands, Lunar Lake, Railroad Valley, Alto Plano
    - Thermal bands (at night and close to ambient air temperature)
      - Still, deep lakes
      - Examples: Mead, Tahoe, Elephant Butte, etc.
- Manmade Targets
  - Same considerations as natural targets
  - Until now, generally limited to use with aircraft sensors because of sensor GSD limitations
  - Can be more difficult to control characteristics in an operational environment
    - Dust, dew, wildlife, consistency...

The Recommended Man-Made Targets

- Deployable 20 meter x 20 meter painted tarpaulins
  - Roughly 5 pixels across for commercial multispectral satellites
  - Larger targets difficult to manufacture and handle
- 4 tarps with different reflectivities (average over 0.4 um - 0.95 um at a 10^{o} zenith angle)
  - 0.0 - 0.05
  - 0.20 - 0.25
  - 0.30 - 0.40
  - 0.50 - 0.55
- Small variations in reflectance within 60^{o} of zenith

The (Almost) Final Calculation

- With a baseline assumption of a Lambertian target

$$R(\lambda) = R_{SS}(\lambda) + R_{MS}(\lambda) + \rho_D(\lambda)\,[R_{DR}(\lambda) + R_{RS}(\lambda)] \,/\, S_{alb}(\lambda)$$

$R(\lambda)$ = spectral radiance at TOA

$R_{SS}(\lambda)$ = spectral radiance singly scattered from sun into line of sight

$R_{MS}(\lambda)$ = spectral radiance multiply scattered from sun and background into line of sight

$\rho_D(\lambda)$ = spectral reflectivity of the Lambertian target

$R_{DR}(\lambda)$ = spectral radiance from direct solar illumination on a 100% reflective Lambertian target

$R_{RS}(\lambda)$ = spectral radiance from sky illumination on a 100% reflective Lambertian target

$S_{alb}(\lambda)$ = spectral reflectivity/albedo of background

Now It's Time to Work With the Image

- Visual Evaluation
  - Check to see if the image displays any properties which might interfere with the radiometric evaluation
    - Excessive or inconveniently located clouds
    - Processing or calibration problems
    - Image artifacts
    - No missing data
- Cropping
  - Typically more convenient to crop the region of interest to increase (ROI) handling and processing convenience
    - Leave a border of at least 25 pixels around the ROI
    - Take care to maintain registration
- MTF effects

Radiometric Restoration for Small Targets

- Man-made targets are often marginally large enough for radiometric (and MTF) testing purposes
  - Need to apply an inverse filter to restore the energy lost through MTF blurring
    - Modulation Transfer Function Compensation (MTFC)
  - Experience has shown that a systematic bias error remains after MTFC
    - Typically <2%
    - A compensation function can be developed by calculating the theoretical radiometric error for combinations of …
      - Target size
      - Sampling phase
      - Orientation angle
      - Target/Background difference

      and deriving a linear function of target size for estimating residual radiometric error vs. target/background difference.

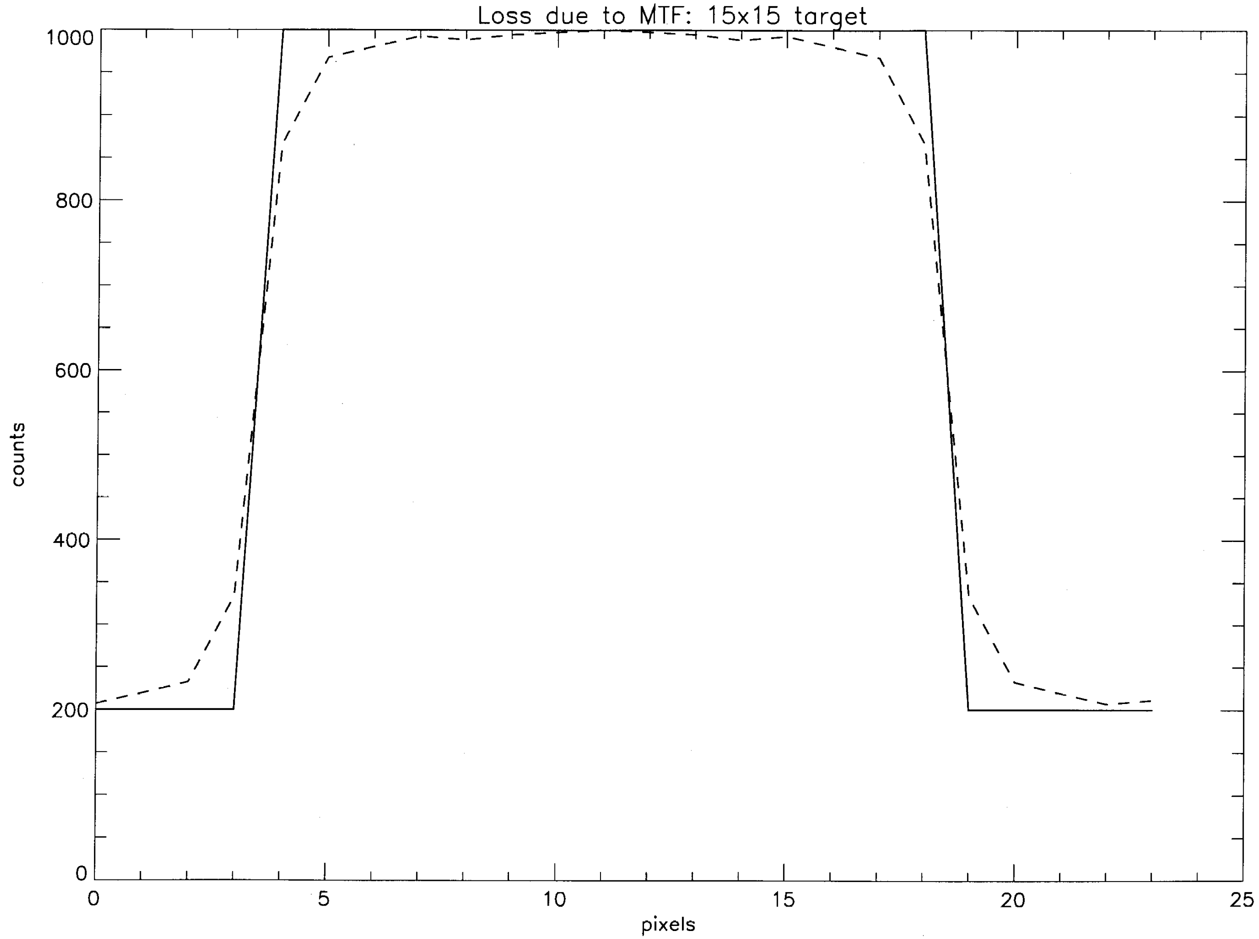
correction = b(size) + m(size)*difference

Radiometric MTFC

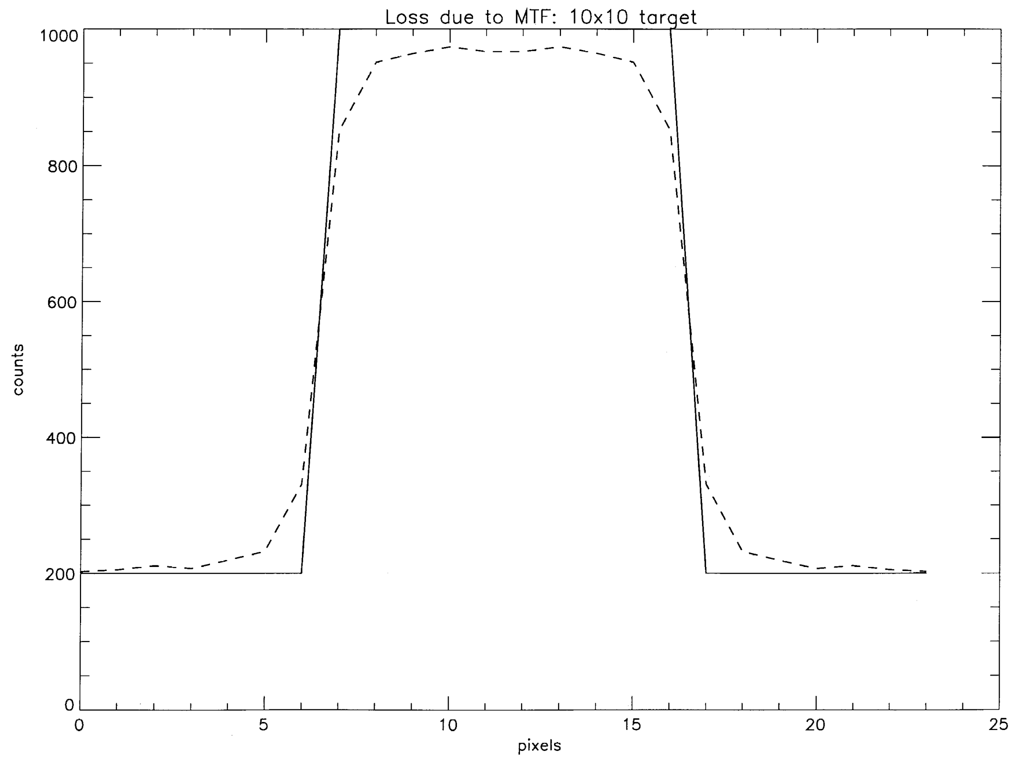
$$w(u,v) = \frac{MTF(u,v)}{MTF^2(u,v) + \dfrac{\sigma_n^2 INT^2(u,v)}{a^2 c^2 \operatorname{sinc}^2(2\pi a v)\operatorname{sinc}^2(2\pi a u)}}$$

σ_n^2 = image noise variance
INT(u,v) = ground processing MTF
c = background to target counts difference
a = target size
$sinc^2$ = power spectrum for 1x1 target
MTF(u,v) = measured MTF
u,v = spatial frequency variables

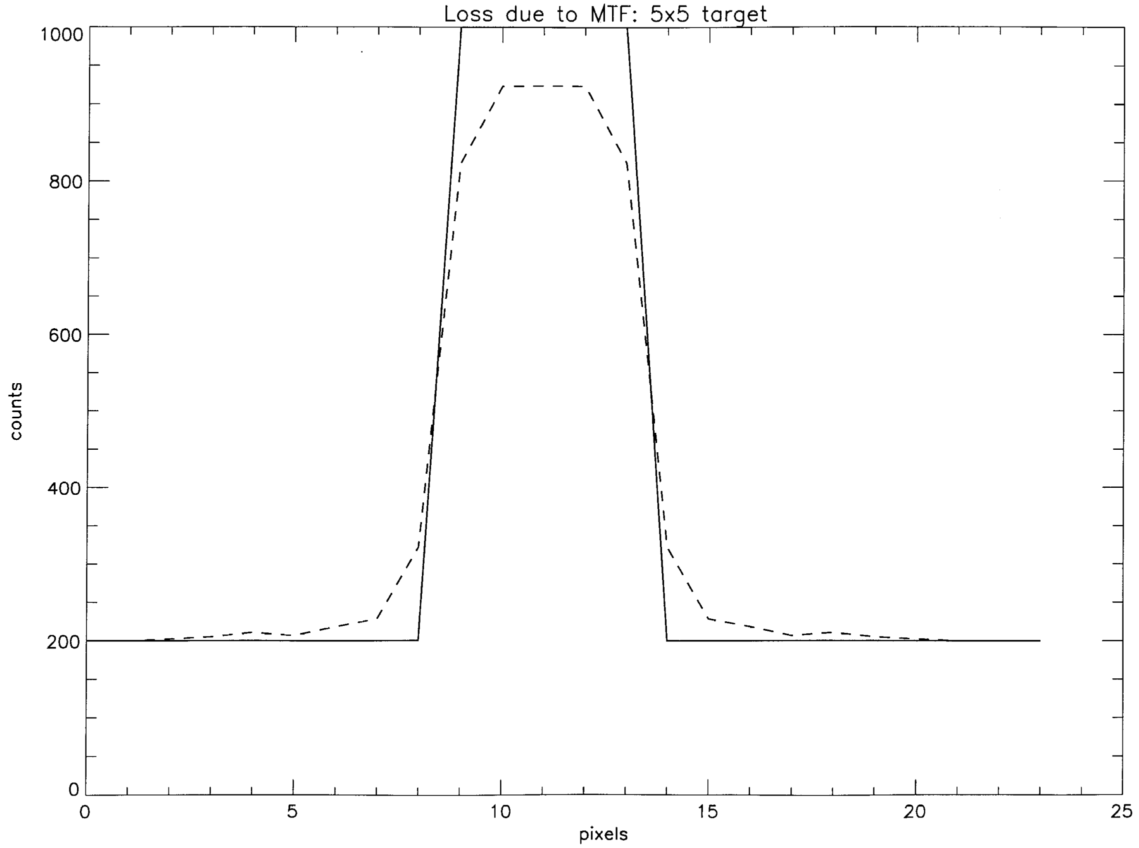
Atlas Band 1 MTF Losses on a 15 Pixel by 15 Pixel Target



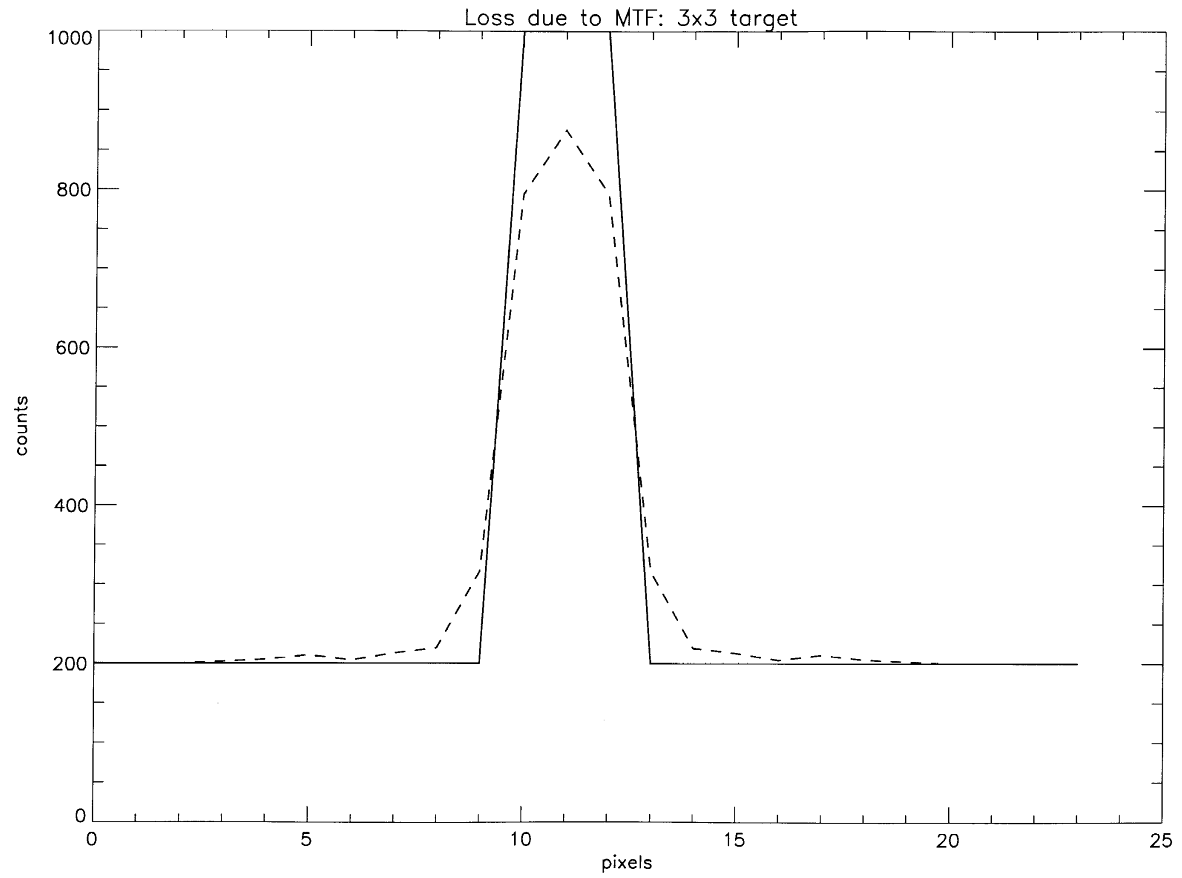
Atlas Band 1 MTF Losses on a 10 Pixel by 10 Pixel Target



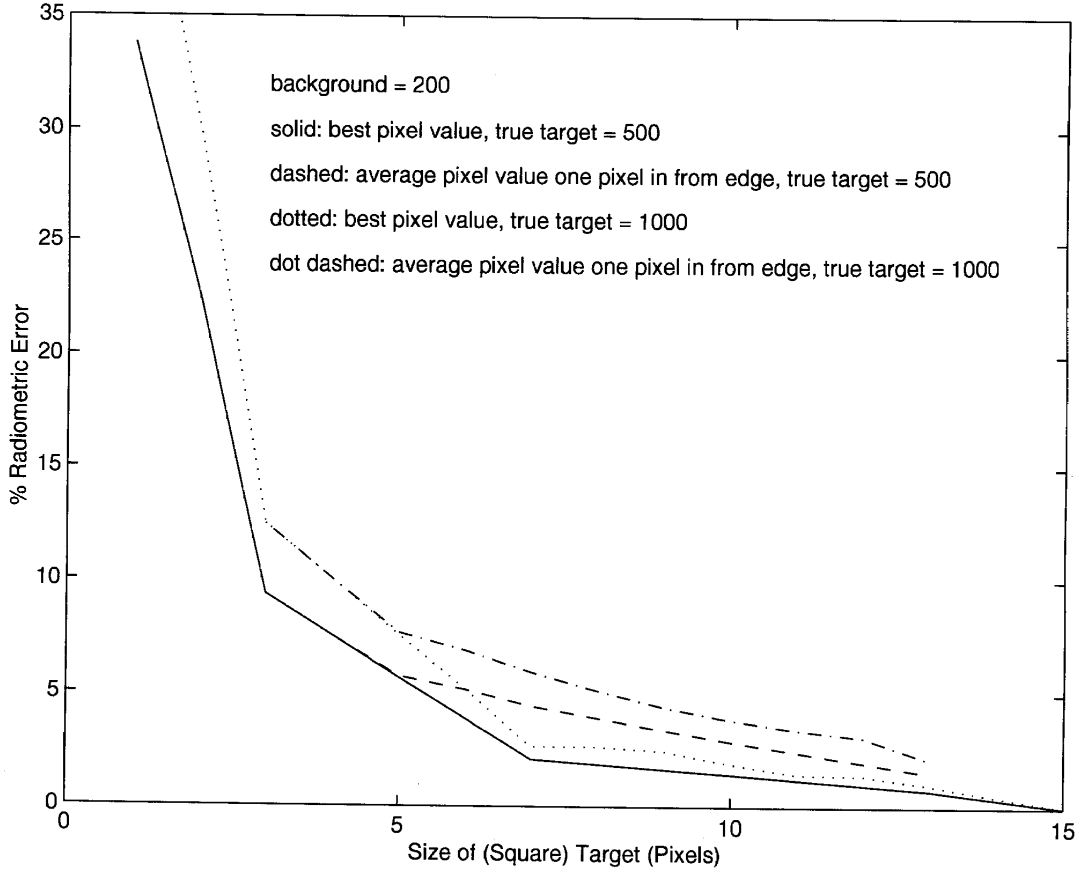
Atlas Band 1 MTF Losses on a 5 Pixel by 5 Pixel Target



Atlas Band 1 MTF Losses on a 3 Pixel by 3 Pixel Target



Radiometric Error vs. Target Size



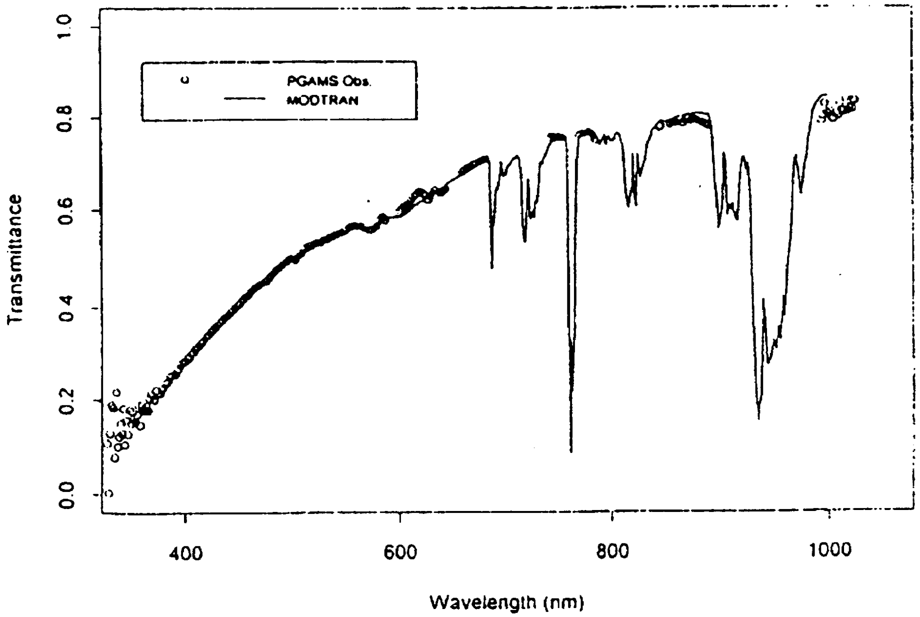
Pixel Selection

- Target pixels selected for evaluation should be subject to the following restrictions:
  - No pixels should be selected which are adjacent to the target edge
  - All pixels selected must pass the 50% determination test
- 50% Determination Test
  - Determine whether the target contrast is positive, negative , or none.
    - If none, either cancel or select all of the target pixels in the ROI
    - Calculate the average background pixel values from 6 to 25 pixels outside of target
    - Determine the extreme (max or min) target pixel value
    - 50% point = background + 1/2 (extreme - background)
    - Select pixels greater than 50% point for positive contrast targets, less than 50% point for negative contrast targets

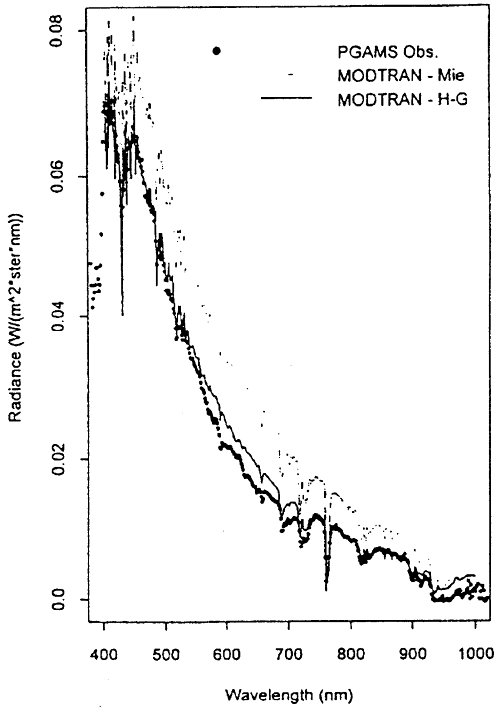
Sources of Error in Methodology

- Extremely difficult to estimate performance and error
  - All techniques are sensitive to ground instrumentation error
    - Calibration of these instruments is problematic
  - Chosen technique is less sensitive to random errors than RTM techniques
- Sensitivity analysis necessary to create error budget
- Previous data from round robin experiments show agreement between this technique and RTM from U of A to within 2% in NIR and 5% in blue
  - U of A estimated accuracy: 2% - 5%
- Best guess (WAG) at error with assumed instrumentation and methodology: 10% under benign conditions

Comparison of Measured to Modeled Spectral Transmission Outside of Water Bands



Spectral Radiance Measured and Modeled with Two Different Scattering Models



PGAMS Sky path radiance spectra compared to MODTRAN3 spectra based on the Mie calculated single-scattering phase function for rural aerosols and the adjusted Henyey-Greenstein phase function (see text). The scattering angle is 120°

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Operational Considerations

- Target (Most are called out in the spec)
- Ground instrument calibration
  - As often as possible
- Collection Conditions
  - Weather
    - As cloud free as possible
      - Cirrus (even subvisual cirrus) clouds can cause significant errors
    - Location
      - The higher, the better
      - High visibility
      - High altitude deserts are typically chosen

Ground Operations Concept

Obtain Collection Date and Time

Obtain Weather Forecasts

Deploy Tarps (I - 4 Hours)

Collect Whole Sky Images Once/Minute Beginning (I - 20 to I + 20 Minutes)

Launch Radiosonde and Begin Collecting Data (I - 30 Minutes)

Begin Photometer Collection (I - X)

Begin MFRSR Collection (I - X)

Collect Visibility Measurement (I+0)

Order ASPAM (I + 8 Hours)

Obtain Imagery (I + ?)

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Test and Verification of the Experiment

- Requires an independent, more accurate measurement of the modeled radiances
  - Absolutely Calibrated Downlooking Spectroradiometer
    - Measure target spectral radiance at ground level at different angles
    - Should be a different instrument than the Sandmeier Goniometer
    - Second Choice: Measure the reflected radiance at ground level under different atmospheric conditions
    - Only verifies part of the modeling approach
  - Vicarious calibration
    - Fly an absolutely calibrated spectroradiometric sensor at as high an altitude as possible (subject to GSD and MTF limitations) and collect spectral radiance readings of the target
    - Closer to full modeling approach verification
    - Used by U of A for their verification

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Improvements and Upgrades

- Better Calibration of Ground Instrumentation
  - Cimel Photometer and MFRSR are not noted for good calibration and can drift significantly over time
- Instrumentation with broader spectral sampling and fine spectral resolution
  - A spectroradiometric device such as PGAMS is desirable
- Better characterization of the error properties of the instruments
- Addition of more diversified instrumentation (e.g. LIDAR)
- Use of BRDF instead of Lambertian reflectance to improve reflected radiance estimates
- Development of a more generalized, finer resolution search technique

Using BRDF Instead of EHDR

- Lab measurements of target BRDF
- Incorporation of data into a BRDF model such as the Nonconventional Exploitation Factors (NEF) database
  - Allows interpolation of estimates between wavelengths and all four angles using Maxwell Beard equations
- Must run MODTRAN and NEF for each angular sky position, multiply both and integrate over hemisphere to obtain total radiance
- (ILLUSTRATION)

Advanced Search Technique

- VAMs have set a precedent for using optimal search techniques for similar problems
  - Potential exists for an automated, modified Levenberg Marquardt optimal search algorithm or similar technique
- New instruments will require a transformation of outputs to the proper domain
- Increase the number and type of parameters to vary in MODTRAN
  - Potential Improvement in Accuracy
    - Best guess: 5%-10% error down to 3%-5% error under benign conditions