MODIS
Thermal Emissive Band
RVS Measurement Data Analysis
Outline

- Basic equations to retrieve RVS
- Drifting of the linear coefficient $b_1$
- Error sources and analysis in RVS retrieval
- RVS fitting equation and procedure
Basic RVS retrieval equations (1)

\[ f(DN_{bcs}) = L_{bcs} \cdot RVS_{bcs} + (\tau - RVS_{bcs}) \cdot L_{sm} + \delta_{bkg} \]  \hspace{1cm} \text{(Eq.1)}

\[ f(DN_{obc}) = \varepsilon \cdot L_{obc} \cdot RVS_{obc} + (\tau - RVS_{obc}) \cdot L_{sm} + \delta_{bkg} \]  \hspace{1cm} \text{(Eq.2)}

\[ f(DN_{svs}) = L_{svs} \cdot RVS_{svs} + (\tau - RVS_{svs}) \cdot L_{sm} + \delta_{bkg} \]  \hspace{1cm} \text{(Eq.3)}

\[ f(DN) = a_0 + a_1 \cdot DN + a_2 \cdot DN^2 \]  \hspace{1cm} \text{(Eq.4)}

where \( \tau \) is the MODIS fixed optics total throughput, and \( L \) is the Planck function radiance integrated over each bandwidth.
Basic RVS retrieval equations (2)

(Eq.1) - (Eq.3) gives

\[ b_1 \cdot dn_{bcs} + (L_{svs} - L_{sm}) \cdot RVS_{svs} + a_2 \cdot dn_{bcs}^2 = (L_{bcs} - L_{sm}) \cdot RVS_{bcs} \]  

(Eq.5)

(Eq.2) - (Eq.3) gives

\[ b_1 \cdot dn_{obc} + (L_{svs} - L_{sm}) \cdot RVS_{svs} + a_2 \cdot dn_{obc}^2 = (\varepsilon \cdot L_{obc} - L_{sm}) \cdot RVS_{obc} \]  

(Eq.6)

where

\[ b_1 = a_1 + 2a_2 \cdot DN_{svs} \]  

(Eq.7)
Basic RVS retrieval equations (3)

(Eq.5) / (Eq.6) gives

\[
\frac{RVS_{bcs}}{RVS_{obc}} = \frac{\varepsilon \cdot (L_{obc} - L_{sm})}{L_{bcs} - L_{sm}} \cdot \frac{dn_{bcs}}{dn_{obc}} \cdot (1 + \Delta_1 + \Delta_2) \quad \text{(Eq.8)}
\]

where correction due to temperature difference between sm and svs is

\[
\Delta_1 = \frac{RVS_{svs} \cdot (L_{sm} - L_{svs})}{b_1 \cdot dn_{bcs} \cdot dn_{obc}} \cdot (dn_{bcs} - dn_{obc}) \quad \text{(Eq.9)}
\]

and the correction due to non-linear term is

\[
\Delta_2 = \frac{a_2}{b_1} \cdot (dn_{bcs} - dn_{obc}) \quad \text{(Eq.10)}
\]
Δ₁, Δ₂ Evaluation

Band 20

Band 25

Band 30

Band 35

RVS correction %

AOI
Drifting of linear coefficient $b_1$

As shown in (Eq.7)

$$b_1 = a_1 + 2a_2 \cdot DN_{svs}$$

where the $a_1$ is a function of FPA temperature, and $DN_{svs}$ drifts as background fluctuates, thus, $b_1$ will fluctuate as $DN_{svs}$ and FPA temperature drift, and hence needs to be retrieved scan by scan as

$$b_1 = RV S_{obc} \cdot \left( \varepsilon \cdot L_{obc} - L_{sm} \right) \frac{d n_{obc}}{} + \text{higher order terms, } (\text{Eq.11})$$
FM1 RVS Highbay Measurement (PC20); Data set [320_2]
Linear Gain \( <b_1 >_{50 \text{ frames}} \) vs. Time(hours of the day; 3/30/98); ch5, 40 scans, side A; T_{bcs}=320K
Error sources in RVS retrieval

- Temperature measurement error in $T_{bcs}, T_{obc}, T_{sm}, T_{svs}$
- OBC effective emissivity $\varepsilon_{obc}$
- DN measurement errors due to cross-talk, finite resolution, ...
Error Analysis in RVS (1)

From (Eq.8), the complete \( rvs \) differential equation is (correction terms are ignored in this analysis)

\[
\frac{d(rvs)}{rvs} = \frac{\partial \ln(rvs)}{\partial \epsilon_{obs}} \Delta \epsilon_{obs} \\
+ \frac{\partial \ln(rvs)}{\partial T_{bcs}} \Delta T_{bcs} + \frac{\partial \ln(rvs)}{\partial T_{obs}} \Delta T_{obs} + \frac{\partial \ln(rvs)}{\partial T_{sm}} \Delta T_{sm} \\
+ \frac{\partial \ln(rvs)}{\partial DN_{bcs}} \Delta DN_{bcs} + \frac{\partial \ln(rvs)}{\partial DN_{obs}} \Delta DN_{obs} + \frac{\partial \ln(rvs)}{\partial DN_{svs}} \Delta DN_{svs}
\]

(Eq.12)
Error Analysis in RVS (2)  
(due to the error in $\varepsilon_{\text{obc}}$)

$$\frac{\partial \ln(rvs)}{\partial \varepsilon_{\text{obc}}} \Delta \varepsilon_{\text{obc}} = \left( \frac{L_{\text{obc}}}{\varepsilon_{\text{obc}} L_{\text{obc}} - L_{\text{sm}}} \right) \cdot \Delta \varepsilon_{\text{obc}} \quad \text{(Eq.13)}$$

This is a systematic bias error, which is independent of the AOI. Since $rvs$ will be renormalized later at a particular AOI angle, this bias error will essentially be “renormalized out” and thus will not contribute to the total $rvs$ error.
Error Analysis in RVS (3)
(due to the error in $T_{bcs}, T_{obc}, T_{sm}$ measurements)

\[
\frac{\partial \ln(rvs)}{\partial T_{bcs}} \Delta T_{bcs} = \left( \frac{-L'_{bcs}}{L_{bcs} - L_{sm}} \right) \cdot \Delta T_{bcs} \quad \text{(Eq. 14)}
\]

\[
\frac{\partial \ln(rvs)}{\partial T_{obc}} \Delta T_{obc} = \left( \frac{\varepsilon_{obc} L'_{obc}}{\varepsilon_{obc} L_{obc} - L_{sm}} \right) \cdot \Delta T_{obc} \quad \text{(Eq. 15)}
\]

\[
\frac{\partial \ln(rvs)}{\partial T_{sm}} \Delta T_{sm} = \left( \frac{-L'_{sm}}{\varepsilon_{obc} L_{obc} - L_{sm}} + \frac{L'_{sm}}{L_{bcs} - L_{sm}} \right) \cdot \Delta T_{sm} \quad \text{(Eq. 16)}
\]

A system bias error in $\Delta T$, combining with the terms in (..), will be constant across the AOIs, thus won’t effect the renormalized $rvs$, only the local fluctuated error in $\Delta T$ will contribute to the errors in $rvs$. 73
Error Analysis in RVS (4)
(due to the errors in $DN_{bc}$, $DN_{ob}$, $DN_{sv}$)

\[
\frac{\partial \ln(rvs)}{\partial DN_{bc}} \cdot \Delta DN_{bc} = \left( \frac{1}{DN_{bc} - DN_{sv}} \right) \cdot \Delta DN_{bc} \\
\frac{\partial \ln(rvs)}{\partial DN_{ob}} \cdot \Delta DN_{ob} = \left( \frac{-1}{DN_{ob} - DN_{sv}} \right) \cdot \Delta DN_{ob} \\
\frac{\partial \ln(rvs)}{\partial DN_{sv}} \Delta DN_{sv} = \left( \frac{-1}{DN_{bc} - DN_{sv}} + \frac{1}{DN_{ob} - DN_{sv}} \right) \cdot \Delta DN_{sv}
\]

(Eq.17)  
(Eq.18)  
(Eq.19)
Error Analysis in RVS (5)
\[ \sigma(RVS) \]

\[ \sigma(rvs) = \sqrt{\sigma^2_{T_{BCS}} + \sigma^2_{T_{OBC}} + \sigma^2_{T_{SVS}} + \sigma^2_{D_{N_{BCS}}} + \sigma^2_{D_{N_{OBC}}} + \sigma^2_{D_{N_{SVS}}}} \]

The RSS ignores the correlation relationship between the variables, thus will result in either over-estimating or under-estimating the total 1-sigma error in \( rvs \).
NEdL from \[ \text{linear gain} \times \sigma(dn) \] compared with SBRS measured value.
Band 20
Detc 05

\[ \text{Err}_\text{DN} \]
\[ \text{Err}_\text{Tbcs} \]
\[ \text{Err}_\text{Tobc} \]
\[ \text{Err}_\text{Tsm} \]
\[ \text{Err}_\text{RSS} \]
\[ \text{Err}_\text{RVS} \]

\( \Delta \text{Tbcs} = 50 \text{mK} \)
\( \Delta \text{Tobc} = 30 \text{ to } 100 \text{mK} \)
\( \Delta \text{Tsm} = 20 \text{ to } 70 \text{mK} \)
Band 21
Detc 05

\[ T_{sm} = 20 \text{ to } 70 \text{mK} \]

\[ T_{bcs} = 50 \text{mK} \]

\[ T_{obc} = 30 \text{ to } 100 \text{mK} \]

\[ \Delta T_{bcs} = 50 \text{mK} \]

\[ \Delta T_{obc} = 30 \text{ to } 100 \text{mK} \]

\[ \Delta T_{sm} = 20 \text{ to } 70 \text{mK} \]
Band 22
Detc 05

\[ \Delta T_{bcs} = 50\text{mK} \]
\[ \Delta T_{obc} = 30\text{ to } 100\text{mK} \]
\[ \Delta T_{sm} = 20\text{ to } 70\text{mK} \]
Band 23
Detc 05

- $\Delta T_{bcs} = 50\text{mK}$
- $\Delta T_{bc} = 30$ to $100\text{mK}$
- $\Delta T_{sm} = 20$ to $70\text{mK}$
**Band 24**

**Detc 05**

- **Err_DN**
- **Err_Tbcs**
- **Err_Tobe**
- **Err_Tsm**
- **Err_RSS**
- **Err_RVS**

\[ \Delta T_{bcs} = 50 \text{mK} \]

\[ \Delta T_{obe} = 30 \text{ to } 100 \text{mK} \]

\[ \Delta T_{sm} = 20 \text{ to } 70 \text{mK} \]

AOI
Band 25
Detc 05

\[ \begin{align*}
\Delta T_{bc} &= 50 \text{mK} \\
\Delta T_{obc} &= 30 \text{ to } 100 \text{mK} \\
\Delta T_{sm} &= 20 \text{ to } 70 \text{mK}
\end{align*} \]

RVS Error %

AOI
Band 27
Detc 05

\[ \Delta T_{bcs} = 50\text{mK} \]
\[ \Delta T_{obc} = 30 \text{ to } 100\text{mK} \]
\[ \Delta T_{sm} = 20 \text{ to } 70\text{mK} \]
Band 29
Detc 05

- Err_DN
- Err_Tbcs
- Err_Tobs
- Err_Tsm
- *- Err_RSS
- - Err_RVS

ΔTbcs = 50mK
ΔTobs = 30 to 100mK
ΔTsm = 20 to 70mK

AOI
Band 30 Detc 05

ΔTbc = 50mK
ΔTobe = 30 to 100mK
ΔTsm = 20 to 70mK
Band 31
Detc 05

- ΔTbcs = 50mK
- ΔTobc = 30 to 100mK
- ΔTsm = 20 to 70mK
\[ \Delta T_{\text{bcs}} = 50 \text{mK} \]

\[ \Delta T_{\text{tbc}} = 30 \text{ to } 100 \text{mK} \]

\[ \Delta T_{\text{sm}} = 20 \text{ to } 70 \text{mK} \]
II.39  Il.49  Il.56  Il.19  26.25  37.79  50.8  56.82  60.31  64.05  64.66  64.66  60.31  64.66  32.79  56.82  60.31  64.66

\[ \Delta T_{bs} = 50 \text{mK} \]

\[ \Delta T_{obc} = 30 \text{ to } 100 \text{mK} \]

\[ \Delta T_{sm} = 20 \text{ to } 70 \text{mK} \]
Band 34
Detc 05

- Err_DN
- Err_Tbcs
- Err_Tobc
- Err_Tsm
- Err_RSS
- Err_RVS

$\Delta T_{bcs} = 50\text{mK}$
$\Delta T_{obc} = 30$ to $100\text{mK}$
$\Delta T_{sm} = 20$ to $70\text{mK}$
Band 35
Detc 05

ATbcs = 50mK
ATobc = 30 to 100mK
ATsm = 20 to 70mK

ΔTbcs = 50mK
ΔTobc = 30 to 100mK
ΔTsm = 20 to 70mK
RVS fitting equations and procedure (1)

The MODIS polarization theory (Appendix A) gives

\[ RVS = \tau \cdot \bar{\rho} + \eta \cdot \bar{\delta\rho} \quad \text{or,} \quad rvs = \bar{\rho} + C \cdot \bar{\delta\rho} \]  

(Eq.20)

where \( \tau \) is the MODIS fix-optics total throughput (or \( A_{11} \) component of the fixed-optics 4x4 Mueller matrix), and \( \eta \) is the \( A_{12} \) component of the matrix, and \( rvs \) is the re-normalized RVS, and

\[ \bar{\rho} = \frac{\rho_s + \rho_p}{2}, \quad \bar{\delta\rho} = \frac{\rho_s - \rho_p}{2} \]  

(Eq.21)

Using (Eq.12), together with \( RVS \) data and \( \rho_s \) and \( \rho_p \) functions fitted to the NPL scan mirror reflectivity data, \( \tau \) and \( \eta \) can be determined by Least-Square fitting procedure, thus, completes the RVS fitting.
RVS fitting equations and procedure (2)

- This procedure assumes that reflectivity measurement accuracy is comparable or better than that of the RVS measurement. Given this presumption, this fitting procedure can be proved to be superior to the direct fitting (e.g., quadratic fitting) of the RVS data, which is primarily due to the fact that Eq. 12 is an exact relationship between the RVS and scan mirror reflectivities.

- If we assume that the fixed-optics parameter $C$ is the same for both the FM1 and PFM, then PFM RVS can be retrieved from the PFM scan mirror reflectivity measurement from NPL as

$$
\text{rvs}_{PFM} = \bar{\rho}_{PFM} + C_{FM1} \cdot \delta \rho_{PFM}
$$

(Eq. 22)
Appendix A: MODIS Polarization Theory (1)

\[ S = D \cdot A \cdot M \cdot L \]

\( S \) = at-detector radiance (a scalar quantity)
\( D = [D,0,0,0] \) is the detector vector
\( A \) = the Mueller matrix for the fixed optics
\( M \) = the Mueller matrix for the rotating scan mirror
\( L \) = the Stokes vector for the at-aperture radiance field

\[ S_{ev} = D \cdot A \cdot M(\rho_{ev}) \cdot L_{ev} + D \cdot A \cdot M(\varepsilon_{ev}) \cdot L_{sm} + \delta_{bkg} \]

\[ S_{sv} = D \cdot A \cdot M(\varepsilon_{sv}) \cdot L_{sm} + \delta_{bkg} \]

\[ \Delta S_{ev} = D \cdot A \cdot M(\rho_{ev}) \cdot L_{ev} + D \cdot A \cdot M(\varepsilon_{ev}) \cdot L_{sm} - D \cdot A \cdot M(\varepsilon_{sv}) \cdot L_{sm} \]
Appendix A: MODIS Polarization Theory (2)

\[ \mathbf{L}_{ev} = [L_{ev}, 0, 0, 0]^T \quad \mathbf{L}_{sm} = [L_{sm}, 0, 0, 0]^T \]

\[ \Delta S_{ev} = D\left\{ \sum_{j=0}^{3} A_{0j} M_{j0}(\rho_{ev}) \right\}L_{ev} + D\left\{ \sum_{j=0}^{3} A_{0j}[M_{j0}(\varepsilon_{ev}) - M_{j0}(\varepsilon_{sv})] \right\}L_{sm} \]

\[ \Delta S_{ev} = RVS_{ev}L_{ev} + (RVS_{sv} - RVS_{ev})L_{sm} \]

\[ RVS = D\sum_{j=0}^{3} A_{0j} M_{j0}(\rho) \]

\[ M_{10} = \frac{1}{2}(\rho_s - \rho_p) \quad M_{00} = \frac{1}{2}(\rho_s + \rho_p) \]

\[ RVS = A_{00} \left[ \frac{\rho_s + \rho_p}{2} \right] + A_{01} \left[ \frac{\rho_s - \rho_p}{2} \right] = \tau_{fix}^{pol} \cdot \vec{\rho} + A_{01} \cdot \delta\vec{\rho} \]
Comparison of Highbay polarized RVS, quadratic fit to Highbay RVS and quadratic fit to NPL average reflectance data
B21 RVS quad_fit (solid line), RVS c_fit (dashed line), rho_avg (dotted line)
B22 RVS quad_fit (solid line), RVS c_fit (dashed line), rho_avg (dotted line)
B23 RVS quad_fit (solid line), RVS c_fit (dashed line), rho_avg (dotted line)
B25 RVS quad_fit (solid line), RVS c_fit (dashed line), rho_avg (dotted line)
B27 RVS quad_fit (solid line), RVS c_fit (dashed line), rho_avg (dotted line)
B28 RVS quad_fit (solid line), RVS c_fit (dashed line), rho_avg (dotted line)
B29 RVS quad_fit (solid line), RVS c_fit (dashed line), rho_avg (dotted line)
B30 RVS quad_fit (solid line), RVS c_fit (dashed line), rho_avg (dotted line)
B31 RVS quad_fit (solid line), RVS c_fit (dashed line), rho_avg (dotted line)
B33 RVS quad_fit (solid line), RVS c_fit (dashed line), rho_avg (dotted line)
$B34$ RVS quad fit (solid line), RVS c fit (dashed line), rho avg (dotted line)
B35 RVS quad_fit (solid line), RVS c_fit (dashed line), rho_avg (dotted line)
Scan Mirror brightness temperatures (Tsm=270K)

These temperatures are determined from the scan mirror absolute radiance emission, i.e., not the net radiance difference between the Earth View scan mirror emission and the Cold Space View scan mirror emission.

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Preliminary Estimated Scan Mirror Signal-to-Noise Ratios (SNRs)

(for radiance emitted from the scan mirror for 1 minute data collect based on T/V measured
SNRs; assumes T_{sm}=270K and T_{fpa} constant at 83K)

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\( M036 = \)

\[ \begin{bmatrix}
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20.5^\circ \\
25.5^\circ \\
30.5^\circ \\
35.5^\circ \\
40.5^\circ \\
45.5^\circ \\
50.5^\circ \\
55.5^\circ \\
60.5^\circ \\
65.5^\circ \\
\end{bmatrix} \]

AOI = 10.5°, 15.5°, 20.5°, 25.5°, 30.5°, 35.5°, 40.5°, 45.5°, 50.5°, 55.5°, 60.5°, 65.5°
Highbay Response vs Scan Angle (RVS)

(Test Results, PFM Retrieval Methodology and On-orbit Validation Issues)

Presented to MODIS Science Team
December 14, 1998
Outline

1) Introduction
2) Highbay RVS measurement approach
3) Scan mirror witness sample polarized reflectance measurements
4) Unpolarized equations used for test data processing results
5) Raw data analysis, corrections and fitting results
6) Summary of SBRS Highbay RVS results
7) Summary of polarized equations used for test data processing
8) Polarized response fitting results
9) RVS Uncertainty Approach and Analysis
10) On-orbit RVS Determination via S/C Maneuver Issues
11) Discussion of phenomenological based RVS retrieval approaches
12) Discussion
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Data Analysis Contributors

- Kwo Fu “Vincent” Chiang
- Tim Dorman
- Gerry Godden
- Shi-Yue Qiu
- Xindong Wang
- Jack Xiong

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- SBRS Systems Engineering and Test Staffs
Overview of Highbay RVS Measurement Approach
Highbay RVS Test Key Features

• Test configuration:
  – MODIS aligned on rotary table (ROTAB)
  – Cold FPAs cooled with BTC
  – OBC Blackbody maintained at 310K
  – MWIR and LWIR PV detectors operated with “optimum CSUB” setting (not applicable for PC detectors)
  – SVS positioned at SVP; operated at ambient temperature
  – BCS aligned and operated at one of two temperature settings (310K and 320K)

• 3 data collects taken (310K_1, 320K_2, and 320K_3)
  – Data collects spanned 8 to 10 hours, each
FM1 Highbay RVS Test Configuration
Summary of FM1 Highbay RVS Measurement Angles for 320K_3 Data Set

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Blackbody Calibration Source (BCS)

MODIS Full Aperture

\[ L_{BCS} = W_{P1} \cdot L(\lambda, T_{P1}) + W_{P2} \cdot L(\lambda, T_{P2}) + W_{P3} \cdot L(\lambda, T_{P3}) \]

BCS Trapezoid Configuration Achieves > 0.998 Emissivity (From SBRS)
RVS [320_3] BCS Effective Temperature; from PRT#1-15; BDATB93.OUT

Temperature (°C)

Time (3-31-1998)

SBRs — T_f*0.929 + T_s*0.066 + T_t*0.004 — Stable Flag
BCS First Bounce Plate Temperature Sensor Arrangement

View is back of BCS
DCS First Bounce Plate 9 PRTs Interpolated Temperature Gradients (Before and After 18:00 Hrs for 320K-3 Collect)
The MODIS On-Board Calibrator (OBC) Blackbody

More than 90% of the reflected light undergoes at least four specular reflections to achieve > 0.992 emissivity

Dimensions: Inches
FM1 RVS (PC20) Blackbody (OBC) Temperature; Average of 12 Thermisters; Data set [310_1]

Average of 4 CSUB

CSUB 1

CSUB 2

CSUB 3

CSUB 4

AOI=Center of B20

AOI=Center of B20

Hours (of the day; 3/28/98)
FM1 RVS (PC20) Blackbody (OBC) Temperature; Average of 12 Thermisters; Data set [320_2]

Average of 4 CSUB

CSUB 1

CSUB 2

CSUB 3

CSUB 4

AOI=Center of B20

Hours (of the day; 3/30/98)
FM1 RVS (PC20) Blackbody (ODC) Temperature; Average of 12 Thermisters; Data set [320.3]

- Average of 4 CSUB
- CSUB 1
- CSUB 2
- CSUB 3
- CSUB 4

AOI = Center of B20

Hours (of the day; 3/31/98)
Channel 5 Linear Gain $<b1_{OBC}>_{50\ frames}$ for 40 Scans vs Experiment Time (Hours)

(310K-1 Data Set; Mirror A; w/50frame×40scan Average and 1−σ Error Bars; % Change from 1st Average Noted on Right Axis)

Note: $b1 - (I_{OBC} - I_{SVS})/dn_{OBC}$
Channel 5 Linear Gain $<b_{1_{UBC}}>$50 frames for 40 Scans vs Experiment Time (Hours)

(320K_2 Data Set; Mirror A; w/50frame×40scan Average and 1-σ Error Bars, % Change from 1st Average Noted on Right Axis)

Note: $b_{1} = (L_{UBC} - L_{SYS})/dn_{UBC}$
Channel 5 Linear Gain $<b_{10BC}>50$ frames for 40 Scans vs Experiment Time (Hours)

(320K_3 Data Set; Mirror A; w/50frame×40scan Average and 1-σ Error Bars; % Change from 1st Average Noted on Right Axis)

Note: $b1=(L_{OCR} L_{VYS})/dn_{OCR}$
Unpolarized Equations Used for Analysis of Highbay RVS Test Data
RVS Equations

Relationship between the BCS path radiance and the detector's response

\[ \text{RVS}_\theta \cdot L_{\text{BCS}(\theta)} + (\tau - \text{RVS}_\theta) \cdot L_{\text{SM}} + L_{\text{BKG}} = \text{DN}_{\text{BCS}}^o + b_1 \cdot \text{DN}_{\text{BCS}}^s \]  

(1)

- \( \text{RVS}_\theta \) - RVS at AOI = \( \theta \)
- \( L_{\text{BCS}(\theta)}, L_{\text{SM}}, L_{\text{BKG}} \) - Radiance of BCS, Scan Mirror, and Background
- \( \tau \) - system effective transmittance
- \( b_1 \) - detector linear response
- \( \text{DN} \) - instrument digital number \( \text{DN} = \text{DN}^o + \text{DN}^s \) (offset term + signal term)
Relationship between the BCS path radiance and the detector's response

\[ \text{RVS}_\theta \cdot L_{SVS(\theta)} + (\tau - \text{RVS}_\theta) \cdot L_{SM} + L_{BKG} = D_{SVS}^0 + b_1 \cdot D_{SVS}^s \]  

(2)

From Equations (1) and (2)

\[ \text{RVS}_{BCS(\theta)} \cdot (L_{BCS(\theta)} - L_{SM}) = b_1 \cdot (\text{D}_{BCS} - \text{D}_{SVS}) \]

\[ + \text{RVS}_{SVS} \cdot (L_{SVS} - L_{SM}) \]  

(3)

For highbay test \( T_{SM} \approx T_{SVS} \). For \( T_{BCS} = 320K \), the second term on the RHS of Equation (3) is \( \sim 0.1\% \), then

\[ \text{RVS}_{BCS(\theta)} = b_1 \cdot \frac{\text{D}_{BCS} - \text{D}_{SVS}}{L_{BCS(\theta)} - L_{SVS}} \]  

(4)
Using the On Board Calibrator (OBC) to correct detector's scan to scan response fluctuation, Equation (4) becomes

$$RVS_{BCS(\theta)} = RVS_{OBC} \cdot \frac{L_{OBC} - L_{SVS}}{DN_{OBC} - DN_{SVS}} \cdot \frac{DN_{BCS} - DN_{SVS}}{L_{BCS(\theta)} - L_{SVS}}$$

(5)

The normalized RVS (to AOI = 10.75°)

$$RVS_{Norm}^{(\theta)} = \frac{RVS_{BCS(\theta)}}{RVS_{BCS(\theta=10.75^\circ)}} = f(DN_S, \lambda, T_S, \varepsilon_{OBC}, \theta)$$

(6)
RVS Uncertainty

Approach 1

\[
RVS^{\text{Norm}}(\theta) = \frac{f(DN_S, \lambda, T_S, \varepsilon_{\text{OBC}}, \theta)}{f(DN_S, \lambda, T_S, \varepsilon_{\text{OBC}}, \theta = 10.75^\circ)} = \frac{f(x_i, \theta)}{f(y_i, \theta = 10.75^\circ)}
\]  

(7)

\[
\frac{\Delta RVS^{\text{Norm}}(\theta)}{RVS^{\text{Norm}}(\theta)} = \sqrt{\sum \left( \frac{\partial f(x_i, \theta)}{\partial x_i} \cdot \frac{\Delta x_i}{f(x_i, \theta)} \right)^2}
\]

(8)

Approach 2

Computer \( RVS^{\text{Norm}}(\theta) \) for Measurement \( i (=1, 2, 3) \) (frame, scan, channel average)

\[
\Delta RVS^{\text{Norm}}(\theta) = \text{stdev}\{RVS^{\text{Norm}}(\theta)_1, RVS^{\text{Norm}}(\theta)_2, RVS^{\text{Norm}}(\theta)_3\}
\]  

(9)
Scan Mirror Witness Sample
Reflectance Measurements
Summary of NPL Scan Mirror Witness Sample Polarized Reflectance Measurements

- 2 witness samples from PFM scan mirror (SN03 and SN04), and 2 witness samples from FM1 scan mirror (SN08 and SN16)
  - SN03 and SN04 samples previously measured by Lincoln Laboratory on two separate occasions
- Measured s and p polarization reflectance of 4 witness samples over 2.50 to 15.15 micron wavelength region, in 10 cm\(^{-1}\) increments, for 10°, 26.7°, 38.0°, 50.0° and 65.5° Angles-of-Incidence (AOIs).
- NPL estimated 95% confidence level uncertainties quoted at:
  ±0.4% for s-polarization for 2.5 to 12.5 microns range, rising to ±0.4% to ±0.7% between 12.5 and 15.15 microns. Except ±0.3% for 10° AOI over the whole wavelength range.
  ±0.3% for p-polarization
- Average reflectance results compare to within ±1% with Lincoln Laboratory measurements for SN03 and SN04 samples
- Significant differences between PFM and FM1 samples exist
Summary of Scan Mirror Witness Sample Polarized Reflectance Measurements

- **Graph Summaries Provided for:**
  - NPL S, P and Average reflectances for SN03, SN04, SN08 and SN16 samples at 6 AOIs
  - Comparisons of LL and NPL SN03 and SN04 measurements
  - Sample-to-sample variations for PFM SN03/SN04 and FM1 SN08/SN16 samples
  - FM1 and PFM Average Reflectances versus wavelength
  - FM1 and PFM Polarization Factors versus wavelength
  - FM1 Band-weighted Average Reflectances versus AOI

- **Table of FM1 Band’s Band-weighted S, P and Average Reflectances for 6 AOIs**
AOI = 38

SN03 S, P and (S+P)/2 Reflectances

SN04 S, P and (S+P)/2 Reflectances

AOI = 38

SN08 S, P and (S+P)/2 Reflectances

SN16 S, P and (S+P)/2 Reflectances

Wavelength (um)
FM1 and PFM Scan Mirror Witness Sample Average
Polarization Factors from NPL Measurements

\[ P_{F_{avg}} = \frac{P_{F_3} + P_{F_4}}{2} \]

\( \text{Wavelength (\(\mu\text{m}\))} \)

AOI = 19
AOI = 26
AOI = 39
AOI = 50
AOI = 60
AOI = 65
PFM Samples Solid
FM1 Samples Dashed
FM1 Scan Mirror Witness Sample Average Polarization Reflectances vs A01
(NPL Measurements of Witness Samples SN08 and SN16 with Quadratic Fit)

B20

B21

B22

B23

B24

B25

B27

B28

B29

B30

B31

B32

B33

B34

B35

B36
Summary of Highbay RVS Measurements
Summary of Data Analysis

- Raw (not-normalized) RVS data results
  - 16 bands, 10 channels*, 3 RVS data collects (310K_1, 320K_2, and 320K_3)
  - data points averaged over 40 scans and ~50 frames†, with 1-sigma error bars
  - data collected at 10 AOIs; repeated measurements at 4 AOIs
  - corrected for drift (via b1 changes), and T_svs ≠ T_sm effect

- Normalized RVS fitted results
  - raw RVS data averaged over: 40 scans; 50 BCS frames† (with a few exceptions regarding # of frames to assure all data in BCS sweet spot)
  - averaged data preliminarily fitted to a Normalized Best-Fit Quadratic (NBFQ) function on channel-by-channel basis
  - RVS data normalized to average response (40 scans; 50 BCS' frames†) at BCS AOI=10.75°*

* B22, channels 1-7, and B36, Channel 6 deleted due to obvious saturation/noise problems
† some exceptions to 50 BCS frames depending on location of BCS sweet spot on band-by-band basis
Summary of Data Analysis
(continued)

- Normalized Best Fit Quadratic chart series provided:
  1) Normalized RVS vs AOI - channel dependent (averaged over 40 scans and 50 BCS frames; for 16 bands and 3 data collects)
  2) Normalized RVS vs AOI - data collect dependent (averaged over 40 scans, 50 BCS frames and 10 channels; for 16 bands)
  3) Normalized RVS vs AOI - grand average (averaged over 40 scans, 50 BCS frames, 10 channels and 3 datasets; for 16 bands)
Channel-by-Channel
Highbay RVS Raw Data Results
(after correction for drift via reference to OBC blackbody)

• Channel 8 charts processed w/Tsm=Tsvs
• Channel 8 chart for 320K_3 w/Tsm≠Tsvs
• Channel 8 chart comparing Tsm=Tsvs results with Tsm≠Tsvs correction
Channel 8 Raw <RVS>40 scans vs AOI for 50 BCS Frames

(310K.1 Data Set; Mirror A; w/50frame×40scan Average and 1−σ Error Bars; Optimum CSUB; Repeat AOIs in Color)

Instrument & Source Drift Corrected via OBC b1 (1st order); $T_{SM}$≠$T_{SVS}$ Term Excluded)
Channel 8 Raw $<RVS>_{40}^{\text{scans}}$ vs AOI for 50 BCS Frames

(320K.2 Data Set; Mirror A; w/50frame×40scan Average and 1−σ Error Bars; Optimum CSUB; Repeat AOIs in Color)

Instrument & Source Drift Corrected via OBC b1 (1st order); $T_{SM} \neq T_{SVS}$ Term Excluded)
Channel B Raw \(\langle RVS\rangle_{40~\text{scans}}\) vs AO1 for 50 BCS Frames

(320K_3 Data Set; Mirror A; w/50frame\times40scan Average and 1-\(\sigma\) Error Bars; Optimum CSUB; Repeat AOIs in Color)

Instrument & Source Drift Corrected via OBC b1 (1st order); \(T_{SW} \neq T_{SWS}\) Term Excluded)
Channel 8 Raw $<\text{RVS}>_{40\text{ scans}}$ vs AOI for 50 BCS Frames

(320K-3 Data Set; Mirror A; w/50frame×40scan Average and 1-σ Error Bars; Optimum CSUB; Repeat AOIs in Color)

Note: Instrument & Source Drift Corrected via OBC b1 (1st order); $T_{SM} \neq T_{SVS}$ Term Included
Channel 8 $\langle RVS \rangle_{TSM=TSVs} / \langle RVS \rangle_{TSM \neq TSVs}$ vs AOI for Data Set [320K_3]
(Mirror A; w/50-frame×40-scan Average; Repeat AOIs in Color)
Normalized RVS with weighted quadratic fit

- Quadratic function normalized at 10.75° AOI
- Channel 8 processed assuming Tsm=Ts vs
- Channel 8 for 320K_3 data collect with Tsm≠Ts vs correction
Channel 8 Normalized $<RVS>_{40 \text{ scans}}$ @ 10.75° vs AOI for 50 BCS Frames with Quadratic Fit
(310K_1 Data Set; Mirror A; w/50framex40scan Average and 1–σ Error Bars; Optimum CSUB; Repeat AOIs in Color)

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Note: Instrument & Source Drift Corrected via OBC b1 (1st order); $T_{SM} \times T_{SVS}$ Term Excluded
Channel 8 Normalized $<\text{RVS}>_{40\text{ scans}}$ @ 10.75° vs AOI for 50 DCS Frames with Quadratic Fit

(320K-2 Data Set; Mirror A; w/50frame x 40scan Average and 1-σ Error Bars; Optimum CSUB; Repeat AOIs in Color)

Note: Instrument & Source Drift Corrected via OBC b1 (1st order); T_{SM} T_{SVS} Term Excluded
Channel 8 Normalized $<RVS>_{40\text{ scans}} @ 10.75^\circ$ vs AOI for 50 BCS Frames with Quadratic Fit

(320K.3 Data Set; Mirror A; w/50frame×40scan Average and 1-σ Error Bars; Optimum CSUB; Repeat AOIs in Color)

Note: Instrument & Source Drift Corrected via OBC b1 (1st order); $T_{SM} \neq T_{SYS}$ Term Excluded
Channel 8 Normalized \( <\text{RVS}>_{40 \text{ scans}} \) @ 10.75° vs AOI for 50 BCS Frames with Quadratic Fit
(320K_3 Data Set; Mirror A; w/50frame\times40scan Average and 1-\( \sigma \) Error Bars; Optimum CSUB; Repeat AOIs in Color)

Note: Instrument & Source Drift Corrected via OBC b1 (1st order); \( T_{SM} \neq T_{SVS} \) Term Included
Normalized RVS (@ 10.75°) and Quadratic Fit vs A01 of 10 Channels for 31OK-1 Data Set; Mirror A

Polynomial coefficients result from the average (dashed line) of unsaturated channels.
Normalized RVS (© 10.75°) and Quadratic Fit vs. A0I of 10 Channels for 320K-2 Data Set; Mirror A

Polynomial coefficients result from the average (dashed line) of unsaturated channels.

For example, the polynomial coefficients for channel B20_CSUB:3 are:

- $q_0 = 0.99865913$
- $q_1 = 0.001493537$
- $q_2 = -2.29035886e-06$

These coefficients are applied to the equations for each channel to fit the data to a quadratic curve.
Normalized RVS (10.75°) and Quadratic Fit vs AOI of 10 Channels for 320K_3 Data Set; Mirror A

Polynomial coefficients result from the average (dashed line) of unsaturated channels.
Quadratic Fit of Normalized RVS (@ 10.75°) of Unsaturated Channels vs AOI; Mirror A

- Average of 3 Data Sets

**Graphs showing quadratic fit data for different CSUBs:**

- **B20, CSUB:3**
  - $Q_0 = 0.99821232$
  - $Q_1 = 0.0001936348$
  - $Q_2 = -2.5431352e-06$

- **B21, CSUB:1**
  - $Q_0 = 0.99900590$
  - $Q_1 = 0.0001065326$
  - $Q_2 = -1.5029622e-06$

- **B22, CSUB:4**
  - $Q_0 = 0.99743269$
  - $Q_1 = 0.0002749561$
  - $Q_2 = -3.690156e-06$

- **B23, CSUB:2**
  - $Q_0 = 0.99877205$
  - $Q_1 = 0.0001252617$
  - $Q_2 = -1.7021943e-06$

- **B24, CSUB:3**
  - $Q_0 = 0.99882318$
  - $Q_1 = 0.0001401480$
  - $Q_2 = -1.9882740e-06$

- **B25, CSUB:2**
  - $Q_0 = 0.99952577$
  - $Q_1 = 8.565841e-05$
  - $Q_2 = -1.542971e-06$

- **B27, CSUB:1**
  - $Q_0 = 0.99711462$
  - $Q_1 = 0.0003435757$
  - $Q_2 = -7.095992e-06$

- **B28, CSUB:2**
  - $Q_0 = 0.99872087$
  - $Q_1 = 0.0001252617$
  - $Q_2 = -1.7021943e-06$

- **B29, CSUB:3**
  - $Q_0 = 0.99462887$
  - $Q_1 = 0.0002762156$
  - $Q_2 = -2.5393033e-05$

- **B30, CSUB:4**
  - $Q_0 = 0.99694315$
  - $Q_1 = 0.0001435556$
  - $Q_2 = -1.3248809e-05$

- **B31, CSUB:1**
  - $Q_0 = 0.99763991$
  - $Q_1 = 0.0003553104$
  - $Q_2 = -1.2463975e-05$

- **B32, CSUB:1**
  - $Q_0 = 0.99692388$
  - $Q_1 = 0.0001252617$
  - $Q_2 = -1.7021943e-06$

- **B33, CSUB:1**
  - $Q_0 = 0.99562105$
  - $Q_1 = 0.0001435556$
  - $Q_2 = -2.8288658e-05$

- **B34, CSUB:1**
  - $Q_0 = 0.99532278$
  - $Q_1 = 0.0003553104$
  - $Q_2 = -2.9598890e-05$

- **B35, CSUB:1**
  - $Q_0 = 0.99488622$
  - $Q_1 = 0.0002762156$
  - $Q_2 = -3.1315856e-05$

- **B36, CSUB:1**
  - $Q_0 = 0.99437562$
  - $Q_1 = 0.0003553104$
  - $Q_2 = -3.3027432e-05$