AIRS Gas Cell Spectral Calibration/Validation

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with thanks to:

Scott Hannon [UMBC],
and Rae Force, Esquire.

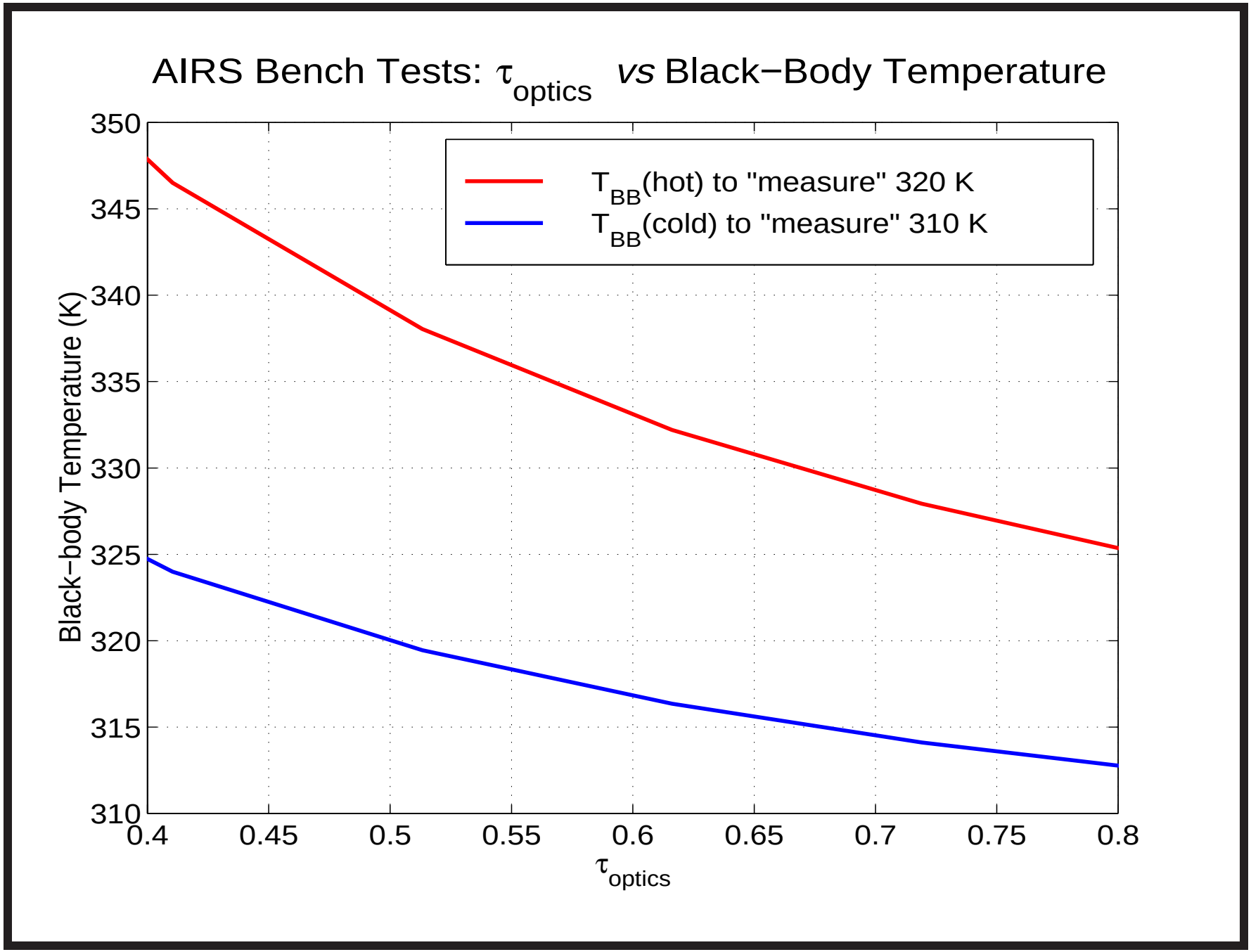
End-to-End System Test of AIRS SRF

- Validate FTS measurements of the AIRS SRF by comparing computed to measured transmission spectra.
- We *may* have accuracies comparable to FTS technique in the 15 μm region.
- We plan to fit for the SRF centers, a width (rubber-band of SRF) and for a parameter that modifies the wing response.
- Method is insensitive to radiometric errors.
- Why does this method work so well (we hope)?
  - AIRS has high S/N.
  - Relevant CO_2 spectroscopy errors are small.
  - Gas cell conditions (low pressure, saturated lines) chosen to ensure high accuracy in the computed transmittance.
  - Optics transmission, radiance can be removed by taking radiance spectra at two different blackbody temperatures.
  - Spectra recorded at two temperatures make method insensitive to absolute errors in the blackbody temperature, emissivity.

AIRS Flight Model (FM) Simulations

- Collimator length $\sim$ 6 meters
- Estimated $\tau_{optics} \sim 0.765$

1. No Gas in Collimator ($\sim$ 300 K):
   - Cold black-body spectrum (310-315 K) $\equiv R^{BB}_{cold}$.
   - Hot black-body spectrum (315-330 K) $\equiv R^{BB}_{hot}$.
   - Retrieve transmittance of collimator elements $\equiv \tau_{optics}$.
2. CO_2,H_2O in Collimator ($\sim$ 300 K):
   - Cold black-body spectrum (310-315 K) $\equiv R^{gas}_{cold}$.
   - Hot black-body spectrum (315-330 K) $\equiv R^{gas}_{hot}$.
   - Retrieve transmittance of CO_2,H_2O $\equiv \tau_{gas}$ using retrieved τ_{optics}.


AIRS Bench Tests: τ_{optics} *vs* Black−Body Temperature
T_{BB}(hot) to "measure" 320 K
T_{BB}(cold) to "measure" 310 K
Black−body Temperature (K)
350
345
340
335
330
325
320
315
310
0.4
0.45
0.5
0.55
0.6
0.65
0.7
0.75
0.8
τ_{optics}

AIRS FM Simulations: Equations

$$R^{BB}_{cold} = B(T^{BB}_{cold})\,\tau_{optics} + B(T^{cell})\,(1 - \tau_{optics}) \quad (1)$$

$$R^{BB}_{hot} = B(T^{BB}_{hot})\,\tau_{optics} + B(T^{cell})\,(1 - \tau_{optics}) \quad (2)$$

Subtracting 1 from 2 yields:

$$R^{BB}_{hot} - R^{BB}_{cold} = \tau_{optics}\left(B(T^{BB}_{hot}) - B(T^{BB}_{cold})\right) \quad (3)$$

And solving for τ_{optics}:

$$\tau_{optics} = \frac{(R^{BB}_{hot} - R^{BB}_{cold})}{\left(B(T^{BB}_{hot}) - B(T^{BB}_{cold})\right)} \quad (4)$$

AIRS FM Simulations: Equations (cont'd)

$$R_{cold}^{gas} = B(T_{cold}^{BB})\,\tau_{optics}\,\tau_{gas} + B(T^{cell})\,(1 - \tau_{optics}\,\tau_{gas}) \tag{5}$$

$$R_{hot}^{gas} = B(T_{hot}^{BB})\,\tau_{optics}\,\tau_{gas} + B(T^{cell})\,(1 - \tau_{optics}\,\tau_{gas}) \tag{6}$$

Subtracting 5 from 6 yields:

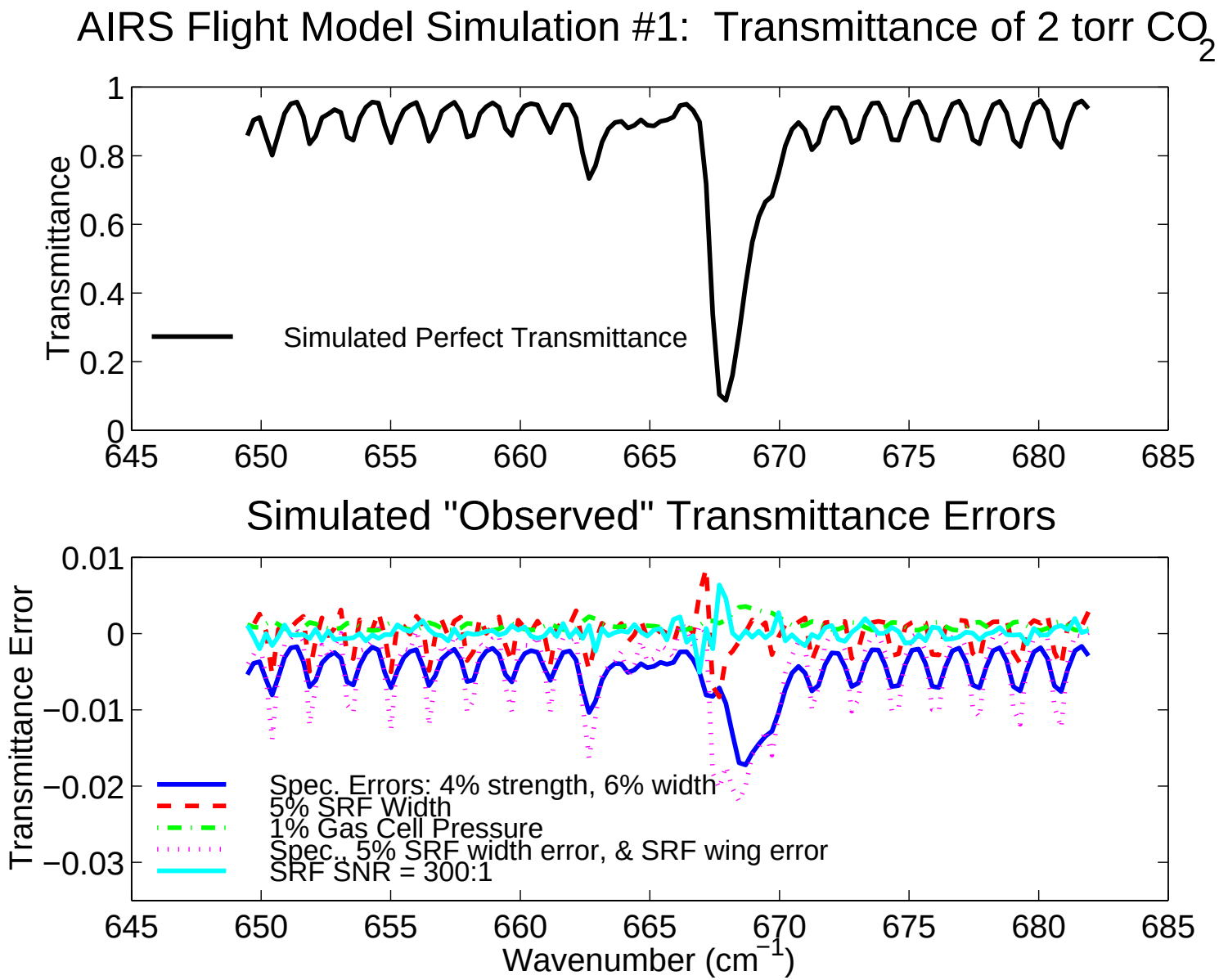
$$R_{hot}^{gas} - R_{cold}^{gas} = \tau_{optics}\,\tau_{gas}\,\left(B(T_{hot}^{BB}) - B(T_{cold}^{BB})\right) \tag{7}$$

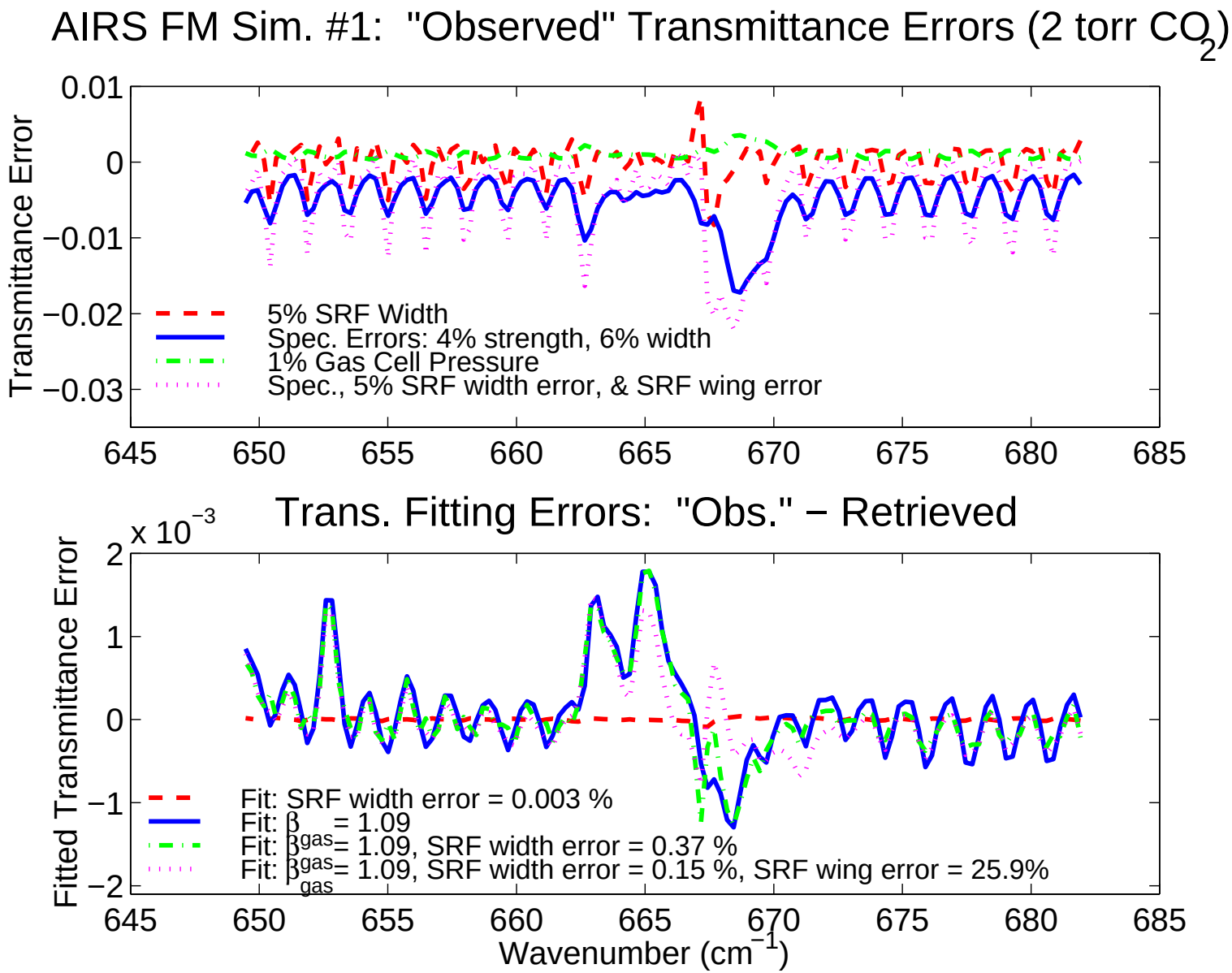
And solving for τ_{gas}:

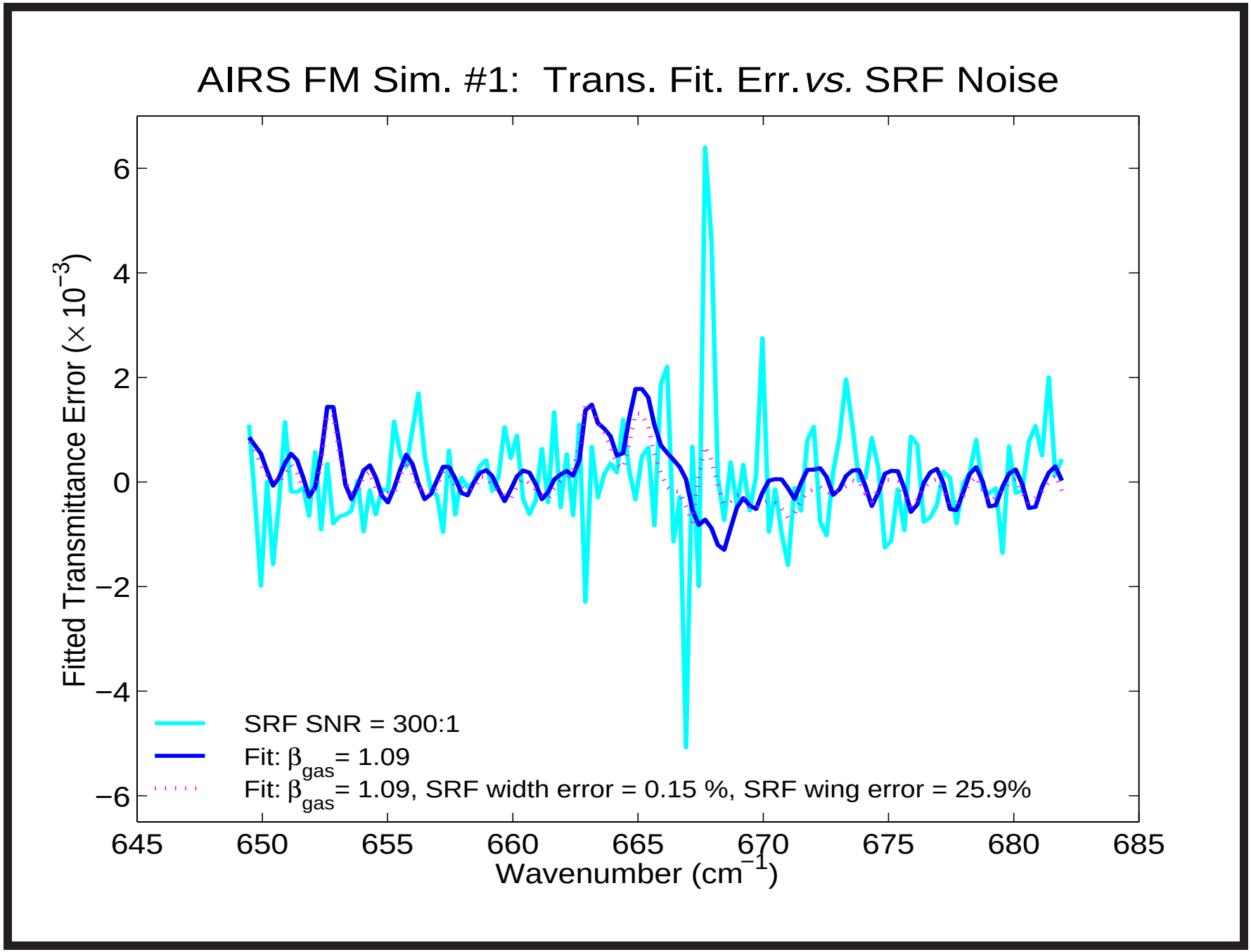
$$\tau_{gas} = \frac{(R_{hot}^{gas} - R_{cold}^{gas})}{\tau_{optics}\,\left(B(T_{hot}^{BB}) - B(T_{cold}^{BB})\right)} \tag{8}$$

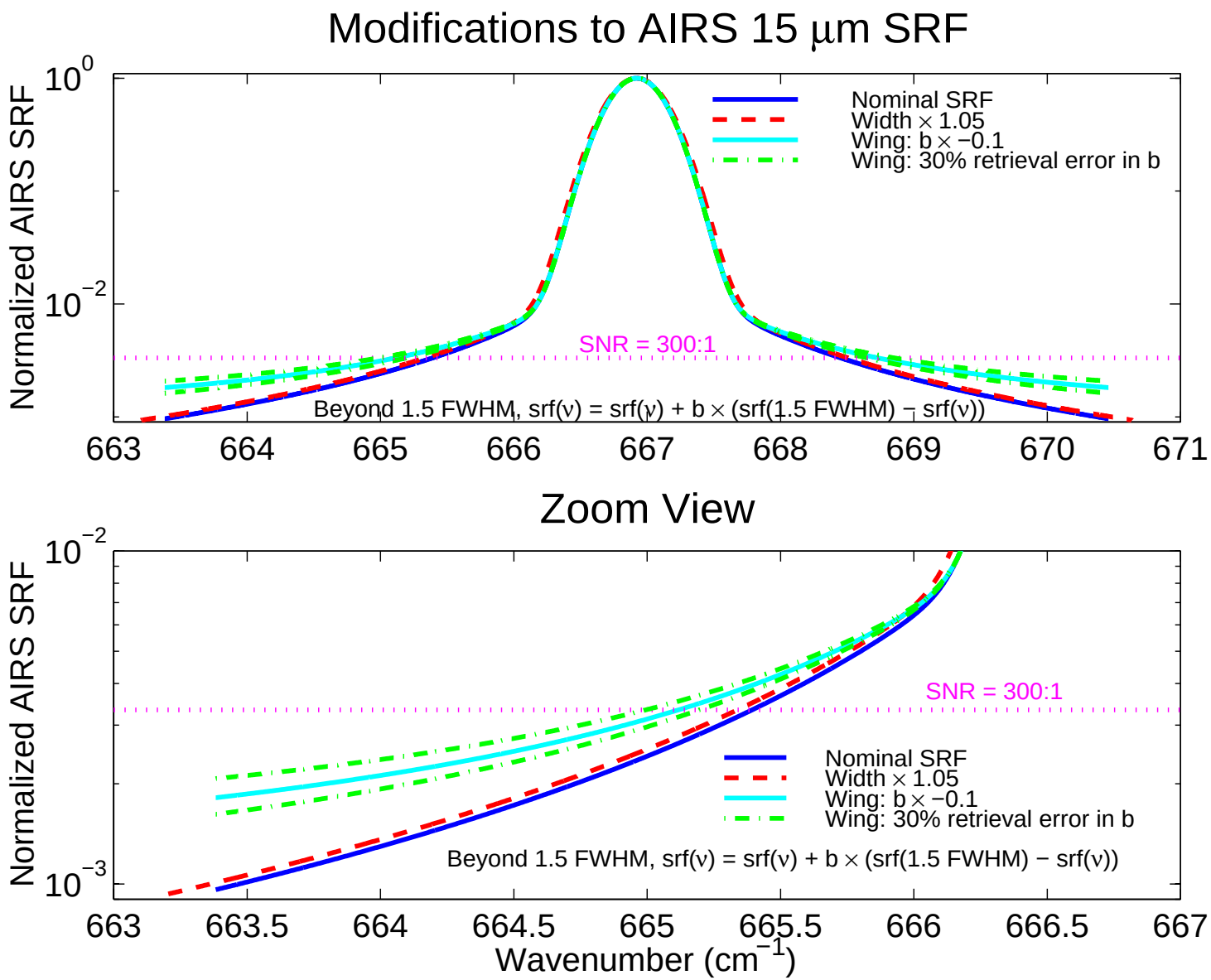
AIRS FM Simulations: Errors

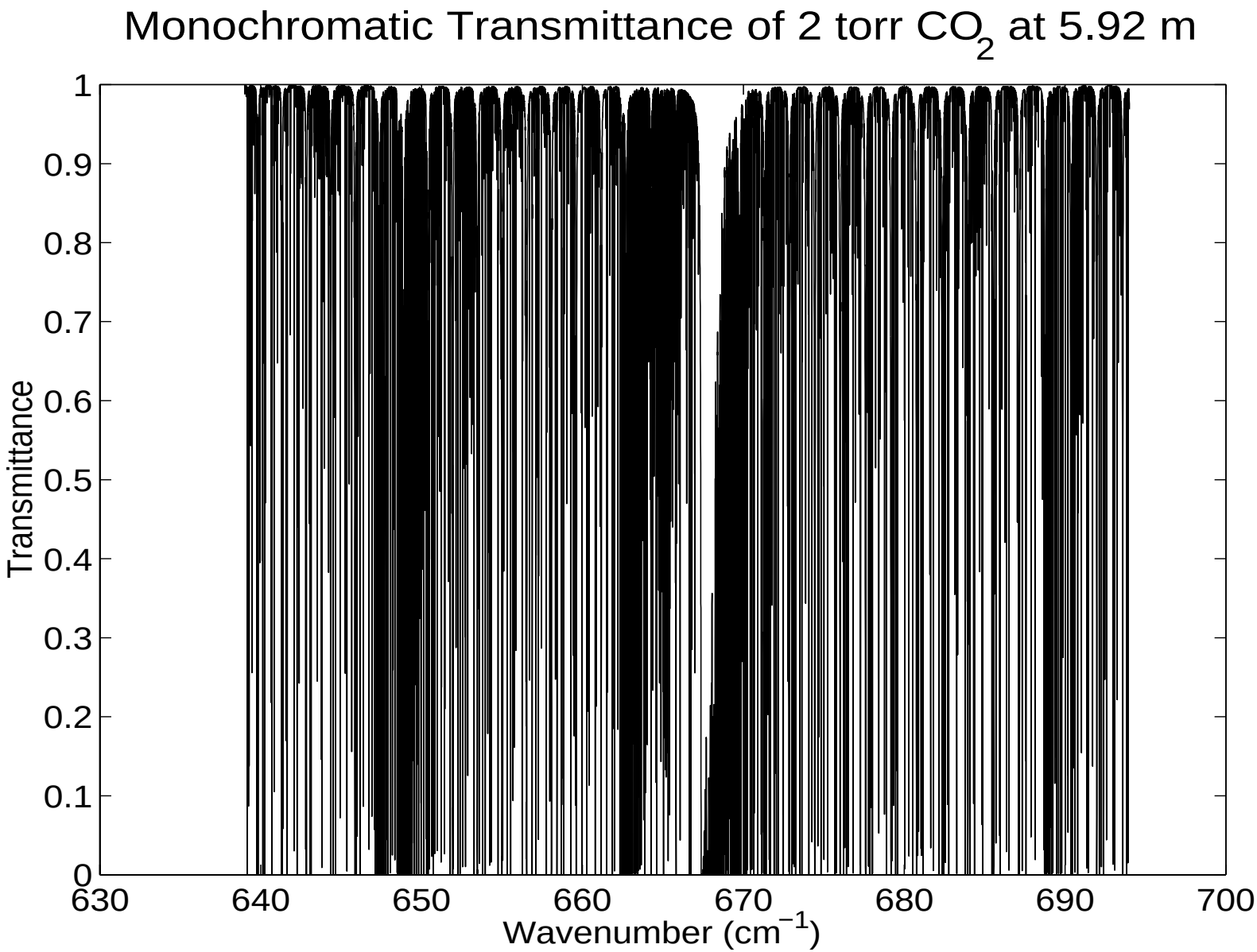
1. Spectroscopic line parameter estimates
   - strength: 2%, 4%
   - width: 4%, 6%.
2. SRF width fit with a rubber-banding of the SRF frequency scale.
3. SRF wing slope fit with:
   beyond 1.5 FWHM,
   $srf(\nu) = srf(\nu) + b \times (srf(\nu = 1.5FWHM) - srf(\nu))$
4. AIRS radiance noise: 0.25 K at 250 K.
5. SRF noise: 300:1 at 15 μm.
6. Uncertainty in the delta temperature of the black-body: 1 K.
7. Uncertainty in the Gas Cell pressure: 1%

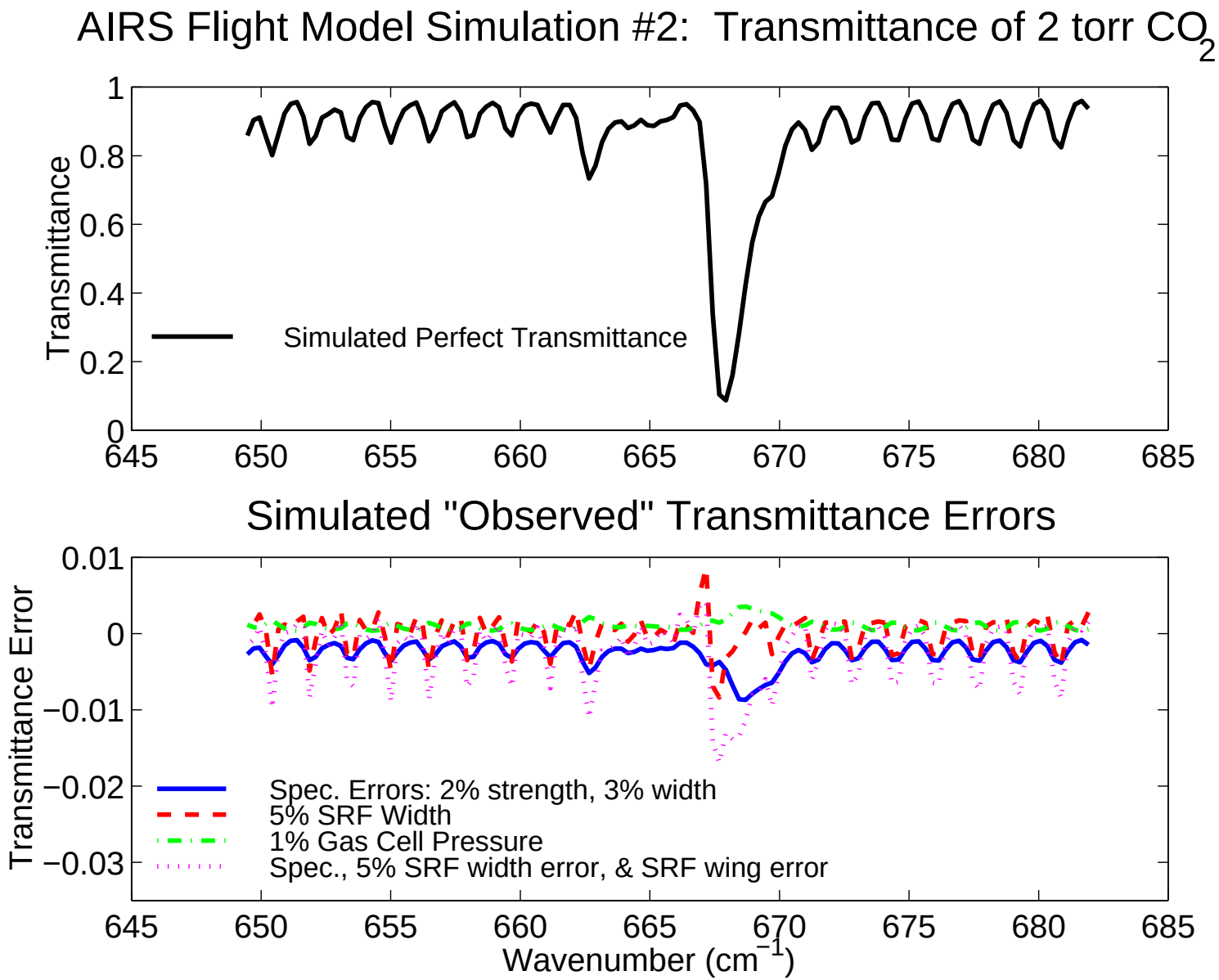

AIRS Flight Model Simulation #1: Transmittance of 2 torr CO_2
Transmittance
Simulated Perfect Transmittance
Simulated "Observed" Transmittance Errors
Transmittance Error
Spec. Errors: 4% strength, 6% width
5% SRF Width
1% Gas Cell Pressure
Spec., 5% SRF width error, & SRF wing error
SRF SNR = 300:1
Wavenumber (cm^{-1})

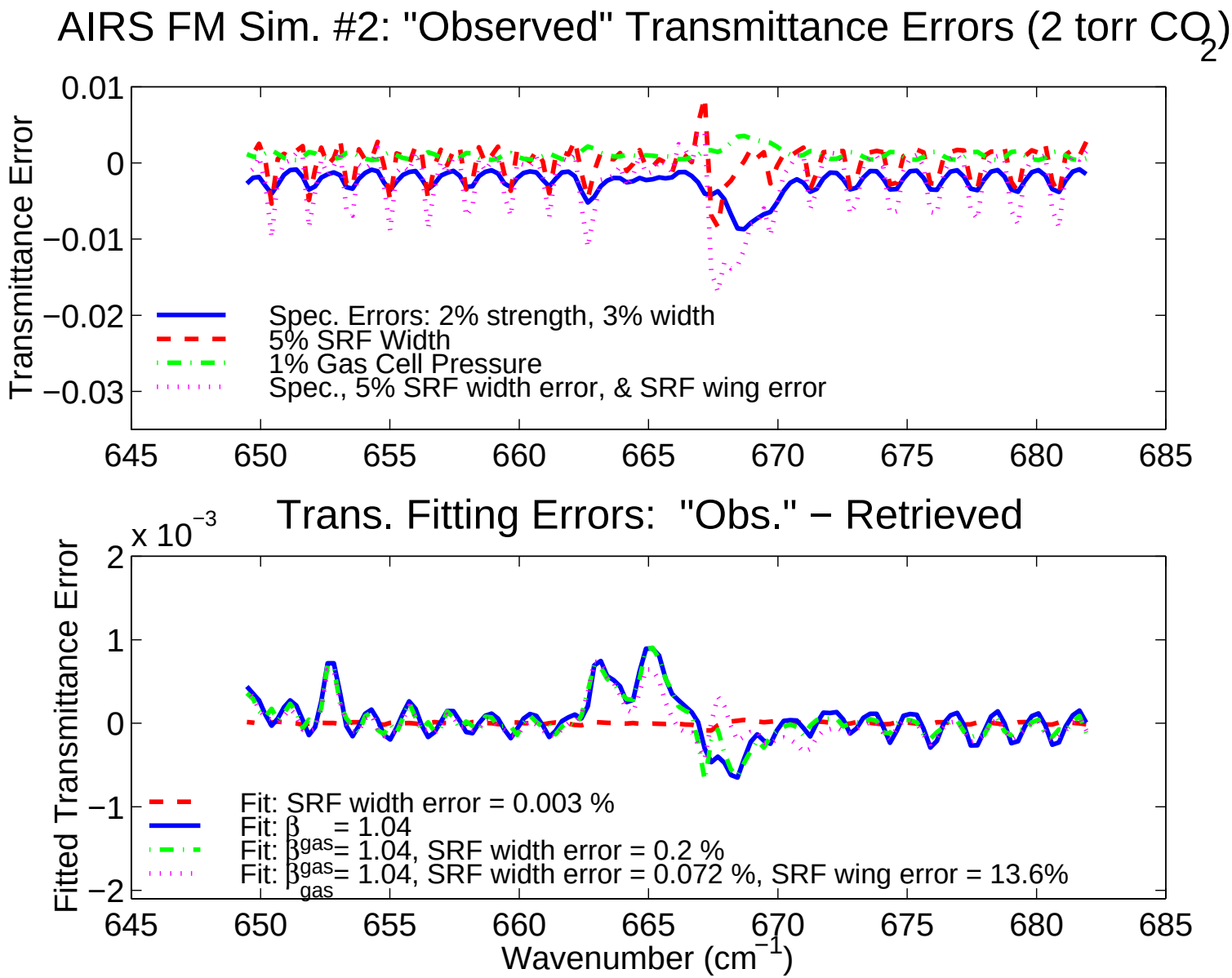

AIRS FM Sim. #1: "Observed" Transmittance Errors (2 torr CO2)
Transmittance Error
0.01
0
−0.01
−0.02
−0.03
5% SRF Width
Spec. Errors: 4% strength, 6% width
1% Gas Cell Pressure
Spec., 5% SRF width error, & SRF wing error
645 650 655 660 665 670 675 680 685
Trans. Fitting Errors: "Obs." − Retrieved
x 10−3
Fitted Transmittance Error
2
1
0
−1
−2
Fit: SRF width error = 0.003 %
Fit: β = 1.09
Fit: βgas = 1.09, SRF width error = 0.37 %
Fit: βgas = 1.09, SRF width error = 0.15 %, SRF wing error = 25.9%
gas
645 650 655 660 665 670 675 680 685
Wavenumber (cm−1)

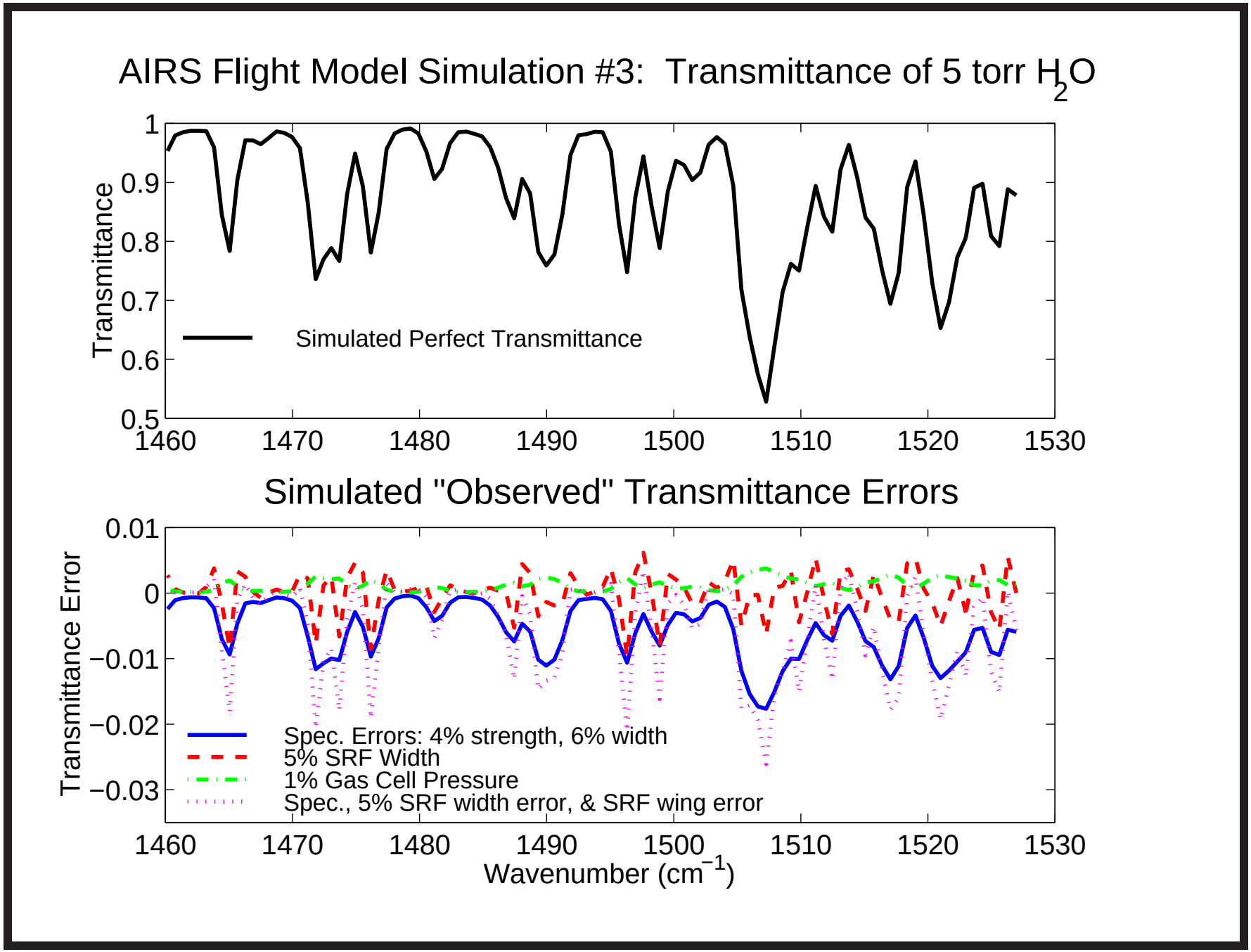

AIRS FM Sim. #1: Trans. Fit. Err. *vs.* SRF Noise
Fitted Transmittance Error ($\times 10^{-3}$)
6
4
2
0
−2
−4
−6
645
650
655
660
665
670
675
680
685
Wavenumber (cm^{-1})
SRF SNR = 300:1
Fit: β_{gas} = 1.09
Fit: β_{gas} = 1.09, SRF width error = 0.15 %, SRF wing error = 25.9%

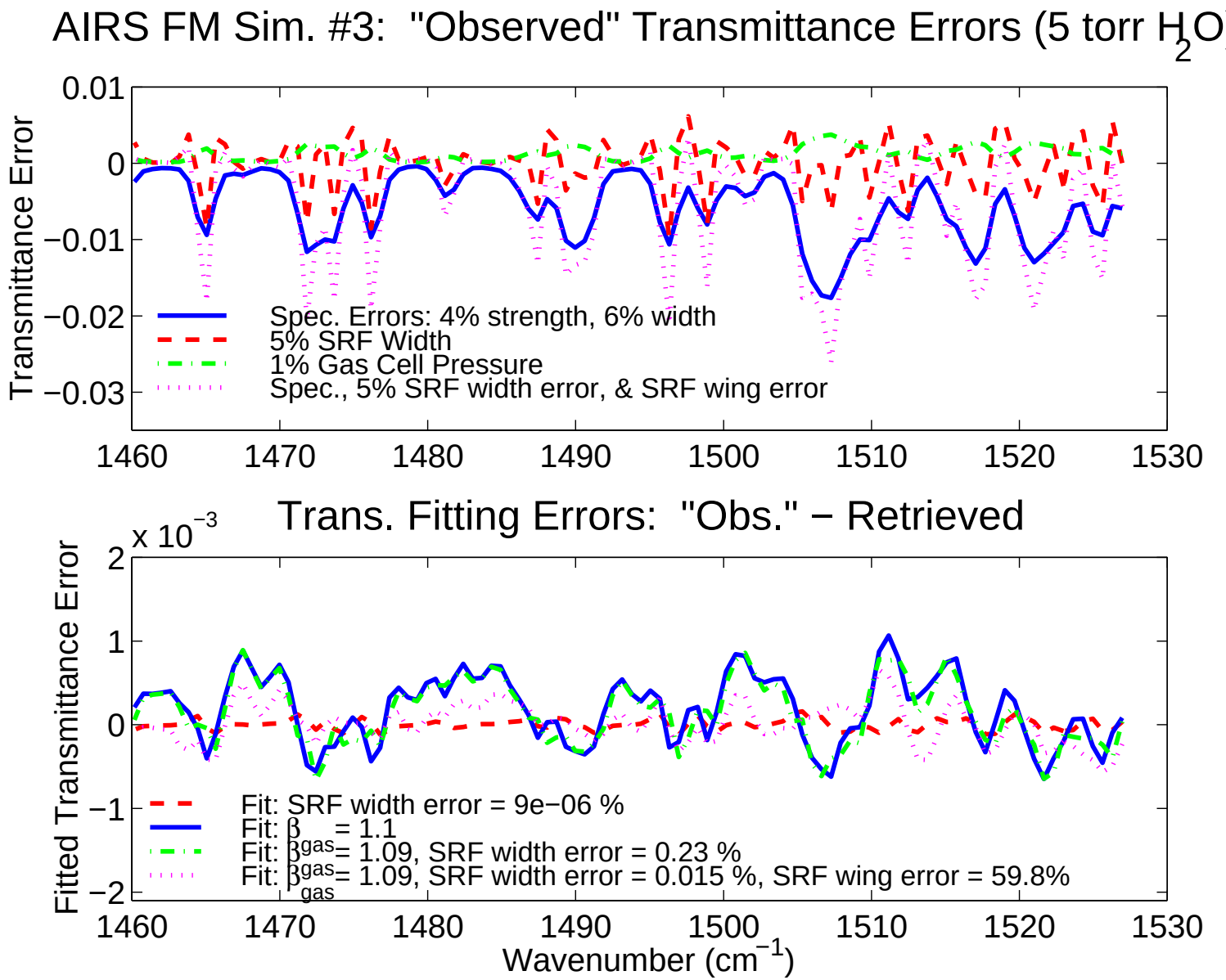

Modifications to AIRS 15 μm SRF
Normalized AIRS SRF
10^0
10^{-2}
Nominal SRF
Width × 1.05
Wing: b × −0.1
Wing: 30% retrieval error in b
SNR = 300:1
Beyond 1.5 FWHM, srf(ν) = srf(ν) + b × (srf(1.5 FWHM) − srf(ν))
663 664 665 666 667 668 669 670 671
Zoom View
Normalized AIRS SRF
10^{-2}
10^{-3}
SNR = 300:1
Nominal SRF
Width × 1.05
Wing: b × −0.1
Wing: 30% retrieval error in b
Beyond 1.5 FWHM, srf(ν) = srf(ν) + b × (srf(1.5 FWHM) − srf(ν))
663 663.5 664 664.5 665 665.5 666 666.5 667
Wavenumber (cm^{-1})

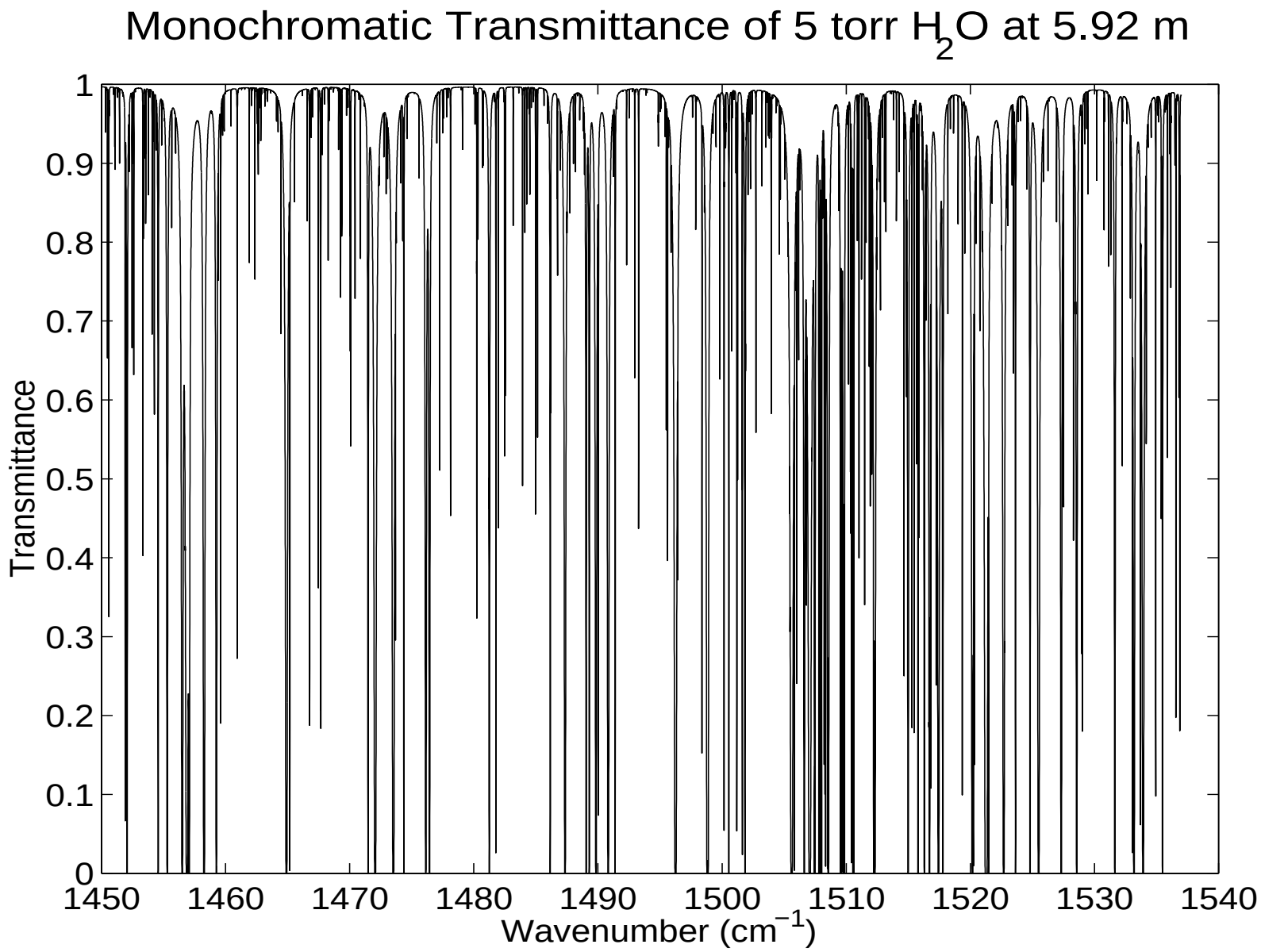

Monochromatic Transmittance of 2 torr CO_2 at 5.92 m
Transmittance
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
630
640
650
660
670
680
690
700
Wavenumber (cm^{-1})


AIRS Flight Model Simulation #2: Transmittance of 2 torr CO_2
Transmittance
Simulated Perfect Transmittance
Simulated "Observed" Transmittance Errors
Transmittance Error
Spec. Errors: 2% strength, 3% width
5% SRF Width
1% Gas Cell Pressure
Spec., 5% SRF width error, & SRF wing error
Wavenumber (cm^{-1})


AIRS FM Sim. #2: "Observed" Transmittance Errors (2 torr CO_2)
Transmittance Error
0.01
0
−0.01
−0.02
−0.03
Spec. Errors: 2% strength, 3% width
5% SRF Width
1% Gas Cell Pressure
Spec., 5% SRF width error, & SRF wing error
645 650 655 660 665 670 675 680 685
Trans. Fitting Errors: "Obs." − Retrieved
x 10^{-3}
Fitted Transmittance Error
2
1
0
−1
−2
Fit: SRF width error = 0.003 %
Fit: β = 1.04
Fit: β^{gas} = 1.04, SRF width error = 0.2 %
Fit: β^{gas}_{gas} = 1.04, SRF width error = 0.072 %, SRF wing error = 13.6%
645 650 655 660 665 670 675 680 685
Wavenumber (cm^{-1})


AIRS Flight Model Simulation #3: Transmittance of 5 torr H_2O
Transmittance
Simulated Perfect Transmittance
1
0.9
0.8
0.7
0.6
0.5
1460
1470
1480
1490
1500
1510
1520
1530
Simulated "Observed" Transmittance Errors
Transmittance Error
0.01
0
−0.01
−0.02
−0.03
Spec. Errors: 4% strength, 6% width
5% SRF Width
1% Gas Cell Pressure
Spec., 5% SRF width error, & SRF wing error
Wavenumber (cm^{-1})


AIRS FM Sim. #3: "Observed" Transmittance Errors (5 torr H2O)
Transmittance Error
0.01
0
−0.01
−0.02
−0.03
Spec. Errors: 4% strength, 6% width
5% SRF Width
1% Gas Cell Pressure
Spec., 5% SRF width error, & SRF wing error
1460 1470 1480 1490 1500 1510 1520 1530
Trans. Fitting Errors: "Obs." − Retrieved
x 10−3
Fitted Transmittance Error
2
1
0
−1
−2
Fit: SRF width error = 9e−06 %
Fit: β = 1.1
Fit: βgas = 1.09, SRF width error = 0.23 %
Fit: βgas = 1.09, SRF width error = 0.015 %, SRF wing error = 59.8%
1460 1470 1480 1490 1500 1510 1520 1530
Wavenumber (cm−1)


Monochromatic Transmittance of 5 torr H2O at 5.92 m
Transmittance
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1450
1460
1470
1480
1490
1500
1510
1520
1530
1540
Wavenumber (cm−1)

AIRS Engineering Model (EM) Simulations

- Chopper in Collimator to simulate Space view: $\sim$ 150 K.
- Gas in transfer optics cell: $\sim$ 1-2 meters.
- Possible air path up to 1 foot!
- Estimated $\tau_{optics} \sim 0.574$.

1. No Gas in transfer optics cell ($\sim$ 300 K):
   - Cold black-body spectrum (310-315 K) $\equiv R^{BB}_{cold}$.
   - Hot black-body spectrum (315-330 K) $\equiv R^{BB}_{hot}$.
   - Retrieve transmittance of transfer optics elements $\equiv \tau_{optics}$.
2. CO_2 in transfer optics cell ($\sim$ 300 K):
   - Cold black-body spectrum (310-315 K) $\equiv R^{gas}_{cold}$.
   - Hot black-body spectrum (315-330 K) $\equiv R^{gas}_{hot}$.
   - Retrieve transmittance of $CO_2 \equiv \tau_{gas}$ using retrieved τ_{optics}.

AIRS EM Simulations: Equations

$$R^{BB}_{cold} = B(T^{BB}_{cold})\,\tau_{optics} + B(T^{cell})\,(1-\tau_{optics}) + DC_{offset} \qquad (9)$$

$$R^{BB}_{hot} = B(T^{BB}_{hot})\,\tau_{optics} + B(T^{cell})\,(1-\tau_{optics}) + DC_{offset} \qquad (10)$$

But, we also have the cold chopper views!

$$R^{chop} = B(T^{chop})\,\tau_{chop} + B(T^{cell})\,(1-\tau_{chop}) + DC_{offset} \qquad (11)$$

Where τ_{chop} is the transmittance between the chopper and the EM.

AIRS EM Simulations: Equations (cont'd)

- We assume the chopper views are identical between the two black-body views.
- Assuming the DC_{offset} does not change during a "scan" of black-body views and cold chopper views, this term cancels!
- Subtracting 11 from 9 and 11 from 10 leaves us with "calibrated" observations R^{cal}_{cold} and R^{cal}_{hot}, respectively:

$$\begin{aligned} R^{cal}_{cold} &= B(T^{BB}_{cold})\,\tau_{optics} + B(T^{cell})\,(1-\tau_{optics}) \\ &\quad - B(T^{chop})\,\tau_{chop} - B(T^{cell})\,(1-\tau_{chop}) \end{aligned} \tag{12}$$

$$\begin{aligned} R^{cal}_{hot} &= B(T^{BB}_{hot})\,\tau_{optics} + B(T^{cell})\,(1-\tau_{optics}) \\ &\quad - B(T^{chop})\,\tau_{chop} - B(T^{cell})\,(1-\tau_{chop}) \end{aligned} \tag{13}$$

AIRS EM Simulations: Equations (cont'd)

Now, subtracting 12 from 13 yields:

$$R_{hot}^{cal} - R_{cold}^{cal} = \tau_{optics} \left(B(T_{hot}^{BB}) - B(T_{cold}^{BB}) \right) \tag{14}$$

And solving for τ_{optics}:

$$\tau_{optics} = \frac{(R_{hot}^{cal} - R_{cold}^{cal})}{\left(B(T_{hot}^{BB}) - B(T_{cold}^{BB}) \right)} \tag{15}$$

AIRS EM Simulations: Equations (cont'd)

Similarly, the DC_{offset} and chopper terms enter in to the EM observations of the transfer optics cell filled with gas, with the same cancelation. This then leaves us with a similar equation for τ_{gas} as for the FM simulation but with the chopper terms included:

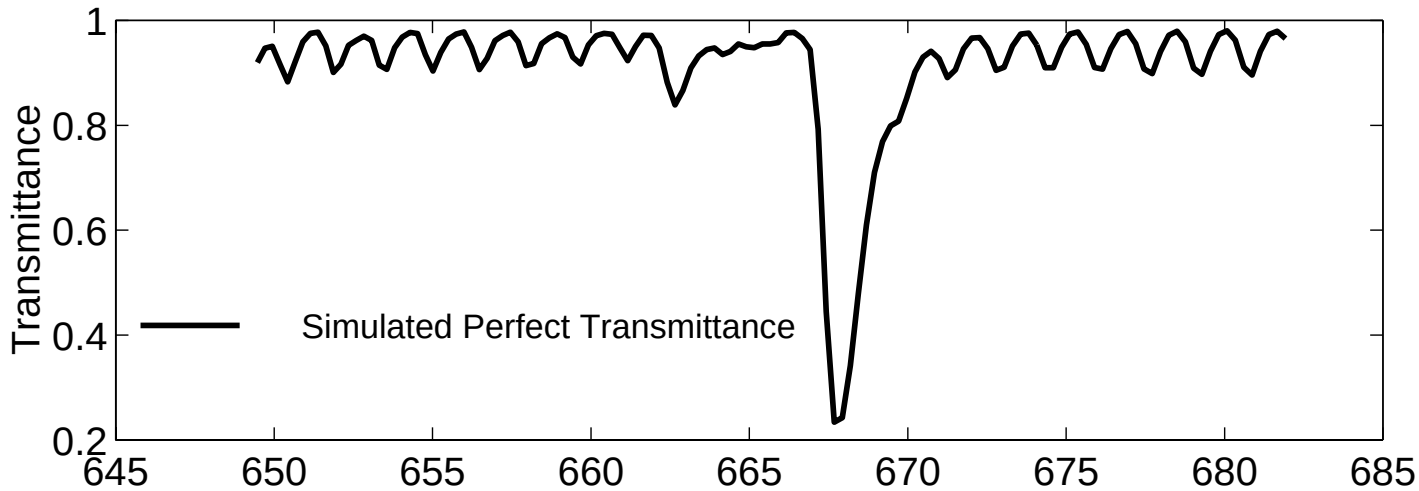
$$\tau_{gas} = \frac{\left(R_{hot}^{gas} - R^{chop}\right) - \left(R_{cold}^{gas} - R^{chop}\right)}{\tau_{optics}\left(B(T_{hot}^{BB}) - B(T_{cold}^{BB})\right)} \tag{16}$$

Where the observed radiances R_{hot}^{gas} and R_{cold}^{gas} really are the difference between black-body/gas cell observations and chopper observations.

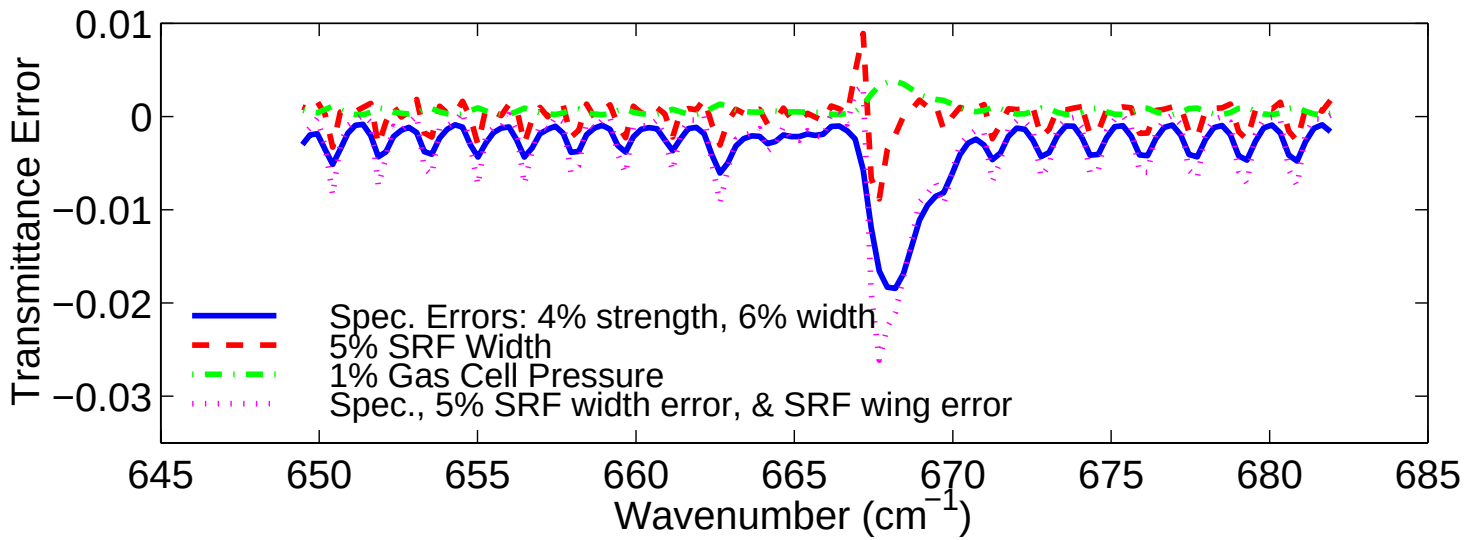
AIRS EM Simulations: Errors

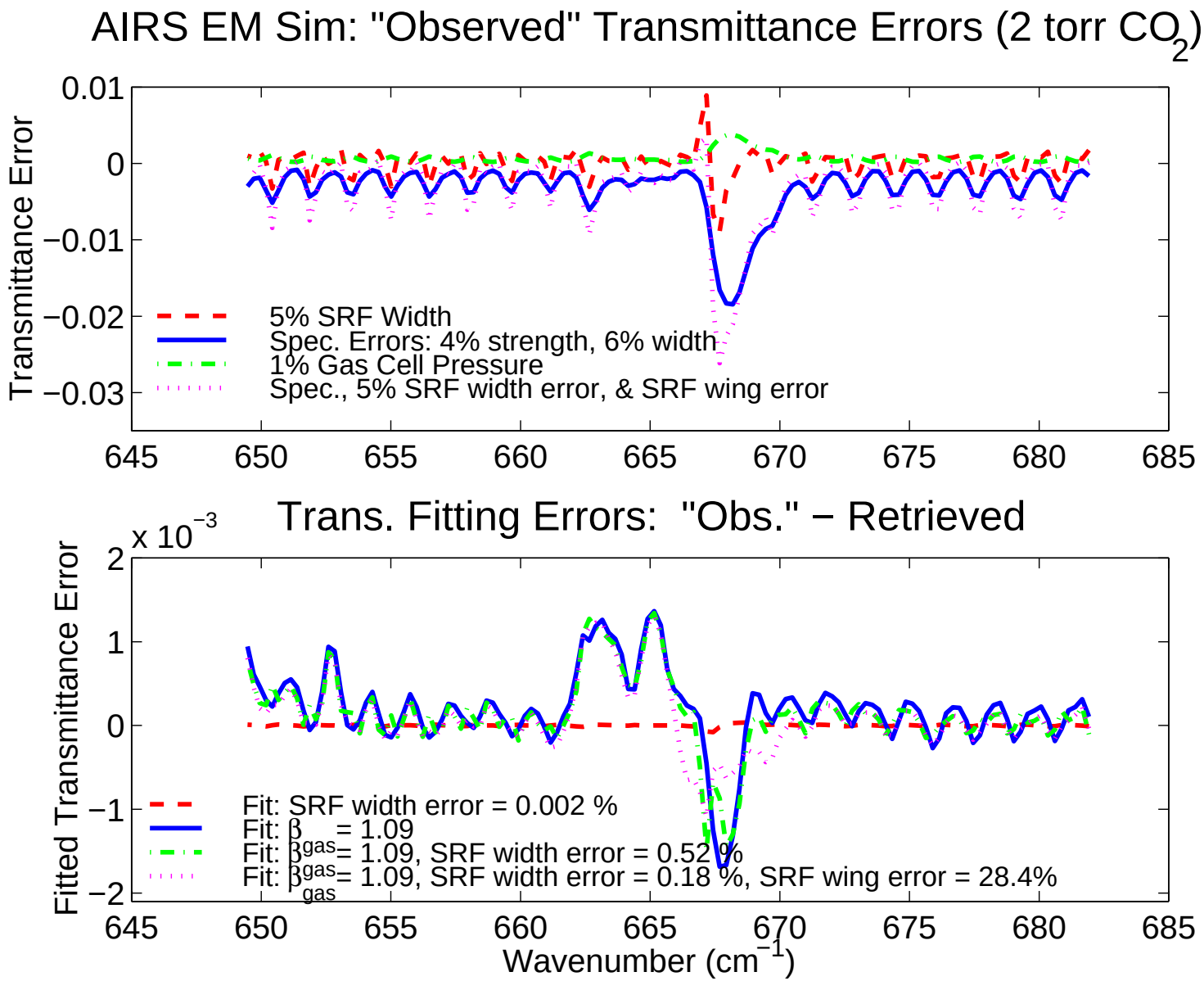
1. Spectroscopic line parameters
   - strength: 4%
   - width: 6%.
2. SRF width fit with a rubber-banding of the SRF frequency scale.
3. SRF wing slope fit with:
   beyond 1.5 FWHM:
   $srf(\nu) = srf(\nu) + b \times (srf(\nu = 1.5FWHM) - srf(\nu))$
4. AIRS radiance noise: 0.25 K at 250 K.
5. SRF noise: 100:1 at 15 μm.
6. Uncertainty in the delta temperature of the black-body: 1 K.
7. Uncertainty in the Gas Cell pressure: 1%

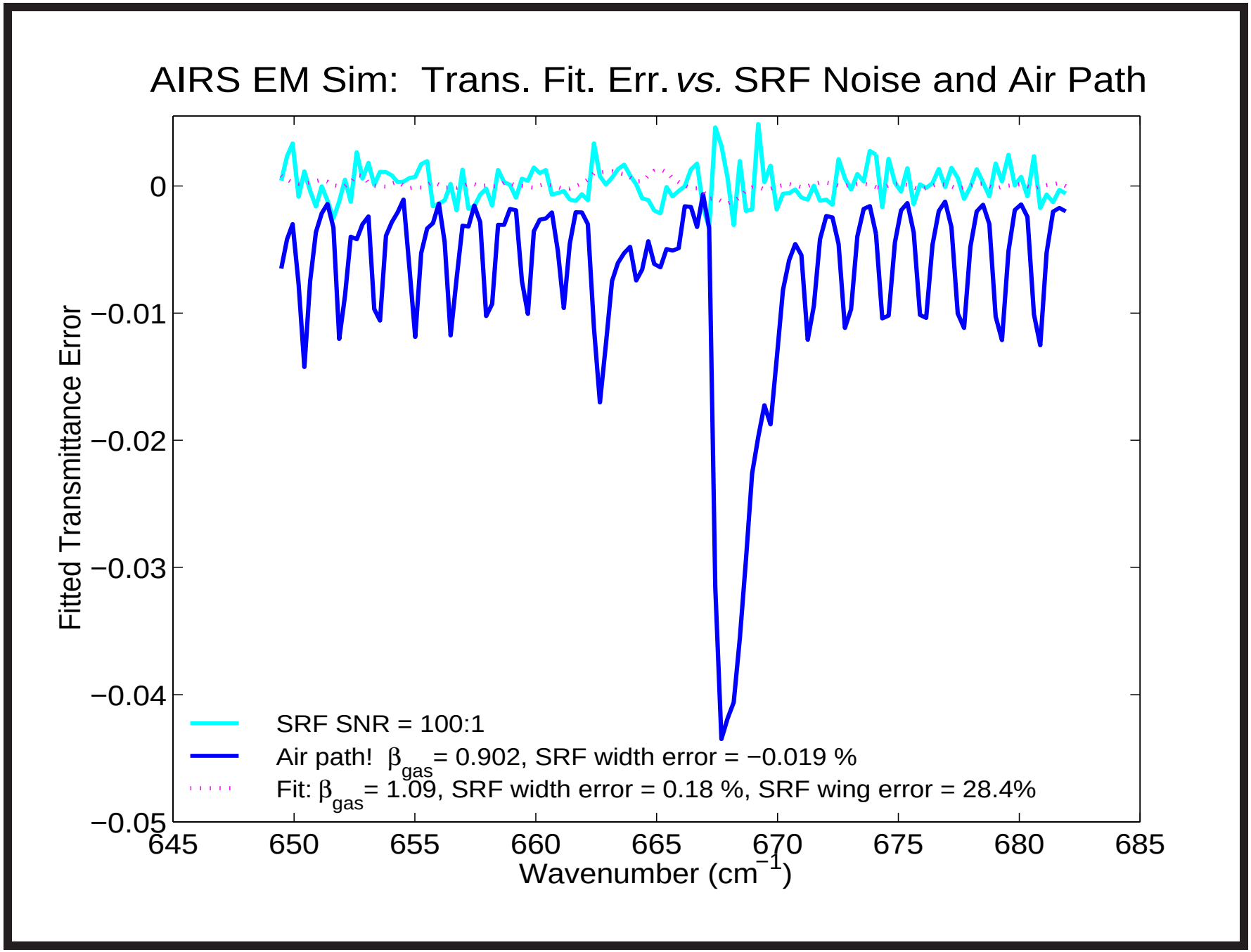
AIRS Engineering Model Simulation: Transmittance of 2 torr CO_2

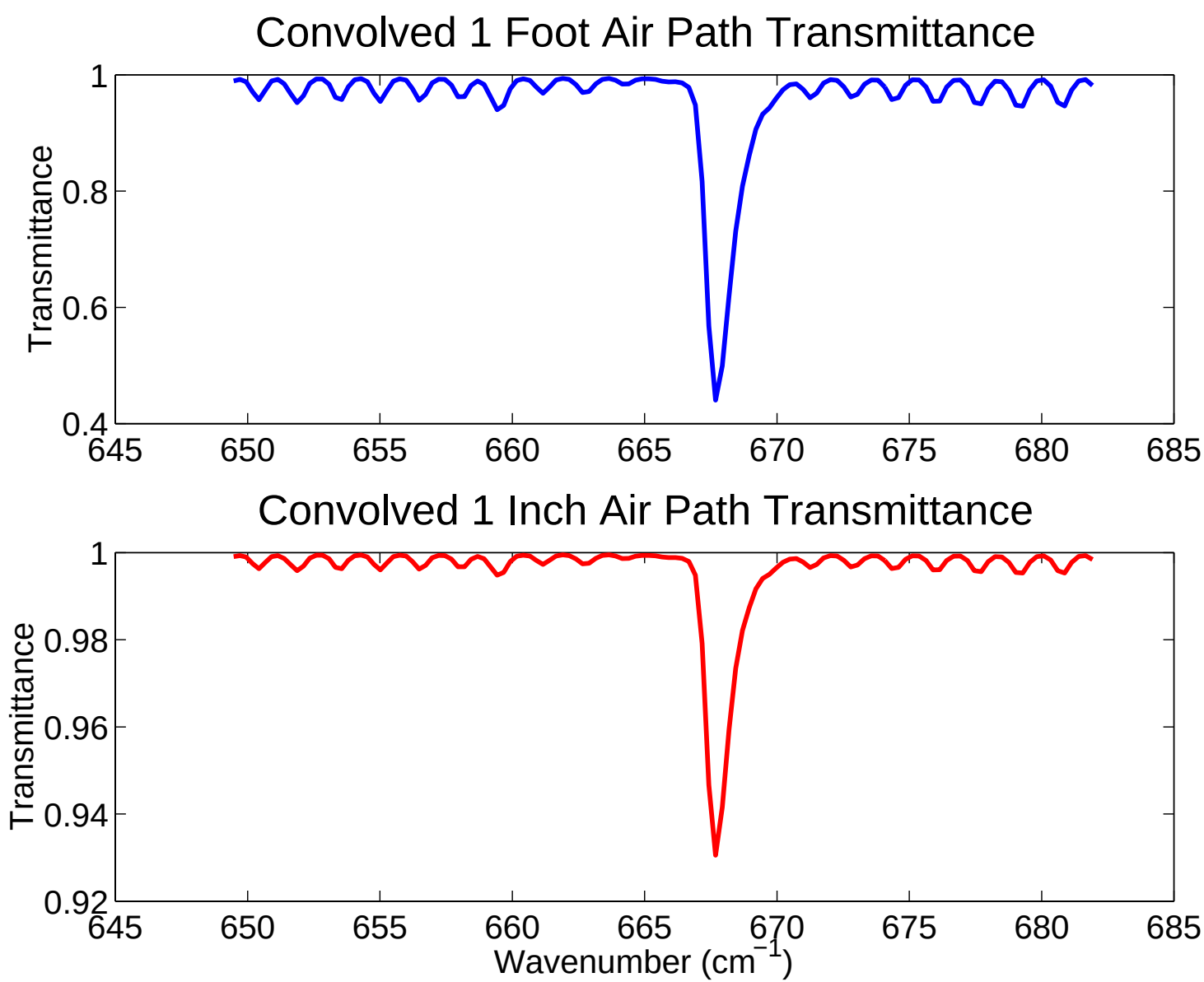


Simulated "Observed" Transmittance Errors




AIRS EM Sim: "Observed" Transmittance Errors (2 torr CO2)
Transmittance Error
0.01
0
−0.01
−0.02
−0.03
5% SRF Width
Spec. Errors: 4% strength, 6% width
1% Gas Cell Pressure
Spec., 5% SRF width error, & SRF wing error
645 650 655 660 665 670 675 680 685
Trans. Fitting Errors: "Obs." − Retrieved
x 10−3
Fitted Transmittance Error
2
1
0
−1
−2
Fit: SRF width error = 0.002 %
Fit: β = 1.09
Fit: βgas = 1.09, SRF width error = 0.52 %
Fit: βgas = 1.09, SRF width error = 0.18 %, SRF wing error = 28.4%
645 650 655 660 665 670 675 680 685
Wavenumber (cm−1)


AIRS EM Sim: Trans. Fit. Err. *vs.* SRF Noise and Air Path
Fitted Transmittance Error
0
−0.01
−0.02
−0.03
−0.04
−0.05
645
650
655
660
665
670
675
680
685
Wavenumber (cm^{-1})
SRF SNR = 100:1
Air path! β_{gas} = 0.902, SRF width error = −0.019 %
Fit: β_{gas} = 1.09, SRF width error = 0.18 %, SRF wing error = 28.4%


Convolved 1 Foot Air Path Transmittance
Transmittance
1
0.8
0.6
0.4
645
650
655
660
665
670
675
680
685
Convolved 1 Inch Air Path Transmittance
Transmittance
1
0.98
0.96
0.94
0.92
645
650
655
660
665
670
675
680
685
Wavenumber (cm^{-1})