The Community Radiative Transfer Model (CRTM) Development for Active and Hyperspectral Sensors

Yingtao Ma[1,2], Quanhua Liu[2], Igor Polonsky[3], Pan Liang[3], Ming Chen[4,2], Benjamin Johnson[5], Cheng Dang[5]

1. Cooperative Institute for Research in the Atmosphere (CIRA), Colorado State Univ. (CSU)
2. STAR/NESDIS/NOAA
3. Atmospheric and Environmental Research (AER)
4. Cooperative Institute for Satellite Earth System Studies (CISESS), Univ. of Maryland (UMD)
5. Joint Center for Satellite Data Assimilation (JCSDA), University Corporation for Atmospheric Research (UCAR)

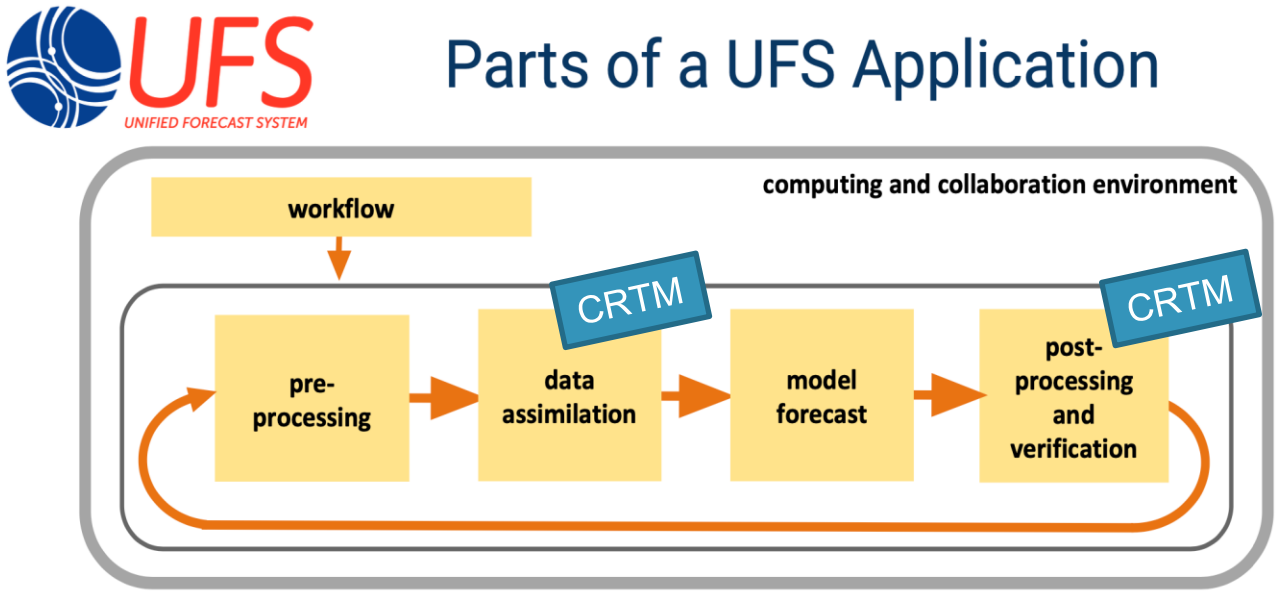
NOAA National Environmental Satellite, Data, and Information Service

Disclaimer: The views, opinions, and findings contained in this presentation are those of the authors and should not be construed as an official NOAA or U.S. Government position, policy, or decision.

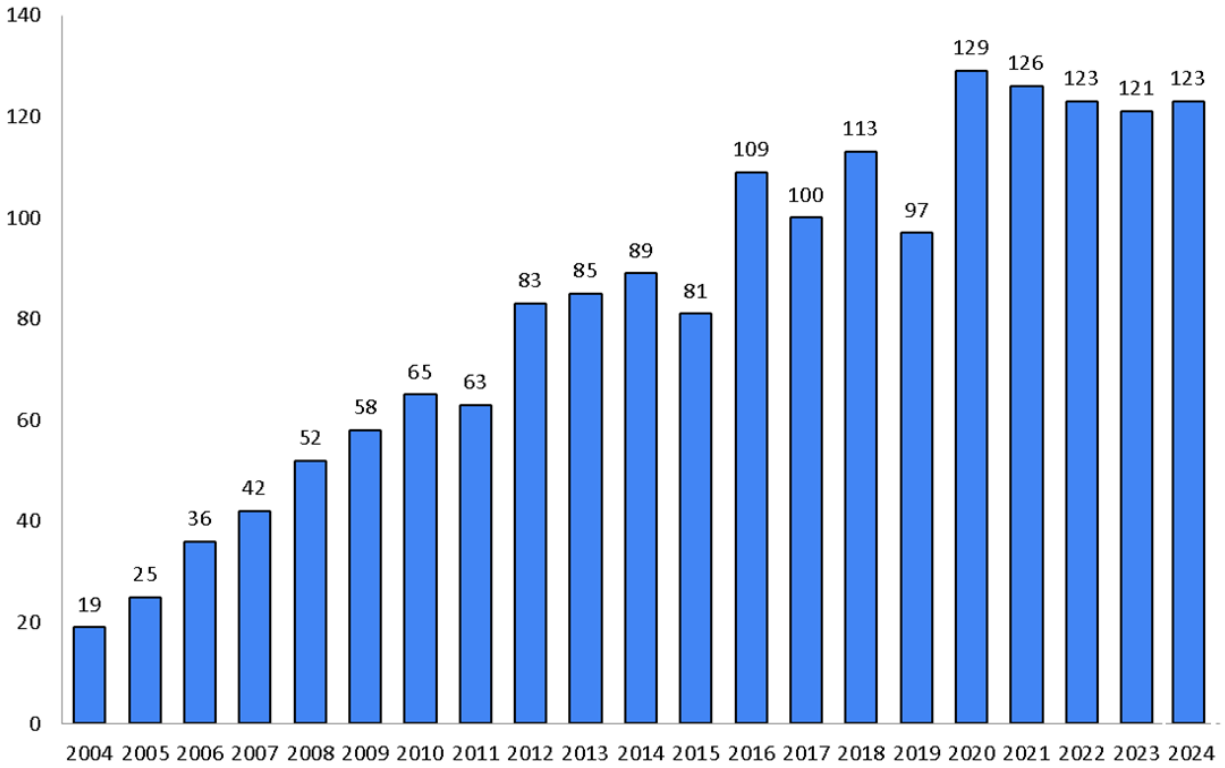
The 105th AMS Annual Meeting will take place from 12 to 16 January 2025 in New Orleans, Louisiana.

CRTM: the critical enabling component

- Satellite radiance **Data Assimilations (DA)** for NWP (e.g. UFS, GFS, RRFS, UPP; GSI, JEDI/UFO)
- **Physical retrievals** of atmospheric and surface state variables (e.g. MIRS, GOES soundings)
- Radiometric data impact assessment in Observing System **Simulation** Experiments (OSSEs)
- Radiometric instrument design, **calibration** and monitoring (e.g. ICVS,MICROS,GSI)
- **Reanalysis** and climate studies (e.g. NOAA CFSR, MERRA, etc.)
- **SmallSat/CubeSat** mission (e.g. TROPICS)
- **Air-quality** monitoring and forecast (e.g. NCAR/AF, NOAA/OAR)
- Scientific **research and education**



CRTM's Role in The Science Community



CRTM Provides the critical link between satellite radiances and physical properties of the atmosphere:

Satellite Data Assimilation -> Analysis, Forecasting
Calibration / Validation
Satellite Simulations
Reanalysis
Real-time Weather Analysis / Support
Satellite Sensor Health Monitoring
Field Experiment Support
Education and Outreach

Representation at WIGOS, GCOS, CGMS, GEWEX, ITWG/ITSC, ICWG, IPWG, LSWG, IWSSM



CRTM – A fast and accurate RT model for satellite radiance simulation and assimilation

Input:
Pressure,
Temperature,
Absorber,
Hydrometeor,
Aerosol,
Surface properties

- Scattering (Cloud, Aerosol, Molecule)
- Gas Absorption
- Surface Emission, Reflection

- Radiative Transfer Solver (ADA)
- Radar simulator
- Aerosol OD calculator

Output:
Forward sensor radiance,
Jacobians/Adjoint/Tangent-linear,
Space radar reflectivity factor,
Aerosol optical depth
Derived surface reflectance and emissivity.

Applications:

Satellite radiance assimilation,
Physical retrieval,
Sensor monitoring,
Cal/Val,
Climate reanalysis



CRTM Development Evolution

Algorithm for UV, VIS, IR, and MW sensors

OPTRAN (H_2O, O_3) -> +Jacobian-K-matrix -> +MW and IR surface emissivity -> + ADA solver for multiple scatterings -> + Clouds -> + Aerosols -> + non-LTE -> + Zeeman-splitting -> + SSU CO_2 cell -> + Hyperspectral simulation(FTS, grating), fully polarized solver, function for deriving surface reflectance

Sensors

Passive microwave, infrared, visible, and ultraviolet sensors, hyperspectral infrared sensors, active sensors

Models

CRTM, CRTM_AOD, CRTM_ActiveSensor

McMillin and Fleming H E, 1976, Liu and Cao, 2019, Johnson et al., 2023

Main features of CRTM

Scattering	**Clouds**: 6 hydrometeor types (water cloud, ice cloud, rain, snow, graupel and hail); Gamma size distribution for small particles, Marshal-Palmer for rain, snow graupel/hail; Mie scattering for MW and water cloud in IR; Nonspherical shape for IR ice cloud; 5 Overlap assumptions (maximum, random, maximum-random, average, overcast). Jacobians for cloud water content and effective radius. **Aerosol**: CRTM, CMAQ, GOCART-GEOS5, NAAPS. **Molecular scattering**.
Gas absorption	Channel-based regression look-up-table; ODPS(Optical Depth in Pressure Space); ODAS(Optical Depth in Absorber Space); Variable H2O, CO2, O3 for broadband sensors, additional N2O, CO and CH4 for hyper-spectral IR sensors. Water vapor continuum treated separately; non-LTE correction for CO2 4.3um band; Zeeman-splitting correction; Training package based on LBLRTM/CLBLM, Rosenkranz, Liebe and MonoRTM; Line parameters using HITRAN database with AER amendments.
Radiative Transfer	Fully polarized Advanced Doubling-Adding (ADA); Successive Order of Interaction (SOI); viewing angle in stream;
Spectral range / Sensors	MW, IR, VIS, and UV; Passive microwave, infrared, visible, and ultraviolet sensors, hyperspectral infrared sensors, active sensors



New development for CRTM

- Polarized radiative transfer(RT) solver. Full Stokes calculation for visible and UV sensors.
- Analytical surface reflectance calculation
- Upgraded IR emissivity model for snow covered surfaces
- Active Radar Support: Support for GPM DPR and CloudSat CPR radar reflectivity, and path integrated attenuation.
- Upgraded Non-LTE, Aerosol model.
- New sensors (ABI-G19, ATMS-N21, FCI-MTG, IRS-MTG-S1, GXI-GeoXO, GXS-GeoXO, MWS-MetOp-SG-A1, OMPS-NPP, N20, N21, VIIRS-J2, DPR-GPM, CPR-CloudSat, …)
- Software Engineering Updates of CRTM
  - CRTM Performance Optimizations with OpenMP threading over profiles and channels
  - Platform independent netCDF format coefficient files (ongoing)
  - CMake build sytem
  - Open source on GitHub (https://github.com/JCSDA/CRTMv3)



Absorbers used for hyperspectral sensors

Gas absorption is computed as sum of various gas components. Regression coefficients are trained for each component. For hyperspectral sensor, 8 components (6 variable gases) are computed: **fix,wco,wlo,ozo,co2,n2o,co,ch4**

Where:

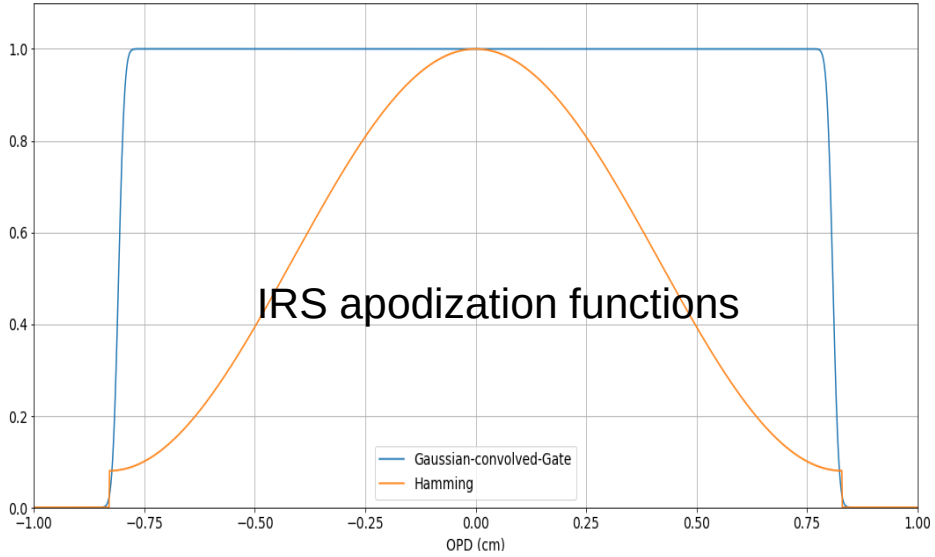
"fix" is O2 plus HITRAN gases other than H2O, O3, CO2, N2O, CO and CH4. "wco" and "wlo" are water vapor continuum and lines, respectively.

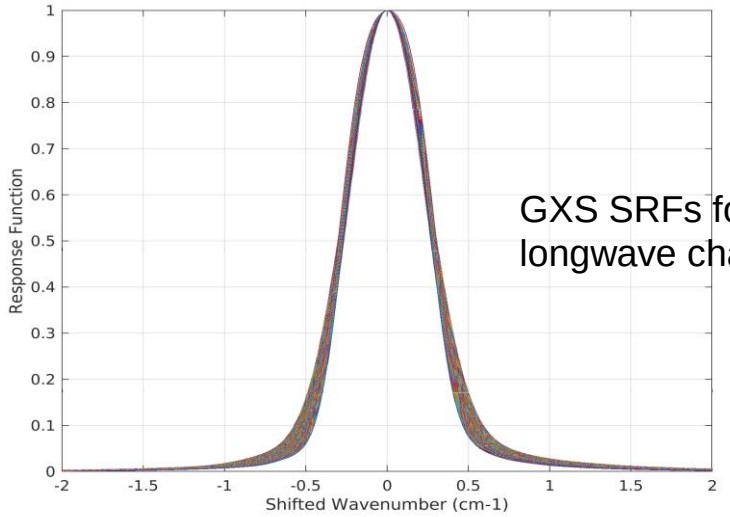
Those in red means the component transmittances are effective transmittance and computed as a ratio between total/(total-gas). For example, the O3 transmittance τ^{O3} is computed as

$$\tau^{O3} = \frac{\tau^{fix+CH4+CO+N2O+CO2+WLO+\boldsymbol{O3}}}{\tau^{fix+CH4+CO+N2O+CO2+WLO}}$$

CRTM simulation of GXS and IRS

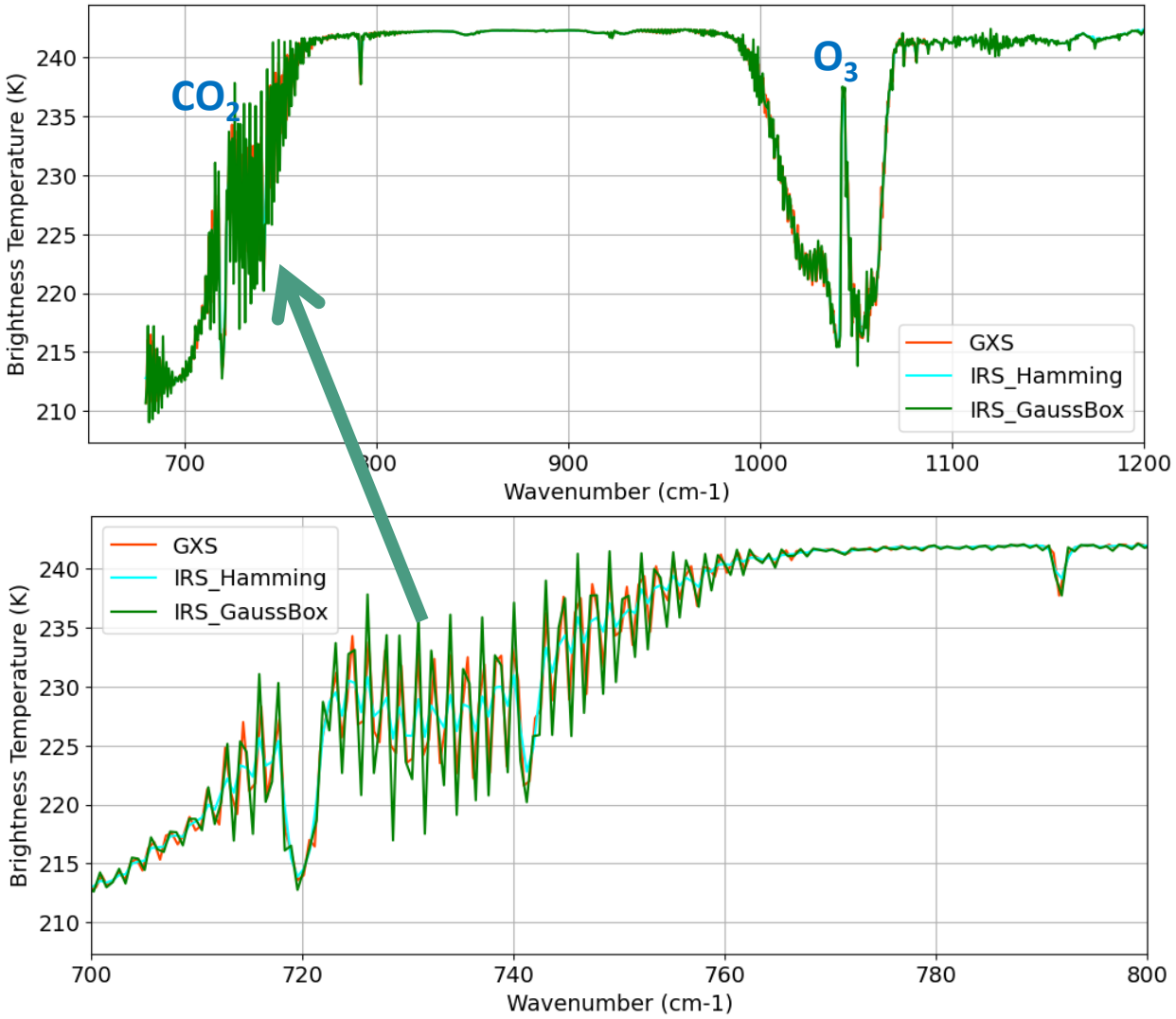
	GeoXO-GXS	MTG-IRS
Type	Grating Spectrometer	Fourier Transform Spectrometer
LW	670-1100 cm-1 (9.13-14.7 µm, WMO website) FWHM: 0.5357 ~ 0.6085 (cm-1) Num channels: 1096	680 to 1210 cm-1 Sampling rate: 0.6037 cm-1 Num channels: 881
MW	1700-2250 cm-1 (4.44-5.92 µm, WMO website) FWHM: 0.5108 ~ 0.6068 (cm-1) Num channels: 1306	1600 to 2250 cm-1 Sampling rate: 0.6031 cm-1 Num channels: 1079
Full disc coverage	60 minutes for Sounding Disk	60 minutes
Spatial resolution	4 km at subpoint	4 km
Launch schedule	2035	2024
applications	Profiles of temperature, water vapor, cloud water, atmospheric wind, ozone, ammonia, nitrous oxide, and carbon monoxide. https://www.nesdis.noaa.gov/our-satellites/future-programs/geoxo/geoxo-sounder-gxs	Atmospheric temperature Height of the top of PBL Height of the tropopause Integrated Water Vapour (IWV) Specific humidity Temperature of the tropopause Wind (horizontal), trace gases. https://www.eumetsat.int/mtg-infrared-sounder

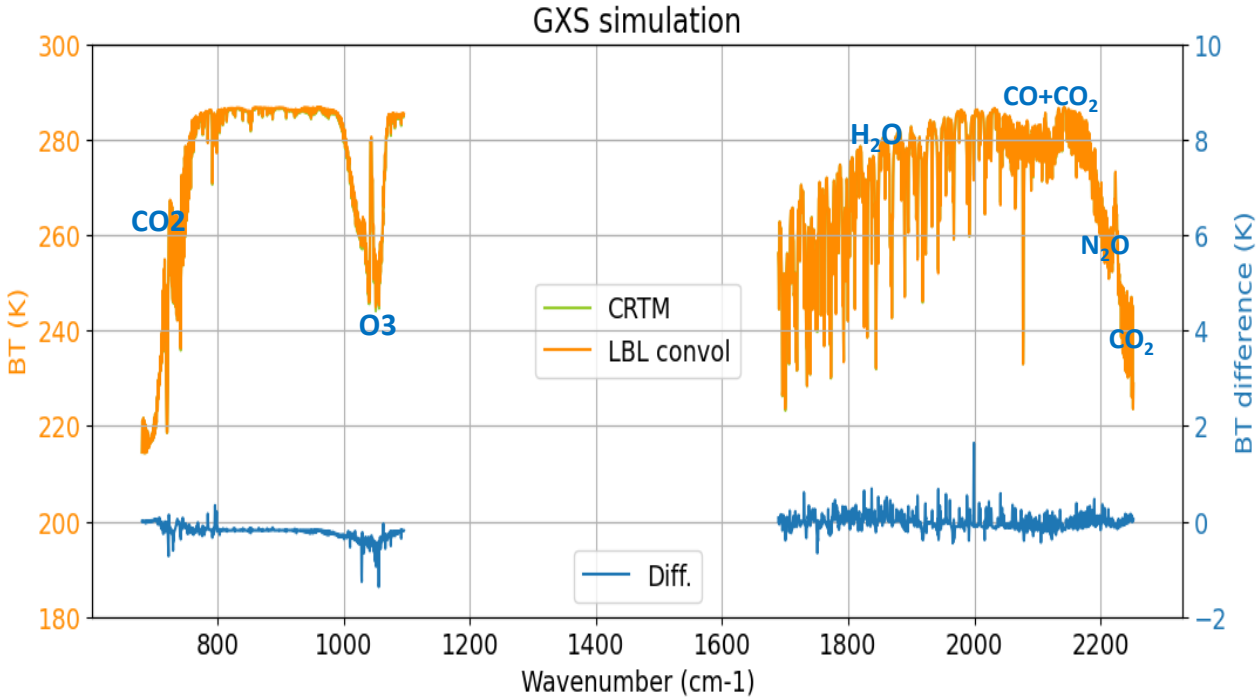




GXS SRFs for 1096 longwave channels.

CRTM simulation of GXS and IRS



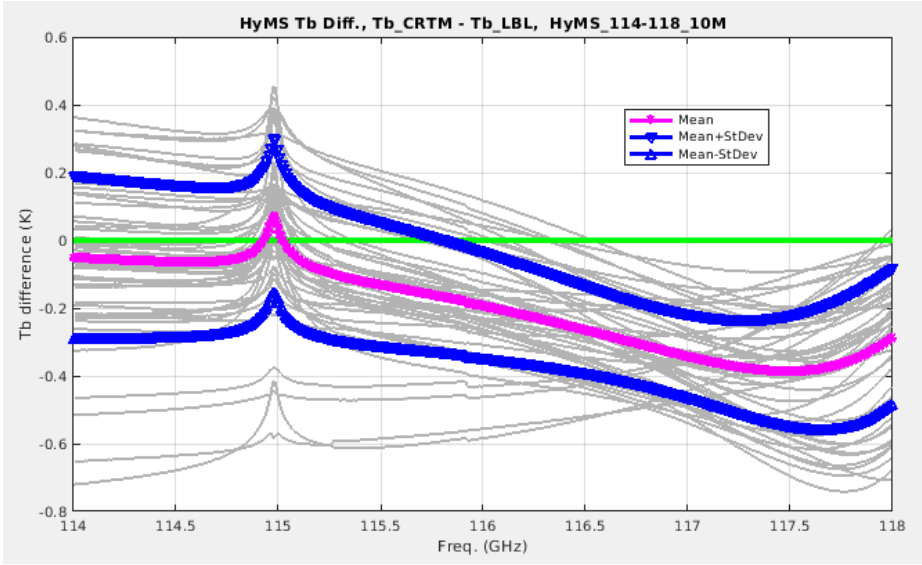


Left: Overlap of CRTM simulations for IRS and GXS longwave bands. Right: GXS simulation and difference between CRTM and convolved LBL brightness temperature (BT).

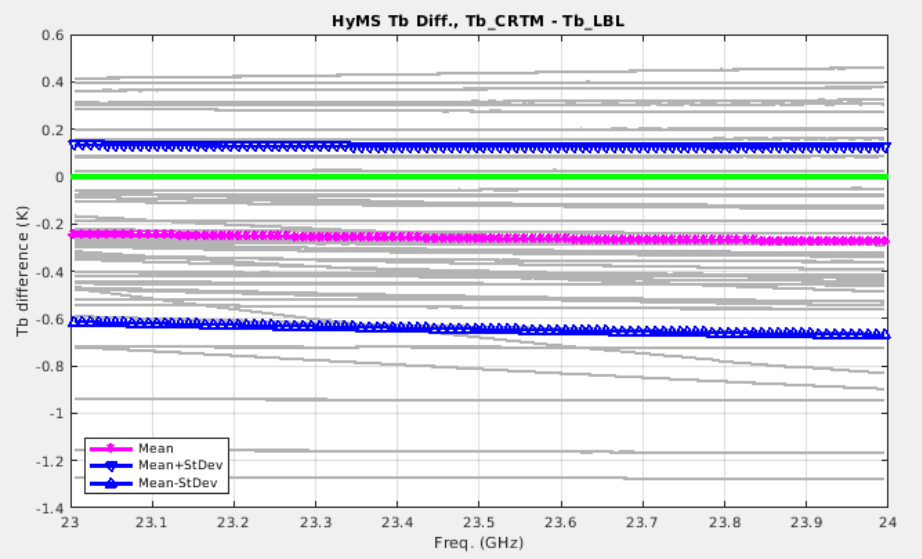
Hyperspectral Microwave Sensor Simulation

Range (GHz)	Interval width (GHz)	Resolution (MHz)	Num. of channels
52-57.5	5.5	1	5500
23-24	1	10	100
114-118	4	10	400
173-183.31	10.31	10	1031
1-23	22	100	220
24-52	26	100	260
57.5-114	56.5	100	565
183.31-330	146.69	100	1466

CRTM coefficients were created for hyperspectral microwave channels with various spectral resolutions in different bands.



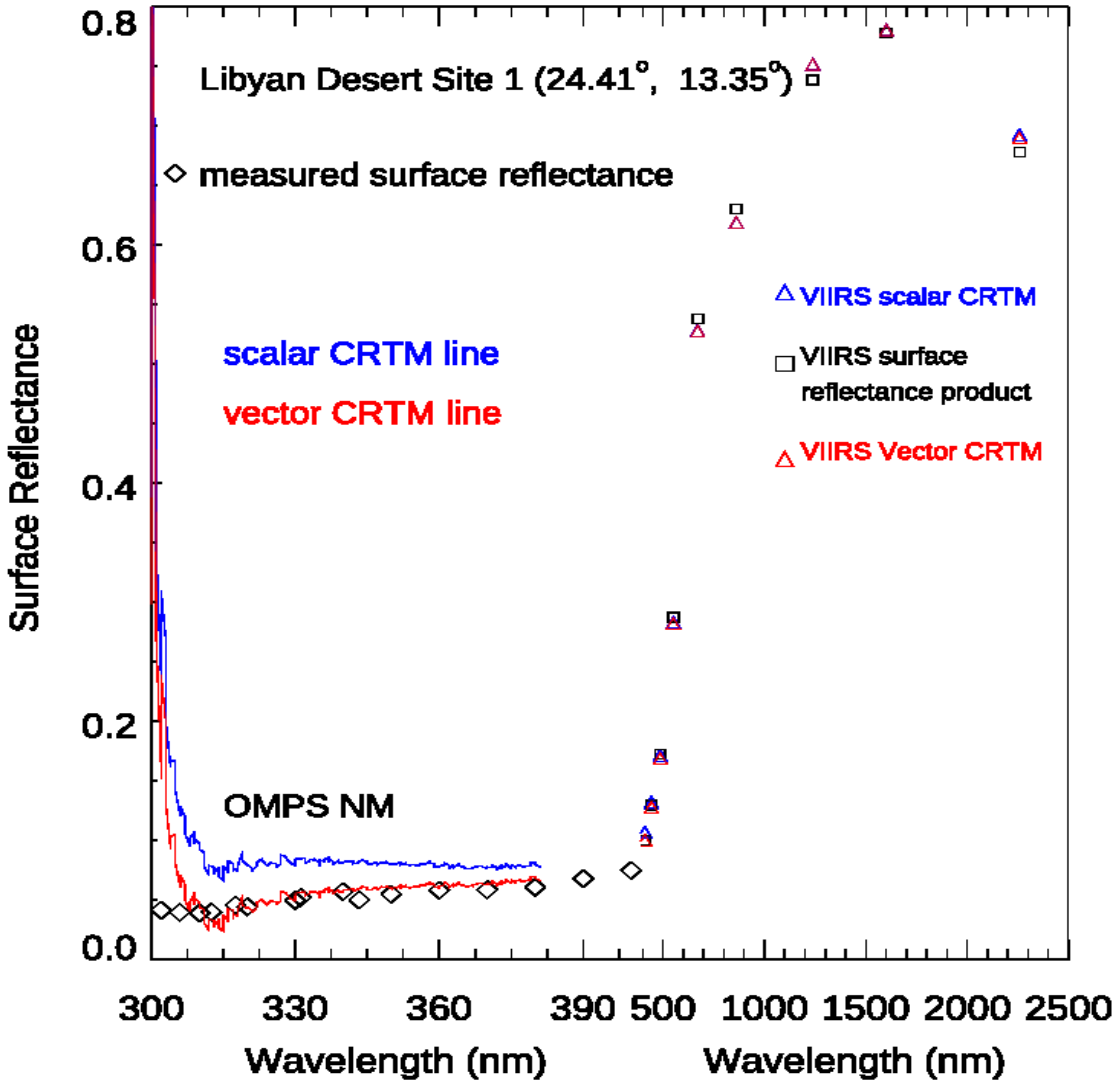
BT diff for 114-118GHz, 10M. Trained with Rosenkranz03.



BT diff for 23-24GHz, 10M. Trained with Rosenkranz03. Validated with the UMBC48 profiles.

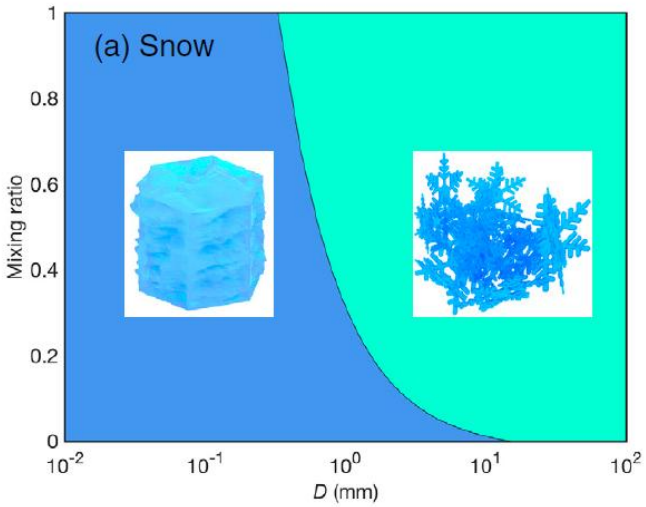
Full polarized RT solver for CRTM 3.0

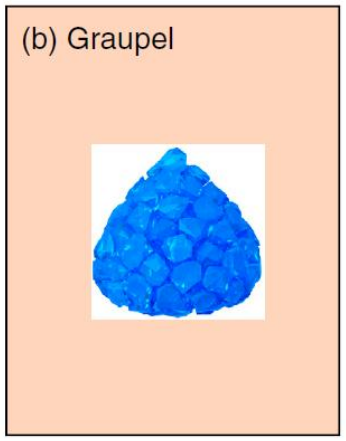
- To fully utilize the polarization information from atmosphere and to exploit the capability of the new sensors, the CRTM is extended to full Stokes calculation for visible and UV sensors
- Figure shows the comparison between the measured and retrieved surface UV reflectance. The blue line is the retrieved surface reflectance from OMPS NM radiance over Libyan desert site 1. For SNPP VIIRS channels, the retrieved and VIIRS product surface reflectance are compared.



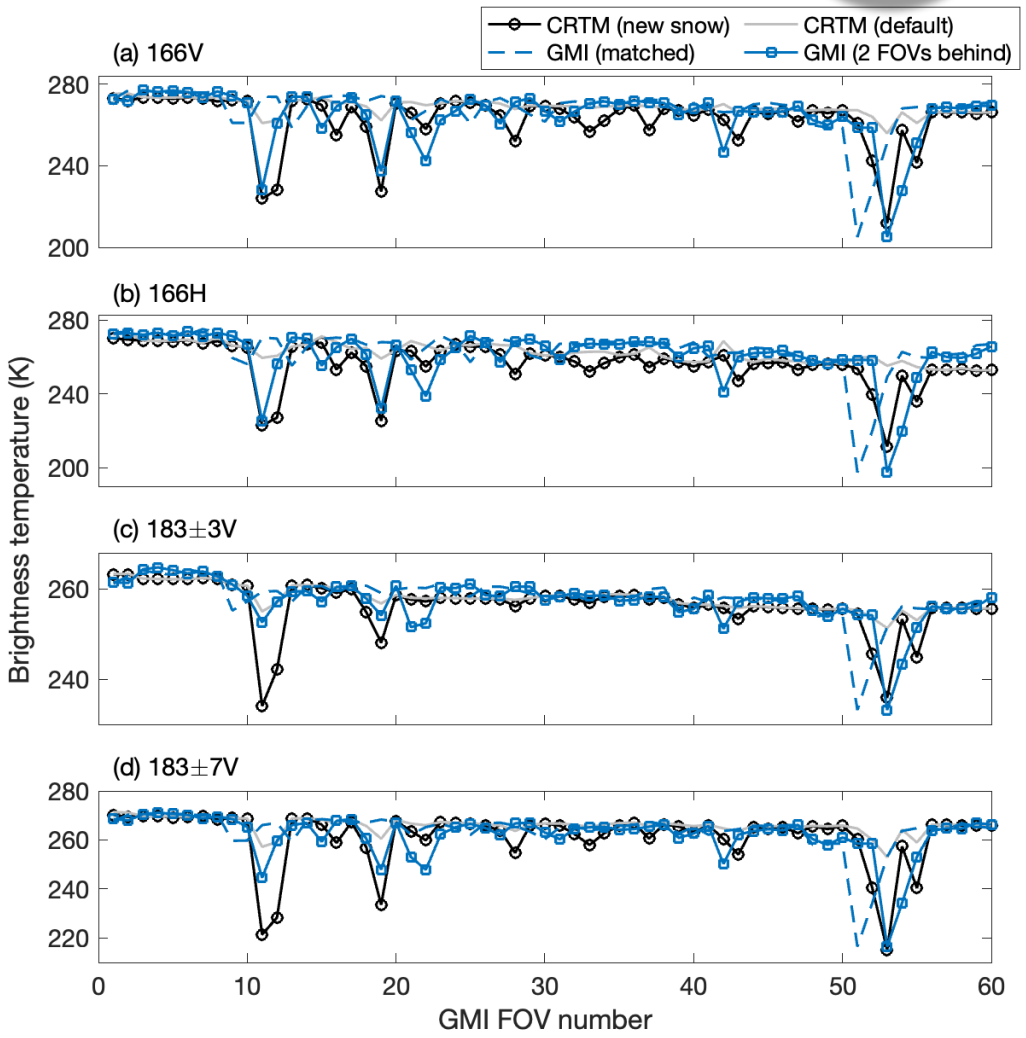
--- Courtesy of Quanhua Liu @ NOAA/STAR

New precipitation scattering (TAMU/STAR) [T. Ren et al, 2022]





The new cloud scattering LUT upgrade the current table with non-spherical particle shape for graupel and snow over UV/VIS/IR/MW spectral ranges; temperature dependence of ice refractive index for MW frequencies; extended spectral range and particle size range; and support for full polarized phase matrix. PSDs follows Thompson et al. 2004 and 2008.



Radar reflectivity and backscattering coeff.

Radar reflectivity is highly correlated with the hydrometeor scattering property. Values above about 45 dBZ signify intense precipitation nearly always caused by thunderstorms. Volumetric equivalent (effective) reflectivity factor *Ze* and volumetric back scattering coefficient β_π for a cloud at height *h* above the surface can be written as

$$Z_e(h) = \frac{\lambda^4}{\pi^5}\frac{\beta_\pi}{|K_w|^2}$$

Satellite measure the "attenuated" reflectivity factor: $Z_{attenuated(h)} = Z_e(h)T(h)^2$

Z_e -- Effective reflectivity factor
β_π -- Backscattering Coeff.
$n(D)$ -- Particle Size Distribution
$\sigma_\pi(D)$ -- Particle backscattering cross section
m_w -- Water refractive index
$T(h)$ – Transmittance between *h* and satellite

$$\beta_\pi = \int_0^\infty n(D)\sigma_\pi(D)dD$$

$$K_w = \left|\frac{m_w^2 - 1}{m_w^2 + 2}\right|$$



CRTM Aerosol Schemes

The CRTM team has improved the user interface
by incorporating various aerosol parameters widely used in aerosol modeling over the past few years

CRTM Version	Aerosol model	Aerosol species	Aerosol properties	References
All versions	CRTM (Default)	dust, sea salt, organic carbon, black carbon, sulfate	**effective radius**, **hygroscopicity (implicit)**	Chin et al., 2002; Han, 2006
v2.4 – v3.1 NetCDF	CMAQ	dust, sea salt, water-soluble, soot, sulfate, water, insoluble, dust-like	effective radius, hygroscopicity (implicit), **radius standard deviation**	Binkowski and Roselle, 2003; Liu and Lu 2016
v2.4.1 – v3.1	GOCART -GEOS5	dust, sea salt, organic carbon, black carbon, sulfate, nitrate	effective radius, **hygroscopicity.** Lognormal size distribution, Spherical or Spheroid shapes.	Colarco et al., 2010
v2.4.1 – v3.1	NAAPS	Bulk aerosol properties: dust, sea salt, smoke, anthropogenic and biogenic fine particles	hygroscopicity	Lynch et al., 2016
v2.4.1 – v3.1	RTTOV-OPAC RTTOV-CAMS (Internal)	dust, sea salt, organic carbon, black carbon, sulfate, nitrate CAMS: aerosol climatology developed by Copernicus Atmosphere Monitoring Service	effective radius, hygroscopicity	RTTOV v13, https://nwp-saf.eumetsat.int/site/software/rttov/rttov-v13/

Future

- Motivation for **AI based CRTM**,
  - Increasing satellite radiance observations (JPSS, GeoXO, Metop-SG, Small/Cube SATs, Hyperspectral sensors (IR and MW, IASI 16,000+ channels)
  - Toward all-sky radiance assimilations (Polarization, Scatterings)
  - Increasing resolution in numerical prediction model
  - AI-based RTM has advantages (Able to approximate any continuous functions, Fast, Easy coding …)
- Principal Component Analysis **(PCA) based CRTM** for hyperspectral sensors
- Improvements to the CRTM **transmittance model**.
- Updates to all **surface emissivity** models
- Improvements to interface enable generic **optical properties** inputs
- **Active sensor** (Radar, Lidar)


THANK YOU
SO MUCH