Development of A Unified Aerosol Retrieval System for Past, Current, and Future Satellite Imagers

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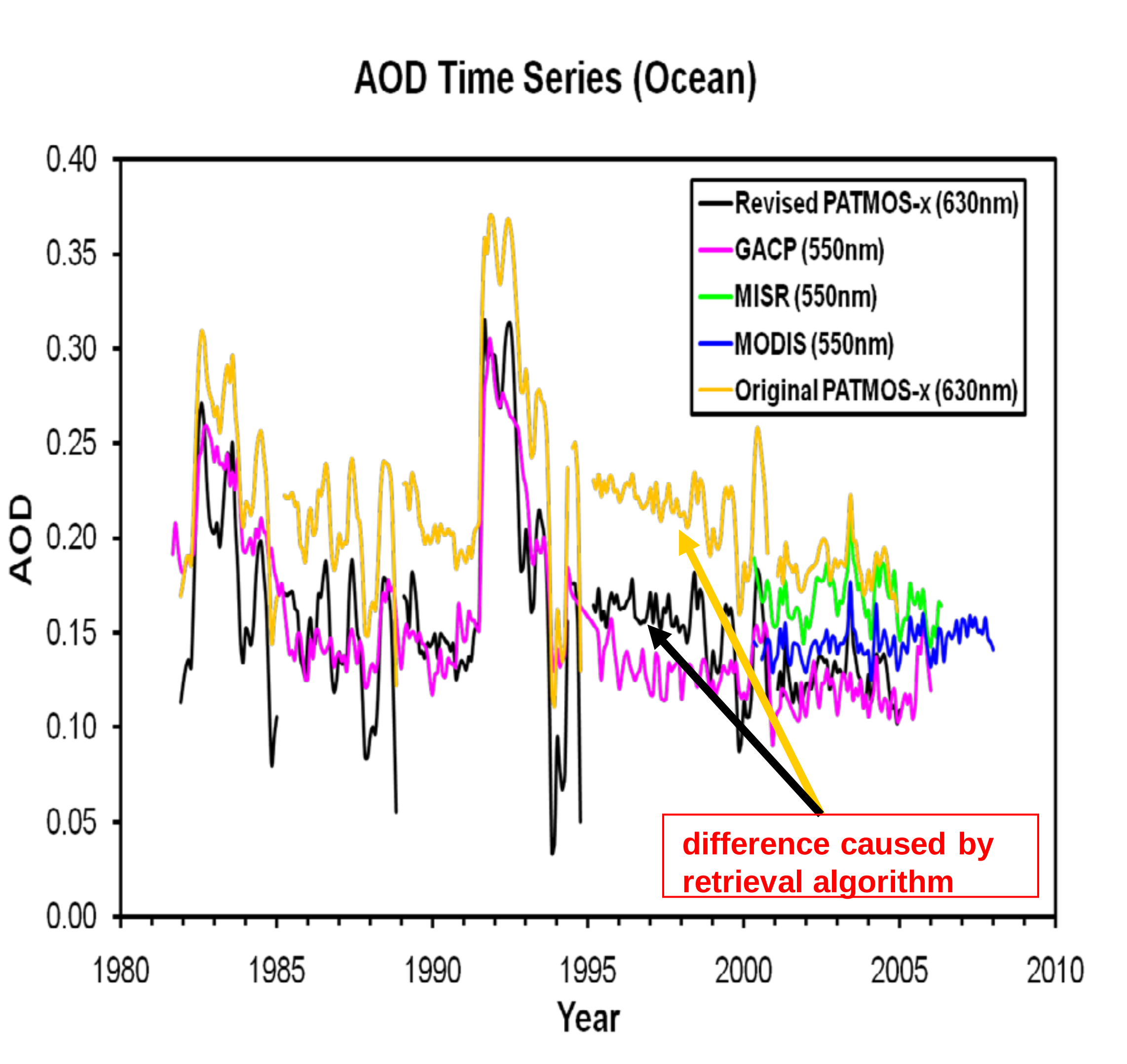
Outline

- Motivation & Objective
- Retrieval Descriptions
  - Aerosol optical thickness (AOT)
  - Aerosol particle size parameter (APSP)
  - Suspended matters (SM)
- Summary of AOT/APSP/SM Retrieval Strategy
- Unified Aerosol Retrieval System
  - Flow chart and data flow
  - Specific design and efficiency consideration
- Retrieval Examples
- Summary and Conclusions
- Future Refinement and Enhancement
- Acknowledgement

Motivation

- NCDC leads the NOAA's Climate Data Records (CDRs) Program in support of climate change studies.
- Aerosol has been identified as an important CDR due to its effect on cloud, earth radiation budget, and surface CDRs.
- We need to develop long-term consistent global aerosol CDR data from past, current, and future satellite observations to ascertain the impact of global anthropogenic emissions on global climate and support the CDR Program.
- First, consistent calibration of sensors on different satellite platforms needs to be achieved, which has been actively performed recently by inter-satellite calibration.
- Then, retrieval algorithms with consistent aerosol model assumptions and surface treatments needs to be applied, which hasn't be tacked effectively.

Example of Impact of Algorithm Difference on AOD Time Series



Evolution History of NOAA/NESDIS AVHRR Aerosol Retrieval Algorithm

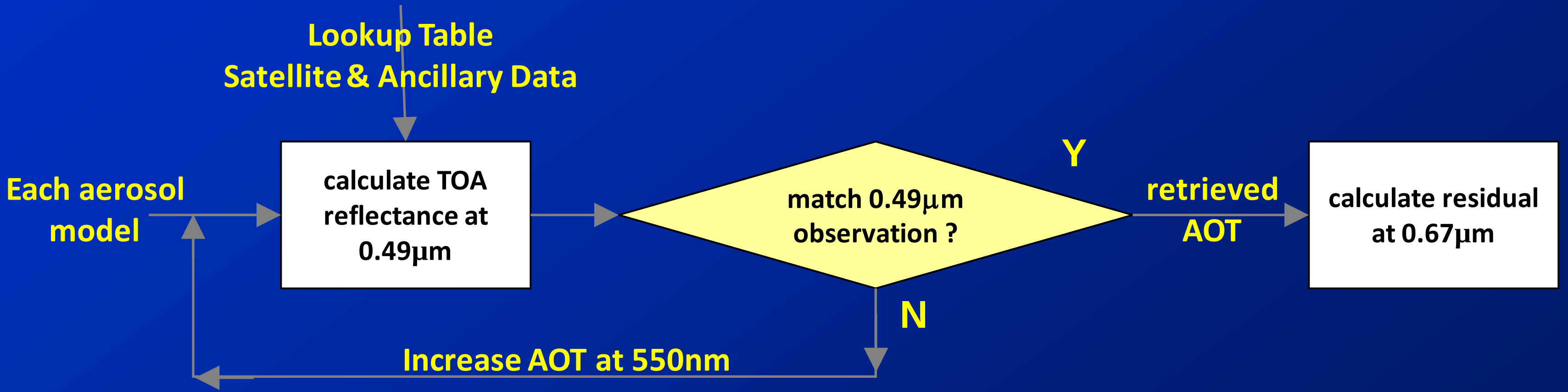
Algorithm (Ocean)	AOD Products	Description
one channel [Stowe et al., 1997]	τ_1 (0.63μm) (PATMOS)	One-mode lognormal size distribution; no absorption; lambertian surface with diffuse glint correction.
independent two channels (yellow line) [Ignatov & Stowe, 2002] (CERES used currently)	τ_1 (0.63μm) τ_2 (0.83μm) (Original PATMOS-x)	Ono-mode lognormal size distribution; no absorption; ocean surface BRDF (V=1m/s); tuned to match the one-channel retrieval.
revised independent two channels (black line) [Zhao et al., 2004]	τ_1 (0.63μm) τ_2 (0.83μm) (Revised PATMOS-x)	Bi-mode lognormal size distribution; weak absorption; ocean surface BRDF (V=6m/s); adjusted according to the AERONET validation.

Objective

- Develop an unified aerosol retrieval system that can be applied to radiometric imagers onboard past, current, and future polar-orbit or geo-stationary satellites to produce consistent global long-term aerosol products suitable for climate change studies.
  - physical retrieval of aerosol optical thickness/depth (AOT/AOD), aerosol particle size parameter (APSP -- Angstrom exponent), and suspended matter (SM) types (volcanic ash, dust, smoke, and sea salt)
  - modular in design to support evolution enhancements
  - simple to implement and efficient/robust for operational use
  - flexible for adapting to different satellite radiometric imagers (such as AVHRR, SeaWiFS, MODIS, JPSS/VIIRS, GOES-R/ABI, SEVIRI, MSI, FY-3 & 4, etc.) to produce consistent long-term global aerosol data product.

Description AOT Retrieval over Land

- AOT at SIR (e.g., 2.2µm) channel is generally small so that TOA SIR reflectance can be well approximated as its surface reflectance for clear-sky condition.
- Over dark or vegetated land surface, surface reflectance in SIR channel is linearly correlated with that in red (0.67µm) or blue (0.49µm) channel (Kaufman et al., 1997).
- Retrieve AOT for each of the 8 aerosol models by matching the observed TOA reflectance in blue (0.49µm) channel and calculate the corresponding residuals in red (0.67µm) channel.



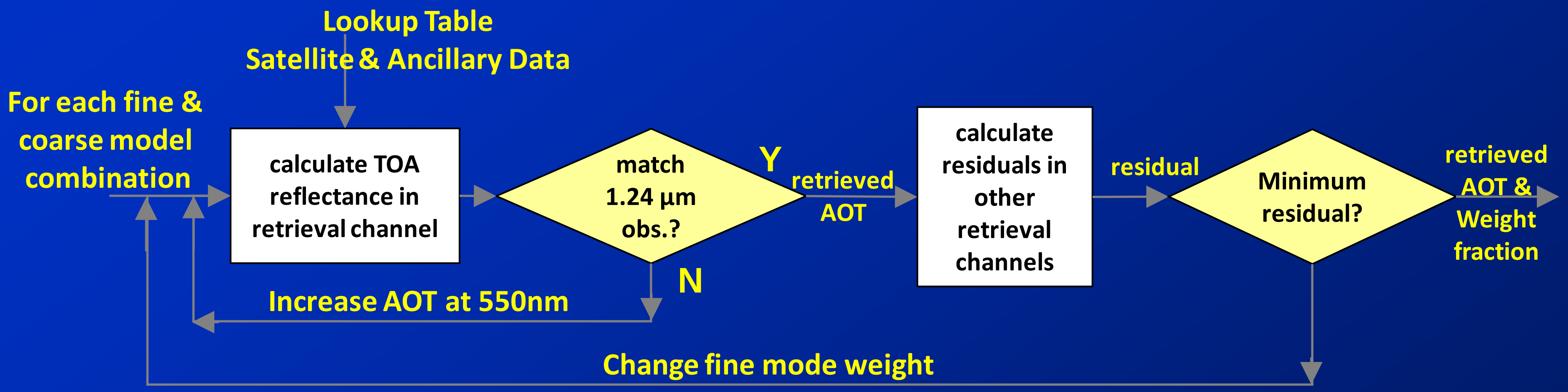
where residual is calculated as: $$residual = (\rho_{0.67\,\mu m}^{cal} - \rho_{0.67\,\mu m}^{obs})^2$$

- Select the aerosol model and AOT with the minimum residual in red (0.67µm) channel as the “best” solution

Description of AOT Retrieval over Ocean

- Assume TOA reflectance can be approximated by a linear combination of contributions from two aerosol modes corresponding to the fine and coarse parts of size distribution with a fine-mode weight (Gordon & Wang, 1994)

- Retrieve AOT and fine mode weight for each combination of candidate fine and coarse aerosol models on the reference channel (1.24 or 0.87μm).



where residual is calculated as: $$residual = \sum_{i=1}^{5} (\rho_{\lambda}^{t} - \rho_{\lambda}^{obs})^2$$

- Select the AOT and combination of fine and coarse modes with minimum residual on the other retrieval channels as the "best" solution.

Derivation of Aerosol Particle Size Parameter (APSP)

(Ångström Exponent α)

- **The Ångström exponent (α) describes the wavelength (λ) dependence of aerosol optical thickness (τ):** $\tau \propto \lambda^{-\alpha}$
- **The Ångström exponent is calculated from AOTs at a pair of wavelengths:**

$$\alpha_{0.45/0.67} = -\frac{\ln \tau_{0.45} - \ln \tau_{0.67}}{\ln 0.45 - \ln 0.67}$$ **(Land)**

$$\alpha_{0.87/1.61} = -\frac{\ln \tau_{0.87} - \ln \tau_{1.61}}{\ln 0.87 - \ln 1.61}$$ **(Ocean)**

- **The Ångström exponent is used as proxy for particle size:**
  - **Large/small values of Ångström exponent indicate small/large particles, respectively.**

Determination of Suspended Matter (SM)

- Use the AOT and APSP in combination with the threshold tests of IR brightness temperature (BT) to classify SM globally at pixel level.

- Each type is flagged with an integer number with 1 for volcanic ash, 2 for dust, 3 for smoke, 4 for sea salt, and 5 for mixed.

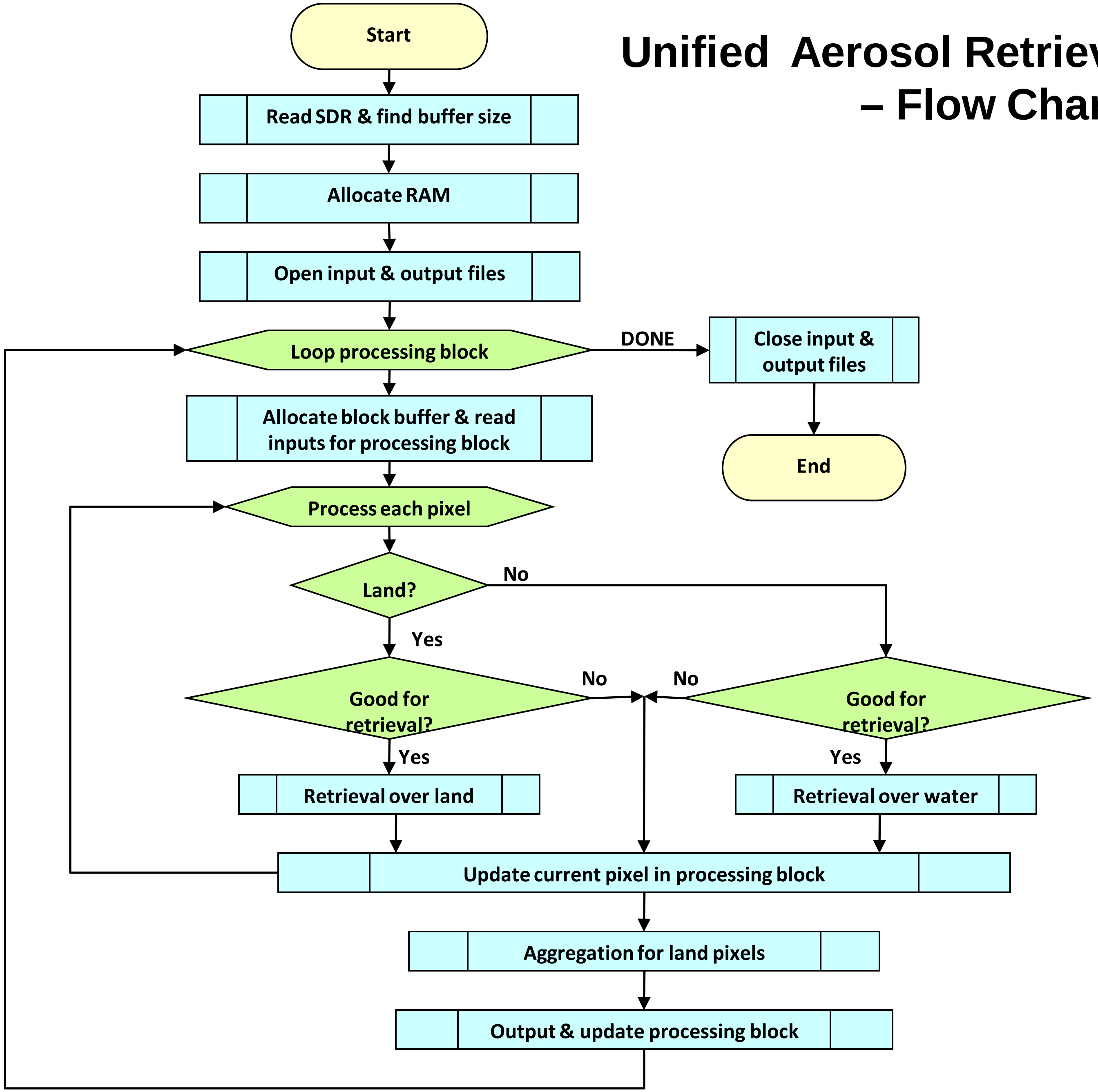
- More refinement and development are expected in the future.

- Volcanic Ash:
  - $BT_{12.01\mu m} - BT_{10.76\mu m} > 0$
- Dust:
  - $BT_{12.01} - BT_{10.76} > 0$ & $BT_{8.55} - BT_{10.76} > 0$ (C1)
  - continental or dust model (C2)
  - C1 & C2 true - dust; only C1 true - mixed
- Smoke:
  - APSP $\alpha > 1.5$ and $\tau_{0.55} > 0.5$ (C1)
  - smoke or urban aerosol model (C2)
  - C1 & C2 true - smoke; only C1 true - mixed
- Sea Salt :
  - $0 < \alpha$ (APSP) < 0.5 and $\tau_{0.55} < 0.25$ (C1)
  - maritime or oceanic aerosol model (C2)
  - C1 & C2 true – sea salt; only C1 true - mixed

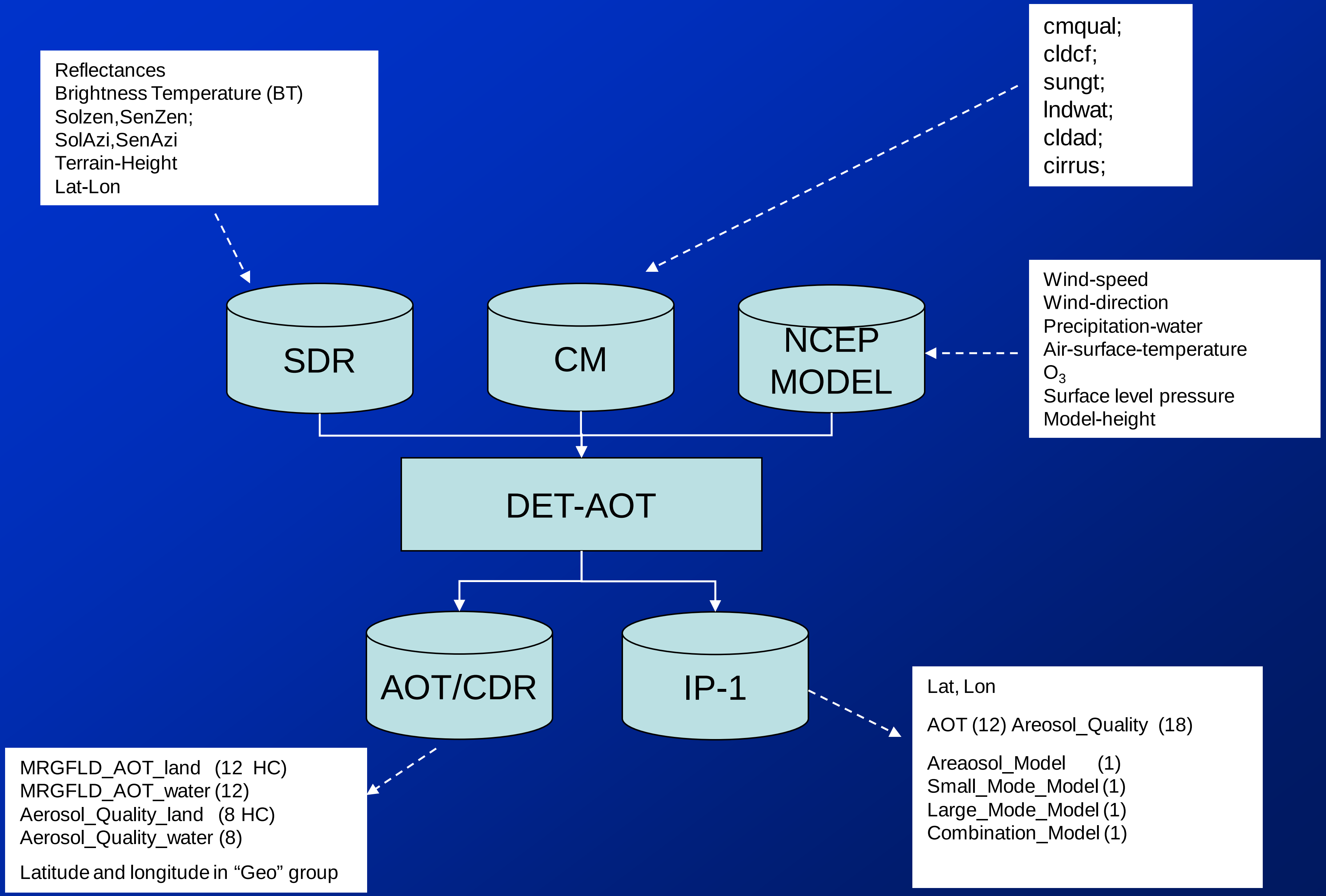
AOT/APSP/SM Retrieval Strategy

- AOT/APSP/SM retrieval
  - uses cloud mask for selecting only "clear" and "probably clear" pixels
  - performed for daytime only
- Radiative transfer
  - Look-up table (LUT) approach
    - Atmospheric LUT for land and ocean, respectively
    - LUT for ocean surface sunglint BRDF calculation
  - Atmospheric absorption
    - Uses parameterization of gaseous absorption for instrument channels
  - Surface reflectance
    - Land: Lambertian – dark target approach
    - Ocean: Lambertian (water leaving + whitecap) + BRDF (sunglint)
- Separate algorithms for land and ocean
- Determines "best" solution of AOT and aerosol model by matching calculated TOA reflectance with observed values in multiple channels

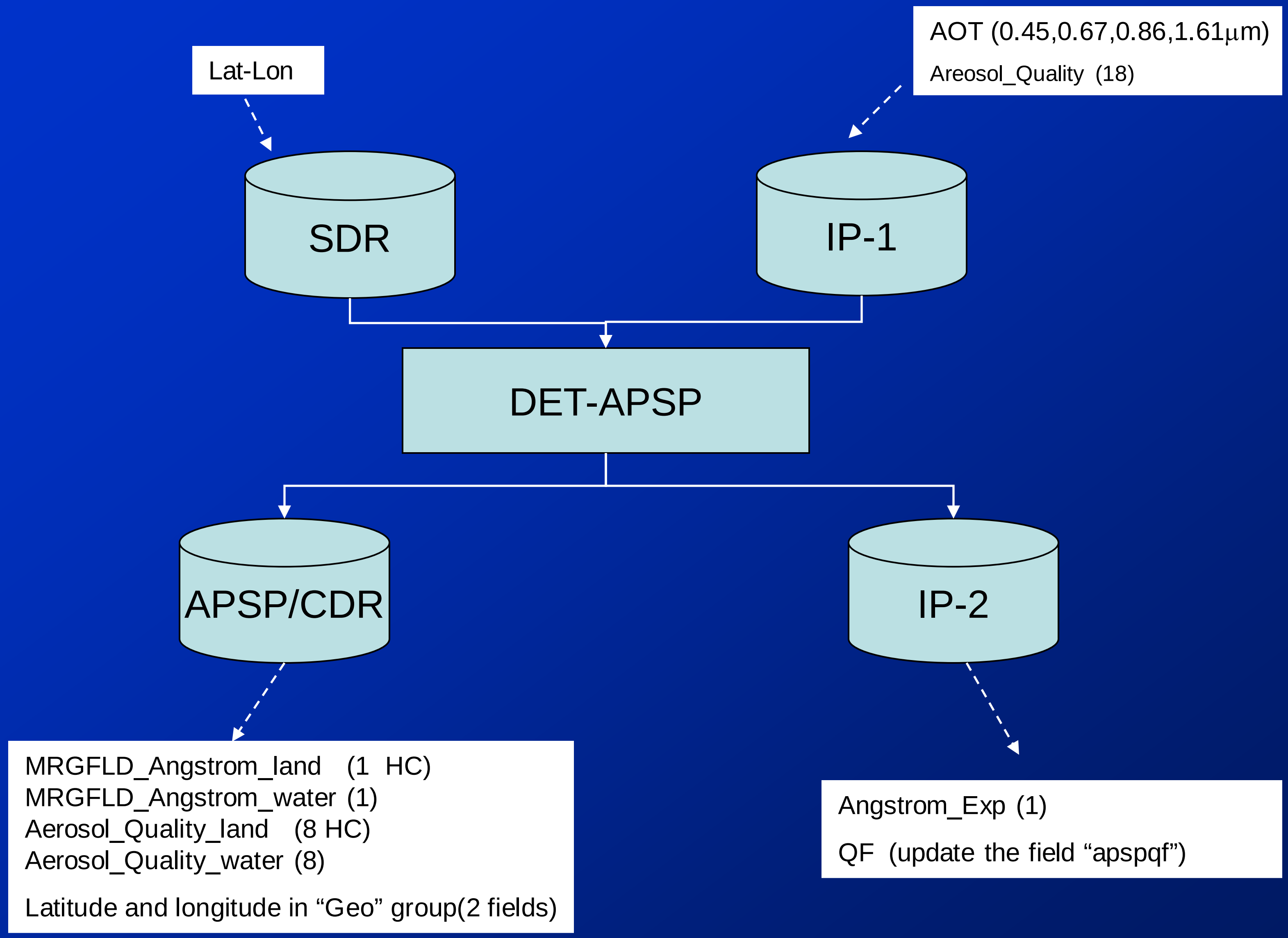
Unified Aerosol Retrieval System – Flow Chart



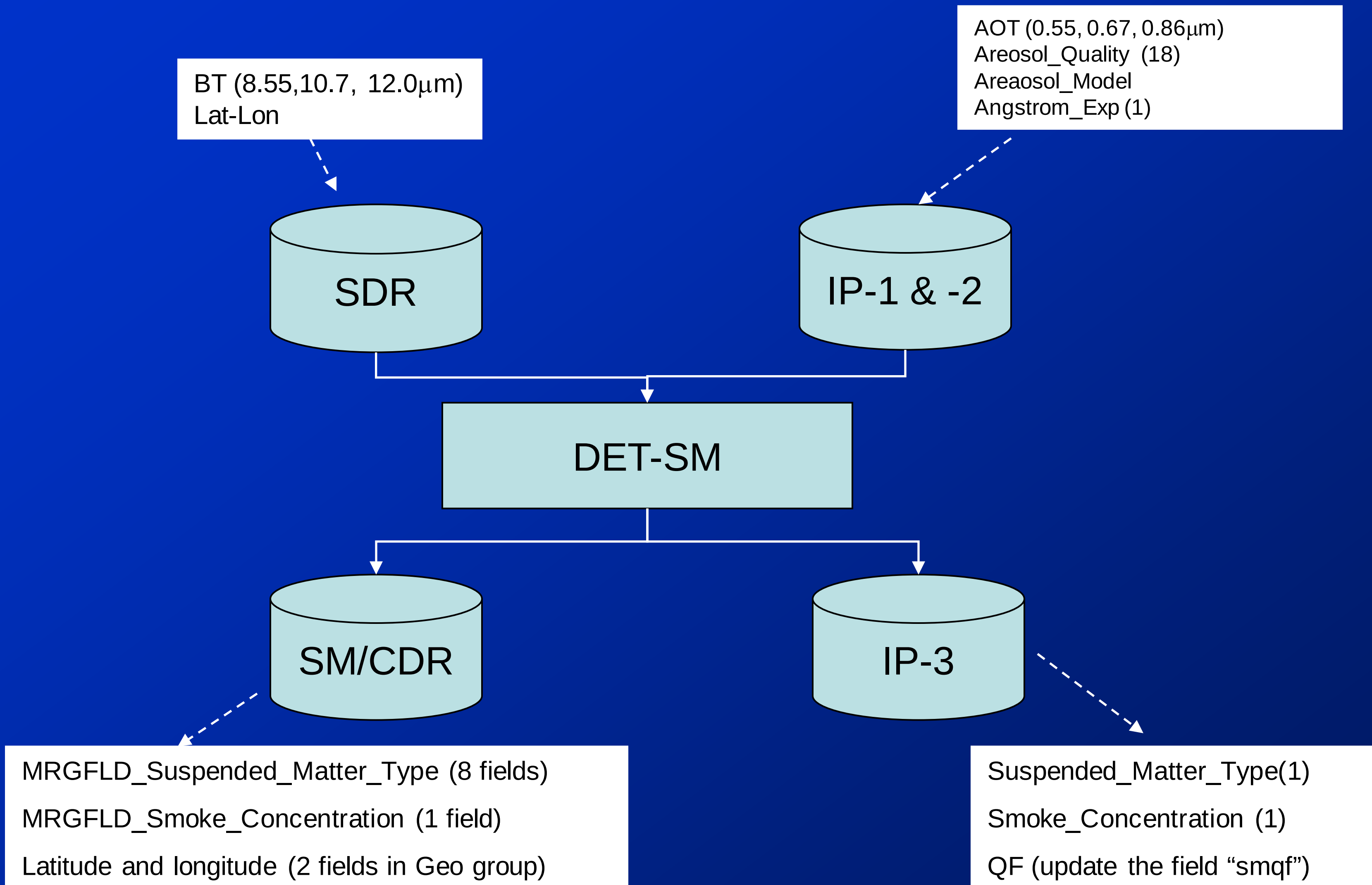
Data Flow for AOT Retrieval Unit



Data Flow for APSP Retrieval Unit



Data Flow for SM Unit



Specific Design and Efficiency Consideration

- **Specific Design**
  - Use object oriented language (C++) to built the general structure. This modular design enhance the independence and re-usability of code as well as facilitate the incorporation of any new update and future enhancement.
  - Options for process AOT for a few selected pixels or for a specific sensor through switch parameters initialized in the configure file.
  - The order of paths for input data in configure file is flexible. Efficient RAM allocation (150MB). Portable on multiple computer platforms (Linux, Unix, and Windows).
- **Efficiency Consideration**
  - Identify the expensive functions (e.g., ExtractAerosolLutData). Split them into 3 parts: 1) calculate variables independent on any pixels (do once for the whole swath when constructing the object of the class); 2) calculate variables depend on pixel's geometry position (do once only for a pixel); 3) search LUT for specific band and model ID (do many times for a pixel).
  - Pay attention to the expensive statements such as those contain function call like exp(), log(), pow() and sqrt() and avoid repeatedly calculate the variables calling these functions.
  - Using efficient LUT design (using scattering angle) and fast searching approach (e.g., limit minimum or bisection method).

Examples of Retrieval Results

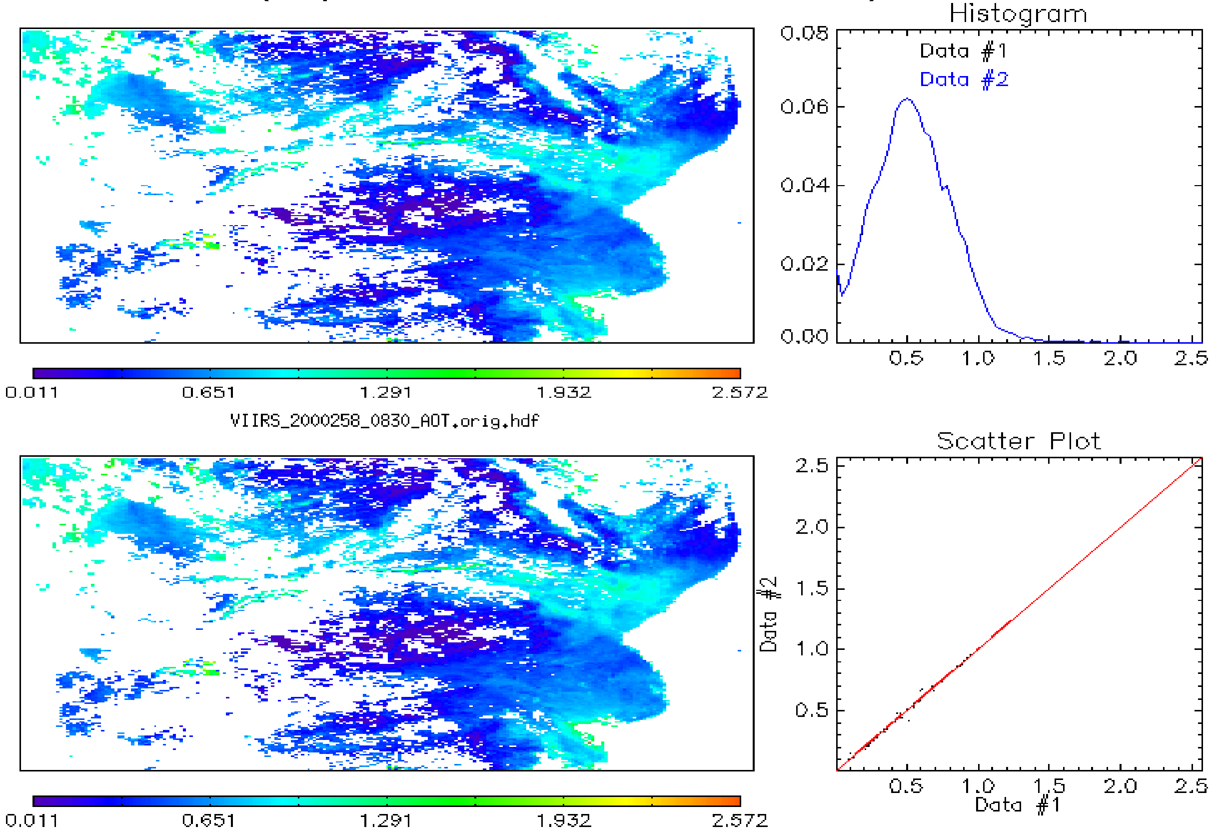
(Comparison of Our VIIRS-type AOT Retrieval

with NGST VIIRS AOT Retrieval Over Land)

(September 14, 2000; 08:30UTC)

VIIRS-type

NGST VIIRS



RAM: 150MB

RAM: 1.5GB

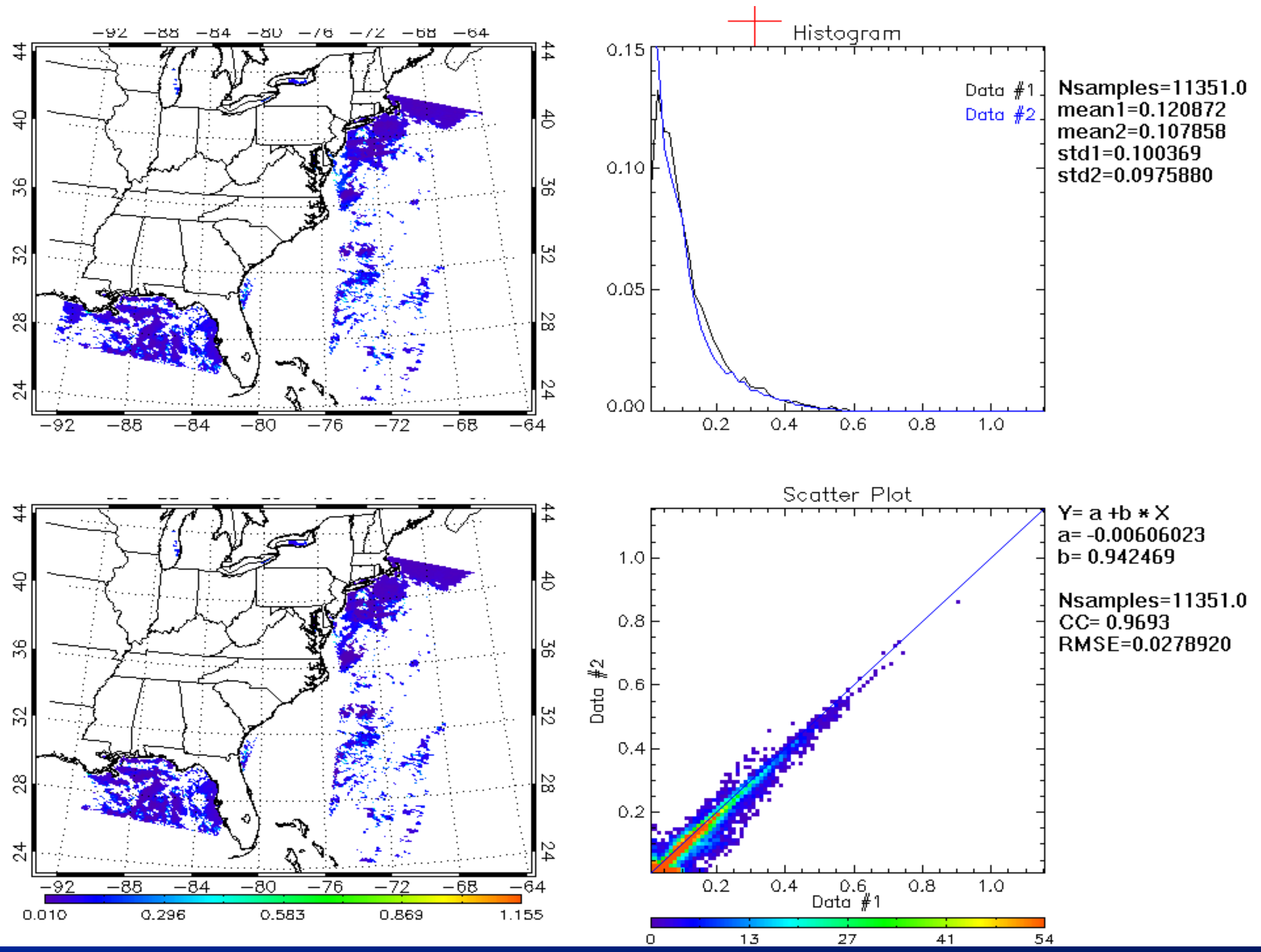
Our retrieval is about 7 times fast than the NGST retrieval (7.6 minutes vs. 56 minutes on a LINUX desktop for a granule)

Comparison of Our VIIRS-type AOT Retrieval with MODIS AOT Retrieval over Ocean

(September 29, 2002; 16:10UTC)

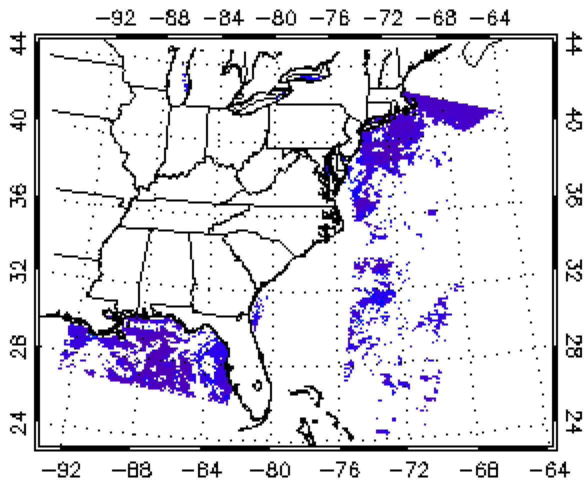
VIIRS-type

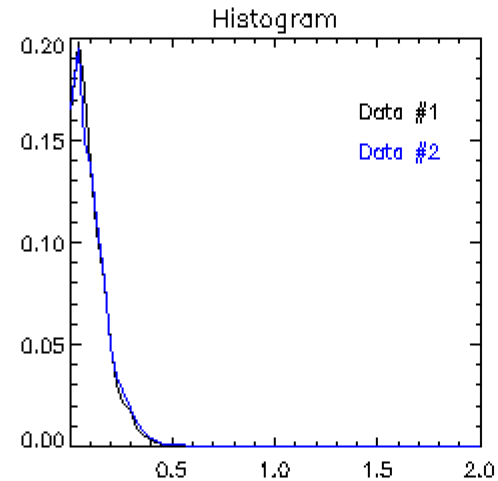
MODIS



Comparison of Our VIIRS-type AOT Retrieval with Our ABI-type AOT Retrieval over Ocean

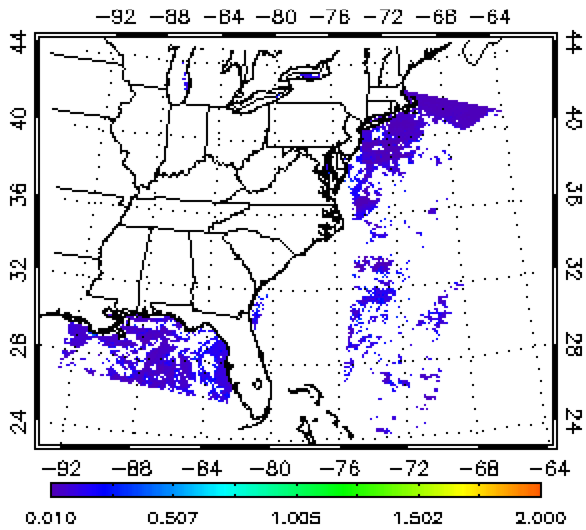
6 Channels (VIIRS-type) (September 29, 2002; 16:10UTC)

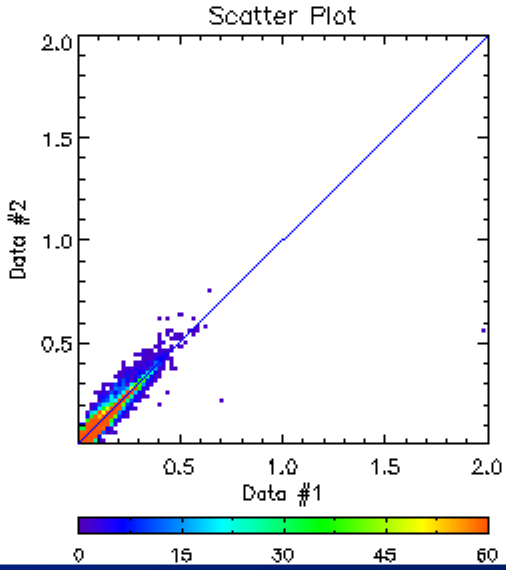




Nsamples=11723.0
mean1=0.116506
mean2=0.121035
std1=0.0838371
std2=0.0876614

4 Channels (ABI-type)





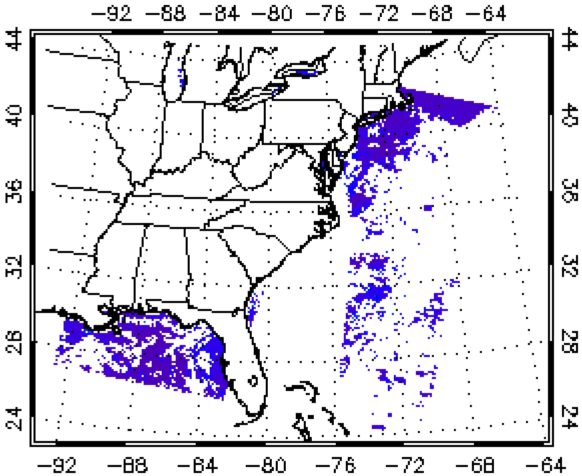
Y= a +b * X
a= 0.00871559
b= 0.964061

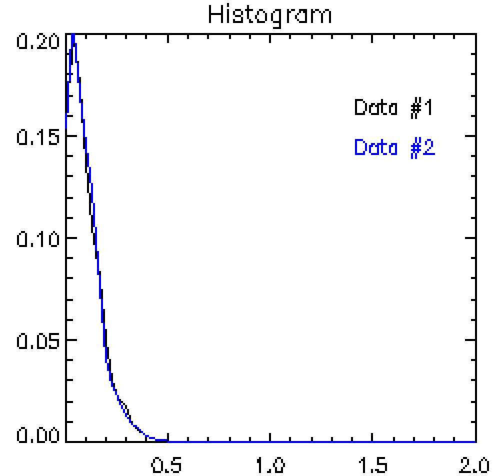
Nsamples=11723.0
CC= 0.9220
RMSE=0.0343719

Comparison of Our VIIRS-type AOT Retrieval with Our AVHRR-type AOT Retrieval over Ocean

6 Channels (VIIRS-type)

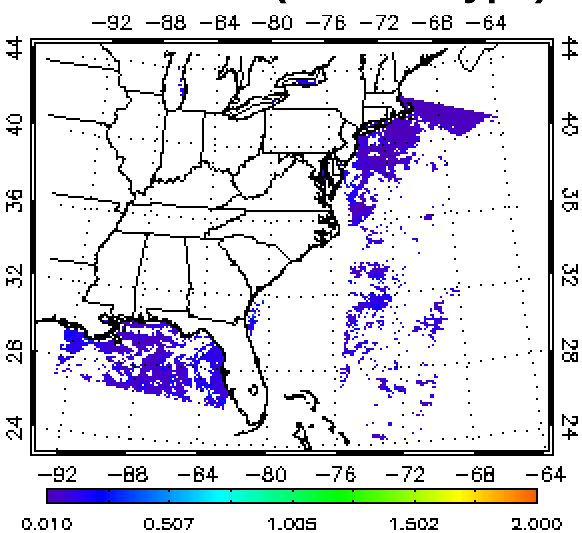
(September 29, 2002; 16:10UTC)

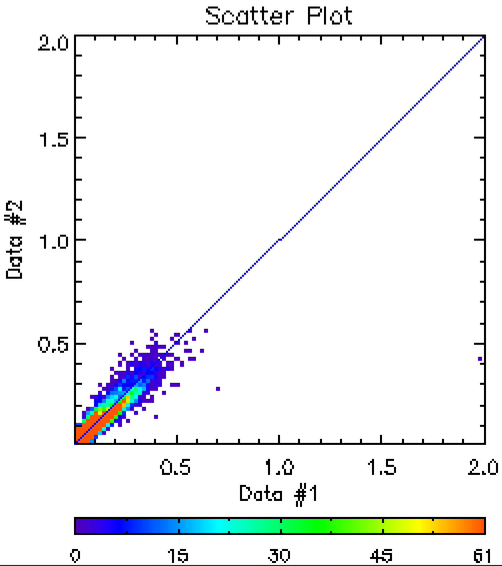




Nsamples=11723.0
mean1=0.116506
mean2=0.115210
std1=0.0838371
std2=0.0789551

2 Channels (AVHRR-type)





Y= a +b * X
a= 0.0173614
b= 0.839860

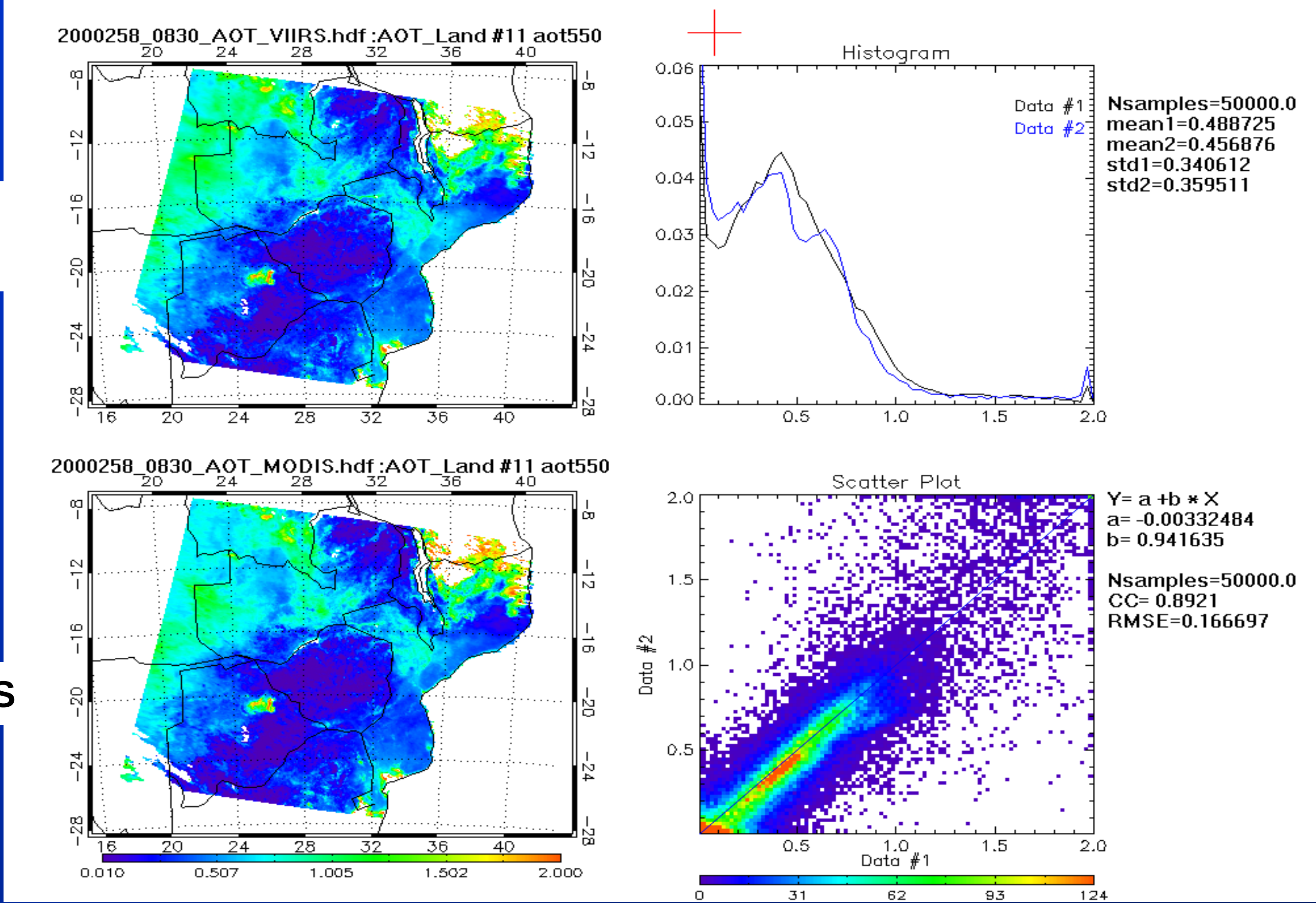
Nsamples=11723.0
CC= 0.8918
RMSE=0.0381829

Comparison of Our VIIRS-type AOT Retrieval with MODIS AOT Retrieval over Land

(September 14, 2000; 08:30UTC)

VIIRS-type

MODIS



Summary and Conclusions

- A unified satellite aerosol retrieval system is under development to retrieval aerosol optical thickness (AOT), aerosol particle size parameter (APSP), and types of suspended matters (SM).
- The retrieval system written in C++ is a physical-based retrieval with a modular design and a specific consideration of computational efficiency and application for various multi-channel imagers.
- AOT retrieval tests by using MODIS measurement have been performed and results are encourage.
- The system can be applied to past, current, and future polar-and geo-orbital imagers for an operational measurement of AOT, APSP, and SM.

Future Effort and Algorithm Enhancement

- Continue the refinement of the retrieval system through validation, especially the validation of APSP & SM.
- Include non-spherical shape in the dust aerosol model.
- Extend the retrieval over land to bright surface (e.g., desert area).
- Account for bidirectional reflectance over land.
- Apply the unified retrieval system to the real measurement of various imagers for the generation of consistent global long-term aerosol products.
- Seeking collaborations to support other CDRs production.

Acknowledgement

- This work is supported by the NOAA's CDR Program at the NCDC.

Thank You!