Scientific Innovations in FengYun Satellite Research and Applications
风云卫星研究与应用中的科学创新

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Outline

• Overview of FengYun satellite mission

• Innovative FY calibration and product validation

• Innovative uses of FY satellite data for CMA operations

• Critical sciences and technologies required for future developments

• Summary and Conclusions
Fengyun Meteorological Satellite by 2040
Satellite Data Records and Their Applications

**L1**
- MWTS radiances
- MWHS radiances
- MWRI radiances
- HIRAS radiances
- MERSI-II radiances
- GAS radiances
- GNOS bending angle
- AGRI radiances
- GIIRS radiances

**L2**
- Cloud and water vapor imagery
- Temperature profile
- Moisture profile
- Aerosol optical depth
- Cloud mask
- Cloud optical parameters
- Cloud phase (liquid/ice)
- Derived motion wind
- Rainfall rate
- Fire and hot spot
- Land surface temperature
- Land surface type
- Normalized vegetation index
- Leaf area index
- Snow Cover
- Soil moisture
- Sea Surface Temperature
- Surface wind speed
- Sea ice concentration

**Applications**
- Convective initiation
- Typhoon location/intensity
- NWP data assimilation
- Pollution and dust monitoring
- Ecological monitoring/assessments
- Agriculture yield estimation
- Renewable energy
- Climate assessment

**EDR algorithm**
- Product validation

**Application systems**
(e.g. NWP, ML)

**Users and Service**

**Instrument calibration**
- In-orbit Monitoring
How to Assess Instrument Noise Correctly?
MWHS Noise Characterization

NEDT estimated from Allan deviation (black bar) and standard deviation (white) for all 15 channels. The number of scan of warm counts used for calculation is (a) 100; (b) 300 and (c) 500, respectively, from the orbit of 3340 on July 8, 2018.

The noise derived from Allan deviation does not depend on the number of scan lines and is very reliable for noise calculation.
How to Validate Level 1B Data?

MWHS Bias Assessment

GPSRO profile data are proved to be the best for simulating the upper air microwave sounding channel radiances which can be used for vicarious calibration of microwave sounding instrument.
Multisensor Remote-sensing Testbed

**Input**
Satellite radiance or Brightness temperature, geolocation information

**Background**
Atmospheric and Surface Parameters
NWP model outputs or climatology profile

**One Dimension Variational (1DVAR)**
for sequential or simultaneous retrievals

**Output**
Atmospheric temperature, moisture, hydrometeor, aerosol, trace gases, profiles

**Forward/Jacobian Operators**
CRTM
RTTOV
ARMS

- Algorithm valid in all-weather conditions, over all-surface types
- Model & instrumental errors are input to algorithm
- Background and observation error covariances are scene-dependent.
- Selection of background from climatology, NWP forecasts, and regressions
- Selection of channels to use and parameters to retrieve
Combined microwave sounding Suite (CMWS) from FY-3D MWTS and MWHS has a better vertical resolution for atmospheric sounding comparing to ATMS.
Comparison of ATMS and CMWS Warm Core

ATMS | CMWS-20 | CMWS-28
Comparison of Atmospheric Profiles Derived from ATMS using MRT and MIRS

Dropsonde 0-900 km from TC center

Collocation threshold: within 33 km & within 30 minutes. Number of collocated dropsondes: 281

Atmospheric profiles from MRT has better accuracy in lower to mid-troposphere.

Slide courtesy of Hu Hao, CAMS
HIRAS Channel Selection

- Principal component analysis is used for channel selection.
- 450 channels is selected,
HIRAS FOV Dependent Bias Correction

- Significant bias variation between four FOVs
- Asymmetric bias between twenty-nine FORs
- Bias correction for every FOVs and FORs
FY-3D HIRAS Derived Atmospheric Profiles

- Data between June 2018 to May 2019 are used for retrieval, validation with ERA5 reanalysis
- 1DVAR is better than regression and machine learning
- The mean temperature RMS is about 1K between 200hPa and 700hPa

*Slide courtesy of He Yanfeng, Anhui Meteorological Bureau*
Cloud Products from FY-4A AGRI

Slide courtesy of Min Min, Sun Yet-Sun University
Validation of FY-4A AGRI Cloud Top Temperature and Height Using Aircraft Ka Radar Observation

Slide courtesy of Zhou Yuqian, CAMS
FY-3D MERSI AOD Retrieval Algorithm

- Bands: 0.41, 0.47, 0.55, 0.66, 0.86, 1.24, 1.64, and 2.13 µm
- Ocean- dark target
  - reflectance contrast between cloud-free atmosphere and ocean reflectance (dark)
  - aerosol optical thickness (0.55-2.13 µm)
  - size distribution characteristics (fraction of aerosol optical thickness in the fine particle mode; effective radius)
- Land – dark target
  - dense dark vegetation and semi-arid regions determined where aerosol is most transparent (2.13 µm)
  - contrast between Earth-atmosphere reflectance and that for dense dark vegetation surface (0.47 and 0.66 µm)
  - aerosol optical thickness (0.47 and 0.66 µm)
  - fraction of aerosol optical thickness in the fine particle mode
- Land – bright target
  - Deep blue for bright reflecting surfaces using 0.41, 0.47, and 0.66 µm

Slide Courtesy of Leiku Yang, Henan Polytechnic University
Validation of AOD Retrieved from MERSI vs. MODIS

Data period: 201406~201505

Slide Courtesy of Leiku Yang, Henan Polytechnic University
Validation of AOD Using Ground-Based Lidar Measurements

Slide Courtesy of Lei Yong, CMA/Atmospheric Sounding Center
Retrieval of Normalized Vegetation Index (NDVI) at Top of Canopy

\[
\rho_{\text{TOA}}(\mu_s, \mu_v, \varphi) = T^0(\mu_s, \mu_v) \left[ \rho_{R+A}^{\text{TOA}}(\mu_s, \mu_v, \varphi) + \frac{\rho_T(\mu_s, \mu_v, \varphi)}{1 - \rho_T(\mu_s, \mu_v, \varphi)S} T^H(\mu_s, \mu_v) T_{R+A}^\downarrow(\mu_s) T_{R+A}^\uparrow(\mu_v) \right]
\]

\(\rho_{\text{TOA}}(\mu_s, \mu_v, \varphi)\): TOA reflectance
\(\rho_{R+A}(\mu_s, \mu_v, \varphi)\): TOA molecular and aerosol reflectance
\(\rho_T(\mu_s, \mu_v, \varphi)\): surface reflectance
\(T^0(\mu_s, \mu_v)\): ozone transmittance
\(T^H(\mu_s, \mu_v)\): water vapor transmittance
\(T_{R+A}^\downarrow(\mu_s)\): downwelling transmittance
\(T_{R+A}^\uparrow(\mu_v)\): upwelling transmittance
\(S\): surface spherical albedo

Slide courtesy of Han Xiuzhen, NSMC
Comparing with TOA NDVI from FengYun-3D MERSI, TOC NDVI have higher greenness in Northeast China, Jiangnan, South China, Loess Plateau and many other places.

*Slide courtesy of Han Xiuzhen, NSMC*
Remote Sensing of Ocean Color from FY-3D MERSI-II

- OCSMART developed by Knut Stamnes was expanded for FY-3D MIRSI-II to retrieve the ocean and water quality parameters.
- Parameters include suspended matter, dissolved organic matter, chlorophyll and other substances.
- OCSMART directly relate the reflectivity of the top of the atmosphere to atmospheric and water body parameters.
- The simulation data sets including atmospheric aerosol concentration, water nutrient elements, chlorophyll concentration are used to train an ocean color algorithms through machine learning.

*Slide courtesy of Knut Stamnes, Steven Institute of technology, New Jersey.*
FengYun Satellite Application Segments and Leadership at CMA

- Severe storm monitoring (NMC-Xu Yinglong)
- Ecological monitoring and assessments (NSMC-Han Xiuzhen)
- NWP data assimilation in GRAPES (CNWP-Li Juan/Han Wei)
- Agro-meteorology applications (NMC-Wu Mengxin)
- Energy (Public Weather Service Center- Shen Yanbo)
- Climate assessments (NCC-Nie Suping)
- Weather Modification (CAMS-Zhou Yuqian)
FengYun Satellite Weather Application Demonstration System

Slide courtesy of Xu Yinglong, NMC
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<th>时间</th>
<th>台风/飓风中英文名称</th>
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<th>台风强度客观估计结果 (m/s)</th>
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平均误差 3.9

*Slide courtesy of Xu Yinglong, NMC*
Monitoring Typhoon Mangkhut Warm Core Evolution Using FY-3D MWTS and MWHS

Himawari-8 Band 13 (10.4 μm) Brightness Temperature (K)

Slide courtesy of Hu Hao, CAMS
Assessing Ecological Condition

Technical Criterion from Ministry of Ecology and Environment (MEE)

生态环境状况评价技术规范(生态环境部, HJ192-2015)

\[ EI = 0.35 \times BRI + 0.25 \times VCI + 0.15 \times WNDI + \\
0.15 \times (100 - LSI) + 0.10 \times (100 - PLI) + ERI \]

where

- **BRI**: biological richness index, 0-100
- **VCI**: vegetation coverage index, 0 - 100
- **WNDI**: water network denseness index, 0 -100
- **LSI**: land stress index, 0 - 100
- **PLI**: pollution load index, 0 - 100
- **ERI**: environmental restriction index reflecting a major ecological destruction and heavy environmental pollution

An area with high biodiversity and biological richness, good vegetation cover, more water, less land stress and pollution is in a good ecosystem condition
Critical EDRs for Ecological Assessments

- Vegetation coverage
- Vegetation net primary productivity
- Soil moisture
- Land surface type
- Land surface temperature
- Air quality products (AOD, PM2.5, O3)

*Slide courtesy of Han Xiuzhen et.al, NSMC*
Ecological Index (EI) from MODIS Products

\[ EI_{EOS} = -0.0565 \times LST + 0.5926 \times F + 0.7086 \times NDVI + 0.3305 \times NPP - 0.1828 \times VPDI + 0.028 \times LUCC \]

In the formula, EI is the ecological environment condition index, LST is the surface temperature, F is the greenness index, NDVI is the normalized vegetation index, NPP is the net primary productivity, VPDI is the drought index, and LUCC is the land use type.

- The principal component analysis is performed for each parameter and the first PCA component is used to determine the contribution of each parameter to EI. This weight setting is stable.

- Notice the coefficients of greenness degree, vegetation index and NPP are all positive, indicating that they jointly contribute positively to better ecology; while the coefficients of heat (surface temperature) and dryness (soil moisture) are negative, indicating that they have a negative impact on the ecological environment.

*Slide courtesy of Han Xiuzhen et.al, NSMC*
Assimilation of FY Data in CMA Global and Regional Assimilation and Prediction System (GRAPES)

Instrument Name

• MicroWave Temperature Sounder (MWTS)
• MicroWave Humidity Sounder (MWHS)
• MicroWave Radiation Imager (MWRI) – In Operation
• GNSS Radio Occultation Sounder (GNOS)
• Hyperspectral Infrared Atmospheric Sounder (HIRAS)
• Advanced Geosynchronous Radiation Imager (AGRI)
• Geosynchronous Infrared Interferometric Sounder (GIIRS)

Status in GRAPES

• operationally used
  ✓ MWHS-2 (FY-3C/D)
  ✓ GNOS (FY-3C)
  ✓ GIIRS (FY-4A)
  ✓ AMV(FY-2D/E/G)

• to be operationally used soon
  ➢ GNOS (FY-3D)
  ➢ HIRAS (FY-3D)
  ➢ MWTS-2 (FY-3D)
  ➢ MWRI (FY-3C/D)

• on-going research
  o AGRI(FY-4A)

Slide courtesy of Li Juan, CMA NWPC.
Assimilation of FY-3D MWTS Data in GRAPES

Neutral to positive impact

All observations + FY-3D MWTS-2 forecast

Slide courtesy of Li Juan, CMA NWPC.
FY-4A GIIRS Impacts in GRAPES 4DVAR

GRAPES global 4D-Var
CTRL : OPER
GIIRS : OPER+GIIRS Temp. Sounding

Impact on wind RMSE (green mean reduction)

Slide courtesy of Han Wei, CMA NWPC.
Accelerating Research to Operation in FengYun Satellite Programs

- Transition the Advanced Radiative Transfer Modeling System (ARMS) to NWP data assimilation

- Transition the multisensor remote sensing testbed for FY atmospheric sounding

- Use FY microwave products in NMC system to enhance the typhoon monitoring capability

- Generate the long-term NDVI data records from FY series of instruments and connect with EOS and NOAA NDVI data records

- Develop comprehensive techniques for assessing the ecological conditions and functions
ARMS is designed with the state-of-the-art radiative transfer sciences, cutting edge software engineering, and flexible interfaces with other fast models. It will serve for many CMA applications including NWP data assimilation, satellite ground processing in instrument calibration and environmental parameters.

Weng, F., X. Yu, Y. Duan, J. Yang, J. Wang, AAS, 2019
On April 29 to May 3, 2019, CMA, EMCWF and JCSRA jointly hosted a joint workshop on radiative transfer models for satellite data assimilation at Tianjin, China. More than 100 scientists from China, US, UK, Germany and Japan attended the workshop.

A science steering committee for radiative transfer (SSC4RT) was formed and 9 distinguished scientists are selected as SSC members. Several critical actions will be taken after the workshop.

The participants reported the major progresses in developing the fast radiative transfer models for satellite data assimilations. In past, the NWP community primarily uses RTTOV (Europe) and CRTM (US). Now, China is developing the Advanced Radiative Transfer Modeling System (ARMS) for Chinese satellite data applications. The SSC recognized the significance of ARMS and will be the third pillar, after RTTOV and CRTM.
National and Regional Remote Sensing Service

National Remote Sensing Operational Products and Service
- Chinese Remote Sensing Product Requirements and Quality Assurance
- Operational Products Generation, Proving Ground Demonstration and Transition to Operation
- National Unified Operational Service Platform
- Satellite data reception, quality control and data sharing service
- Major technology Advances, Ground-Based Validation
- International User Services and Technical Exchange

National Remote Sensing Operational Consultation and Discussions

Provincial Special Remote Sensing Operational Service

Provincial Remote Sensing Service
- Plan local remote sensing service
- Provincial remote sensing data acquisition and data service
- Local evaluation and applications of national-level products and local feedbacks
- Develop special remote sensing application, product and service enhancement
- Provincial-level guidance to local government, technical support and training

Service Area
- Agriculture
- Forest
- Water Resources
- Ecological Environment
- Academia and University
- .......

International Service
- “Belt & Road”
- Asean
- Shanghai-Agreement
- China Arabian
- China-Africa
- ......
Assessing Ecological Function: Wind Prevention and Sand Fixation - 防风固沙

Technical Criterion of Ecosystem Status Evaluation
生态环境状况评价技术规范(环境保护部, HJ192-2015)

\[
EC_{wpsf} = 0.60*[0.24*\text{vegetation coverage index} + 0.1*\text{protected area ratio}*100+0.22*\text{forest area ratio} + 
0.22 * \text{water and wet land area ratio} + 0.14*(100-\text{farm and construction land area ratio}*100) + 0.10*(100-\text{land desertification area ratio}*100] + 0.40*[0.45*(100-\text{major pollutant emission intensity})+0.10*\text{rate of pollutant emission meeting the standard}*100+0.10*\text{city polluted water collective processing rate}*100+0.15*\text{rate of water quality reaching the standard}*100+0.15*\text{rate of air quality reaching the standard}*100+0.05*\text{rate of collective drinking water source reaching the standard}*100]}
\]
Assessing Ecological Function: Water and Soil Conservation - 水土保持

Technical Criterion of Ecosystem Status Evaluation
生态环境状况评价技术规范(环境保护部, HJ192-2015)

$$EC_{wsc} = 0.60*[0.23*\text{vegetation coverage index} + 0.13*\text{protected area ratio}*100 + 0.23*\text{forest area ratio} + 0.18*\text{water and wet land area ratio} + 0.13*(100-\text{farm and construction land area ratio}*100) + 0.10*(100-\text{moderate to high land desertification area ratio}*100) + 0.40*[0.45*(100-\text{major pollutant emission intensity}) + 0.10*\text{rate of pollutant emission meeting the standard}*100 + 0.10*\text{city polluted water collective processing rate}*100 + 0.15*\text{rate of water quality reaching the standard}*100 + 0.15*\text{rate of air quality reaching the standard}*100 + 0.05*\text{rate of collective drinking water source reaching the standard}*100]$$
Assessing Ecological Function: Water Conservation - 水源涵养

Technical Criterion of Ecosystem Status Evaluation
生态环境状况评价技术规范(环境保护部, HJ192-2015)

\[ EC_{wc} = 0.60\times[0.25\times \text{water conservation index} + 0.20\times \text{protected area ratio} \times 100 + 0.15\times \text{forest area ratio} + 0.10\times \text{grass area ratio} + 0.15\times \text{water and wet land area ratio} + 0.15\times (100 - \text{farm and construction land area ratio} \times 100)] + 0.40\times[0.45\times (100 - \text{major pollutant emission intensity}) + 0.10\times \text{rate of pollutant emission meeting the standard} \times 100 + 0.10\times \text{city polluted water collective processing rate} \times 100 + 0.20\times \text{rate of water quality reaching the standard} \times 100 + 0.10\times \text{rate of air quality reaching the standard} \times 100 + 0.05\times \text{rate of collective drinking water source reaching the standard} \times 100] + \text{ecological capability adjustment index} \]
Assessing Ecological Function: Biodiversity Conservation - 生物多样性维护

Technical Criterion of Ecosystem Status Evaluation
生态环境状况评价技术规范(环境保护部, HJ192-2015)

\[ EC_{bc} = 0.60 \times [0.23 \times \text{biological richness index} + 0.20 \times \text{protected area ratio} \times 100 + 0.15 \times \text{forest area ratio} + 0.10 \times \text{grass area ratio} + 0.15 \times \text{water and wetland area ratio} + 0.15 \times (100 - \text{farm and construction land area ratio} \times 100)] + 0.40 \times [0.45 \times (100 - \text{major pollutant emission intensity}) + 0.10 \times (\text{rate of pollutant emission meeting the standard} \times 100) + 0.10 \times (\text{city polluted water collective processing rate} \times 100) + 0.20 \times (\text{rate of water quality reaching the standard} \times 100) + 0.10 \times (\text{rate of air quality reaching the standard} \times 100) + 0.05 \times (\text{rate of collective drinking water source reaching the standard} \times 100)] + \text{ecological capability adjustment index} \]
Mission Dependent NDVI Products

Assessing ecology conditions from different satellite missions could be significantly different.

*Slide courtesy of Nie Suping, NCC*
A JMR Special Issue for Satellite Ecological Remote Sensing

Journal of Meteorological Research

专刊征文启事

题目：卫星生态遥感与应用

Satellite Ecological Remote Sensing and Applications

近十年，卫星观测已广泛用于生态环境监测。2018年生态遥感年度报告首次指出2000年至2017年全国植被覆盖率增加了3.7%。同时，全国及重点区域气溶胶光学厚度相对于16年的平均值下降了19.3%。2018年2月12日，美国航天局推特报告指出，“世界变得比20年前更绿了”，“来自NASA地球”的卫星资料显示，是中国和印度的人类活动主导了地球变绿！”。过去，人们怀疑从卫星观测得到的地球变绿可能与卫星仪器性能衰变或一系列卫星数据衔接不紧密造成的结果。本期专刊将介绍国家生态监测的最先进卫星遥感反演算法和产品应用，为这一专刊投稿的作者多是来自卫星仪器标定，产品算法反演和应用的研究业务一线专家和骨干。该专刊将为气象卫星生态遥感与环境监测奠定坚实的基础，并将推动气象卫星在国家生态文明建设中的应用，部分文章还将深入研究中国生态变化与天气和气候变化的关系。

Papers for this special issue are solicited for, although not limited to, the following topics:
1. Remote sensing fundamentals of land and ocean products from satellites.
2. Atmospheric air quality products from satellites.
3. Applications of satellite derived products for monitoring of ecological environment.
4. Impacts of meteorological conditions and climate variability on ecology.

Slide courtesy of Yi Lan, JMR
Summary and Conclusions

• Innovative algorithms are being tested for Fengyun satellites and generate the products with a quality similar or better than those from other missions.

• Many of Fengyun satellite application facilities have been established at CMA and research institutes, making very impressive progresses.

• FengYun satellite program requires developments of critical sciences and technologies such as fast and accurate radiative transfer models, advanced data assimilation system, severe weather monitoring, and ecological assessment tools, etc.

• Uses of FY satellite for ecological assessments are unique and reflect China’s national priority ("绿水青山就是金山银山" - Lucid Waters and Lush Mountains are Invaluable Assets)