Observations of Atmospheric Dynamics in 3D with LEO-GEO and GEO-GEO Stereo Imaging

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Collaborations

• NOAA Collaboration
  – Jaime Daniels, Houria Madani (Carr Astro), Wayne Bresky, Jeff Key
  – Focuses on GEO-GEO combinations
  – In progress with preliminary results

• NASA Collaboration
  – Dong Wu, Michael Kelly (APL), Jie Gong
  – Focuses on LEO-GEO combination
  – First-year finished, second year starts March 1st
  – Starting to work with JPL
MISR & GOES-R

- Motivation
- Method
- Results
- Validation

MISR Special Issue of Remote Sensing:


3D = Velocity with 3D location of Wind in the atmosphere
Motivation

- MISR & GOES each have different strengths and weaknesses for Wind observations
  - MISR measures cross-track velocity well and altitude (parallax), but in-track velocity couples to altitude
  - GOES-R measures two wind components well, but operational wind products must infer altitude from IR temperature
- MISR & GOES should be better together than each working alone and therefore solve both problems.
- Advanced “Image Navigation and Registration (INR)” with the new GOES-R series makes using GOES-R with MISR attractive (geo-registration better than ~200 m @ nadir).
MISR & GOES-R

- LEO on NASA Terra S/C
- Fore & Aft-looking Cameras
  - An: nadir looking
  - Af, Aa: ±26.1°
  - B, C, D: oblique viewing
- Red Band
  - 275 m resolution
  - 360 km swaths
- Winds: Zong, Davies, Muller & Diner, 2002

- GOES-16 stationed at -75.2°
- GOES-17 stationed at -137.2°
- Advanced Baseline Imager
  - Full-Disk (5, 10, 15-min. refresh)
  - CONUS (5-minute refresh)
  - Meso (30, 60-sec. refresh)
- Red Band
  - 500 m resolution
- NOAA Operational Winds
MISR Multi-Angle Imagery

- Color Separation shows Disparities between Cameras
  - In-track is Parallax + (mostly) V-wind
  - Cross-track is (mostly) U-Wind
- MISR Wind Challenge is the separation of Parallax from V-Wind

(R,G,B) = (Aa, An, Af)
\[ \Delta t = (45s, 0, -45s) \]

MISR Red Band (672 nm)

SOM Projection over WGS84 Ellipsoid (Blocks 60, 61, 62 on P024 O098797)

U (East)
V (North)
Track
275 m
GOES Multi-Temporal Imagery

- Color Separation shows Disparities between Frames
  - Pure Atmospheric Motion
  - No Parallax
- $T_0$ picked close to MISR An Time
- CONUS scene used here

Advanced Baseline Imager (ABI)
(R,G,B) = ($T_0$-5min, $T_0$, $T_0$+5min)

ABI Band 2 (B02)
(640 nm)

275m
(Native 500 m)

Remapped into MISR SOM Projection
Disparity Measurements

- 40x40 MISR pixel templates
- 8 x 8 MISR pixel sampling (2.2 km)
- Normalized Cross Correlation
- Subpixel resolution by Interpolation
Disparities

Disparities with respect to MISR AN Camera

\[ \Delta Y_{SOM} (m) \]

\[ \Delta X_{SOM} (m) \]

Legend:
- AA
- AF
- GOESE-
- GOESE+
- GOESE0
- Self

Science at work
Wind Retrieval Model

- MISR An is designated reference \((n = 0)\)
- Solve for states at each site; \(\vec{\epsilon}_n\) is a function of
  - 3 positions \((\vec{\delta}_0)\)
  - U & V winds
  - (optionally W wind)
  - No synchronization
- Two global “Bundle Adjustment” states allow fine adjustment of MISR block to align better with GOES imagery
- Nonlinear, sparse-matrix solution of order \(5N+2\sim10^4\) per MISR block

Minimize: 

\[
\chi^2 = \sum_{n=1}^{N} \vec{\epsilon}_n^T W_n \vec{\epsilon}_n
\]

\[
\vec{\delta}(t_n) = \vec{\delta}_0 + \vec{v} \cdot (t_n - t_0)
\]
Residual Disparities

- A Cameras + GOES-16
- Disparities ~15 km
- Residuals < 275m

Block 61 on P024 O098797
MISR+GOES over CONUS 2018

One Frame of 5-minute GOES CONUS Imagery

MISR Path 024

Jointly Retrieved 3D-Winds with 2.2 km sampling

P0240098797B53:77 + GOES-16, N=111894
OR_ABI-L2-CMPC-M3C02_G16_s20181961702256_e20181961705039_c20181961705156.nc

A Cameras

PBL

Latency (deg)

0 100 m/s
Florence MESO 2018

One Frame of 30-Second GOES MESO Imagery

Low-altitude winds feeding in warm, moist air
MISR+GOES Full Disk 2018

One Frame of M4 5-minute GOES FD Imagery

N=14,366

M4 (FD every 5 minutes)

Emulated M6 (FD every 10 minutes)

N=7,008

Emulated M3 (FD every 15 minutes)

N=3,772

A Cameras
Comparison to MISR Winds
MISR Wind-Height Correlation

*Slope = -100 s

*Davies, Horváth, Moroney, Zhang & Zhu, 2007

Mueller, Wu, Horváth, Jovanovic, Muller, Girolamo, Garay, Diner, Moroney & Wanzong, 2017
Comparison to GOES Winds

**U Wind**
- $\mu = -0.04$ m/s
- $\sigma = 0.56$ m/s
- N=1514

**V Wind**
- $\mu = 0.13$ m/s
- $\sigma = 0.54$ m/s
- N=1514
Comparison with GOES IR Height Assignments

GOES DMW Pressure (hPa)

\[ \mu = 34.8404, \quad \sigma = 60.235 \text{ hPa}, \quad N=941 \]

GOES DMW Height above MSL (m)

\[ \mu = -356.14, \quad \sigma = 611.1741 \text{ m}, \quad N=941 \]

>> Estimated LEO-GEO 3D-Winds Retrieval Uncertainty
Validation: Clear-Sky Terrain

- Height Error over Terrain (m):
  - $\mu=8.0$ m
  - $\sigma=95.2$ m
  - $N=9606$
  - $< 200$ m

- U-Wind Error over Terrain (m/s):
  - $\mu=0.01$ m/s
  - $\sigma=0.11$ m/s
  - $N=10044$
  - $< 0.5$ m/s

- V-Wind Error over Terrain (m/s):
  - $\mu=0.09$ m/s
  - $\sigma=0.12$ m/s
  - $N=10044$
  - $< 0.5$ m/s
W Winds

- W-Component is observable according to the math model

- Usually W-wind is small, so we generally constrain it to zero

- Interpretation as a true “wind” requires confirmation, may be
  - Cloud-top growth/collapse
  - Artifact of side-looks at cloud

- Apparent quality improves with number of poses
W-Component Retrievals

W-Component

UV vs. UVW Retrievals

Comparison with MISR A + 1 GOES

IR&D Full Disk G-13, -16 (Test Slot)

17 September 2017 18:00Z

No Synchronization
STAR Study

- NOAA can do parallax 3D-Winds NOW

- Objective of our present work is to prove this in a way that has a path into operations to provide alternative height assignments for DMWs

- Validations/comparisons will quantify the quality of parallax heights
  - Comparison with IR height assignments
  - MISR-GOES winds
  - Rawinsondes and aircraft wind *in situ* measurement

No synchronization

Trade-off between vertical resolution and coverage
STAR Study Methodology

- Remap G-17 into G-16 fixed grid
- Match each triplet using operational winds matching & clustering algorithm
- Ingest matches into MISR/GOES-heritage retrieval model
- Use MISR/GOES-heritage matching for ground-point validation

Can Mix CONUS/MESO/FD
CONUS Retrievals with GOES-16, -17 (Test Slot)

B02

Retrieved GEO-GEO 3D Winds

Matches from NOAA code

CONUS-CONUS

PRELIMINARY
B02 CONUS Validations

MISR + GOES

Near-Neighbor Retrieval Comparison

\[ y = 0.98516x + 195.6331 \]

Ground Retrievals

\( \mu = 135.8165, \sigma = 188.1058 \text{ m; N=4793} \)

\( \mu = 0.080916, \sigma = 0.16018 \text{ m/s; N=5185} \)

\( \mu = 0.047215, \sigma = 0.1926 \text{ m/s; N=5185} \)

Preliminary
IR Full Disk G-16, -17 (W Slot)

3D-Winds for Band 14 FD January 16 2019 20:00

θ~100m/s

FD-FD
We see less ground with this band than with Band 2
• 2.55 % of good retrievals are ground for Band 14
• 11.25% of good retrievals are ground for Band 2
Full Disk WV 3D-Winds

Just for Fun!

FD-FD

Did we retrieve the height? TBD

PRELIMINARY
WV 3D-Wind Comparisons with DMW Products
The Future

- LEO-GEO Constellations
- LEO-LEO Leader-Follower
- Cubesat Deployments

- International Partners
- Hosted Payloads