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Radar Interferometry

Dealing with atmospheric errors for individual interferograms

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Atmospheric refraction

The traveling path is not a direct line

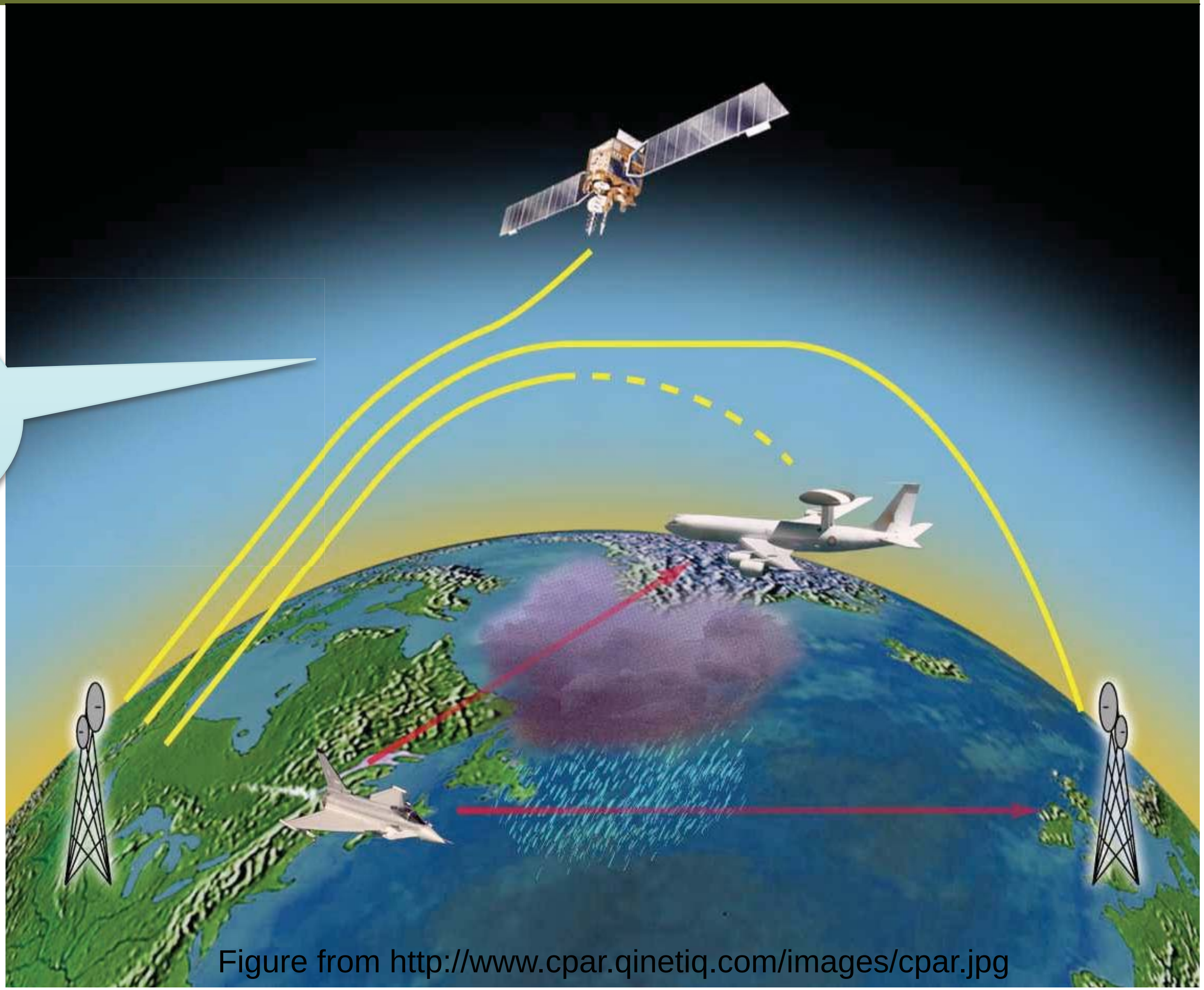
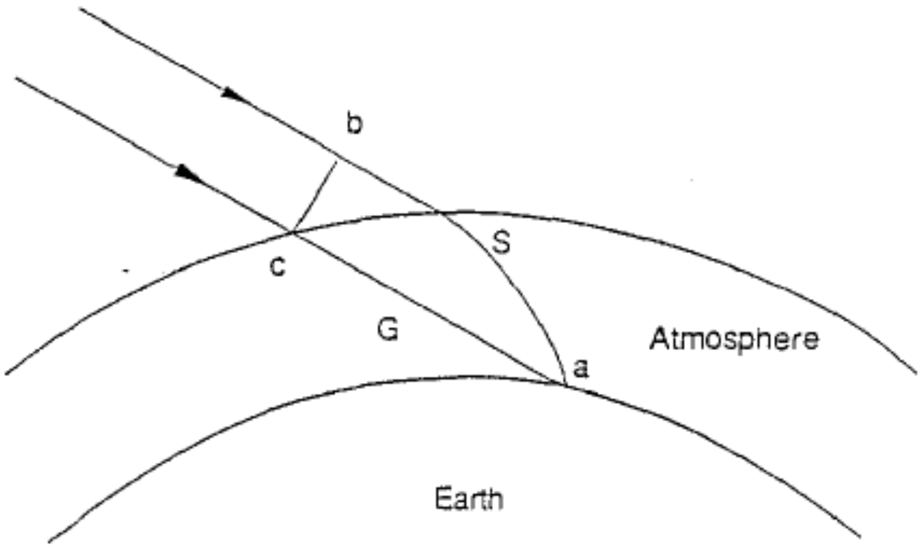


Figure from http://www.cpar.qinetiq.com/images/cpar.jpg

Atmospheric refraction

- Radar signals are bent and slow down in the atmosphere
  - Distance is different from a straight line
  - Traveling time is longer than in the vacuum



Atmospheric refraction – time delay

- Excess path length

$$\Delta S = 10^{-6} \int_S N \cdot ds$$

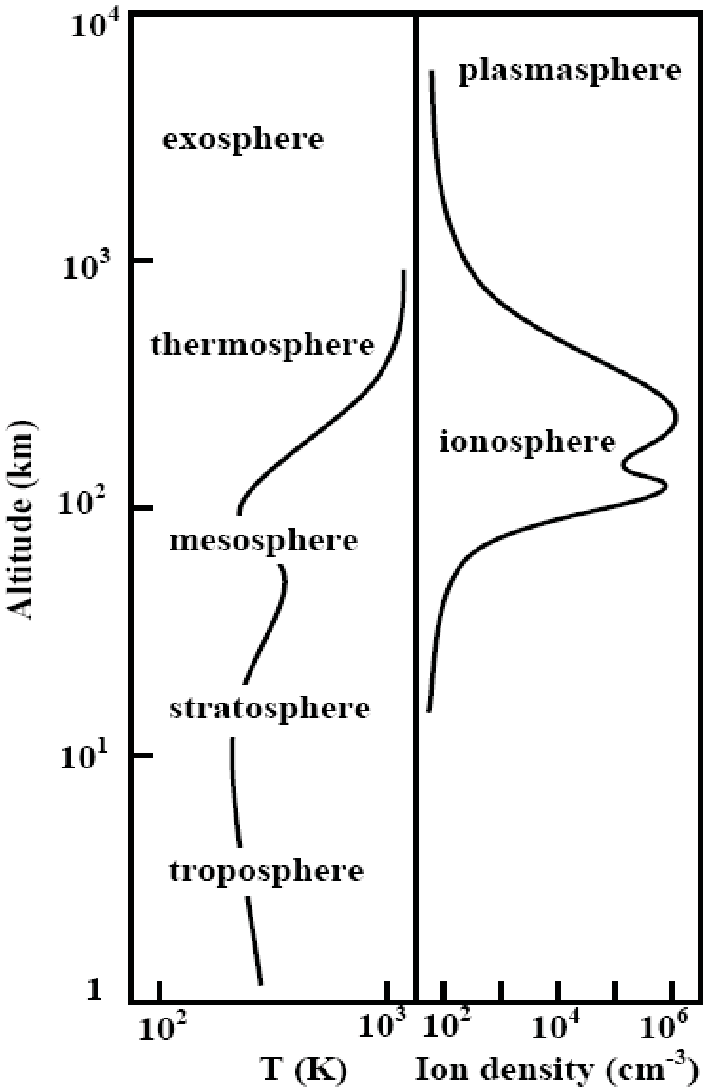
where *N* is refractivity: $N = (n-1) \times 10^{-6}$

- Need to consider two different effects:

  - Topospheric delay

  - Ionospheric delay (Wednesday)

Basic structure of the atmosphere



- **Troposphere:**
- Contains 80% of air mass
- Contains 99% of water vapour
- Air temperature decreases with altitude
- ~12km thick on average

  ~16 km in the Tropics

  ~9km in the Polar Regions
- Not dispersive (up to 30 GHz)

Zenith Tropospheric Delay (ZTD)

- Assuming a spherically symmetric atmosphere, the zenith tropospheric delay (ZTD) can be expressed as:

$$ZTD = ZHD + ZWD$$

- *ZHD:* Zenith Hydrostatic Delay
- *ZWD:* Zenith Wet Delay

Zenith Hydrostatic Delay (ZHD)

❖ ZHD can be obtained using the *Saastamoinen* model [*Saastamoinen*, 1972; Davis et al., 1985]:

$$ZHD = 0.0022768 \times \frac{P_s}{f(\varphi, H)}$$

$$f(\phi, H) = 1 - 0.00266\cos(2\varphi) - 0.00028H$$

- P_s is total surface pressure in hPa;
- φ: latitude in degrees; *ZHD:* in meters;
- *H*: station height in km above the geoid

Zenith Hydrostatic Delay (ZHD)

- Typical ZHD = 2.3 m.
- 1 hPa error in surface pressure can lead to 2.3 mm error in ZHD;
- Surface pressure data can be obtained from radiosondes, GPS stations, space-based sensors (MODIS, MERIS), ECMWF, etc.
- Error in ground-based surface pressure is usually less than 0.2 hPa, so …
- Surface pressure from MODIS, MERIS, ECMWF: Not accurate enough!

Zenith Wet Delay (ZWD)

- ZWD can be estimated from surface measurements [*Saastamoinen*, 1972]:

$$ZWD = 0.002277\left(\frac{1255}{T} + 0.05\right)e_W$$

$$e_W = RH \cdot \exp\left(-37.2465 + 0.213166 \cdot T - 2.56908 \cdot 10^{-4} \cdot T^2\right)$$

- *T* is surface temperature in degrees Kelvin;
- RH: Relative humidity in percentage
- e_W is water vapour partial pressure in hPa;
- Low accuracy: 2~5 cm of ZWD

Zenith Wet Delay (ZWD)

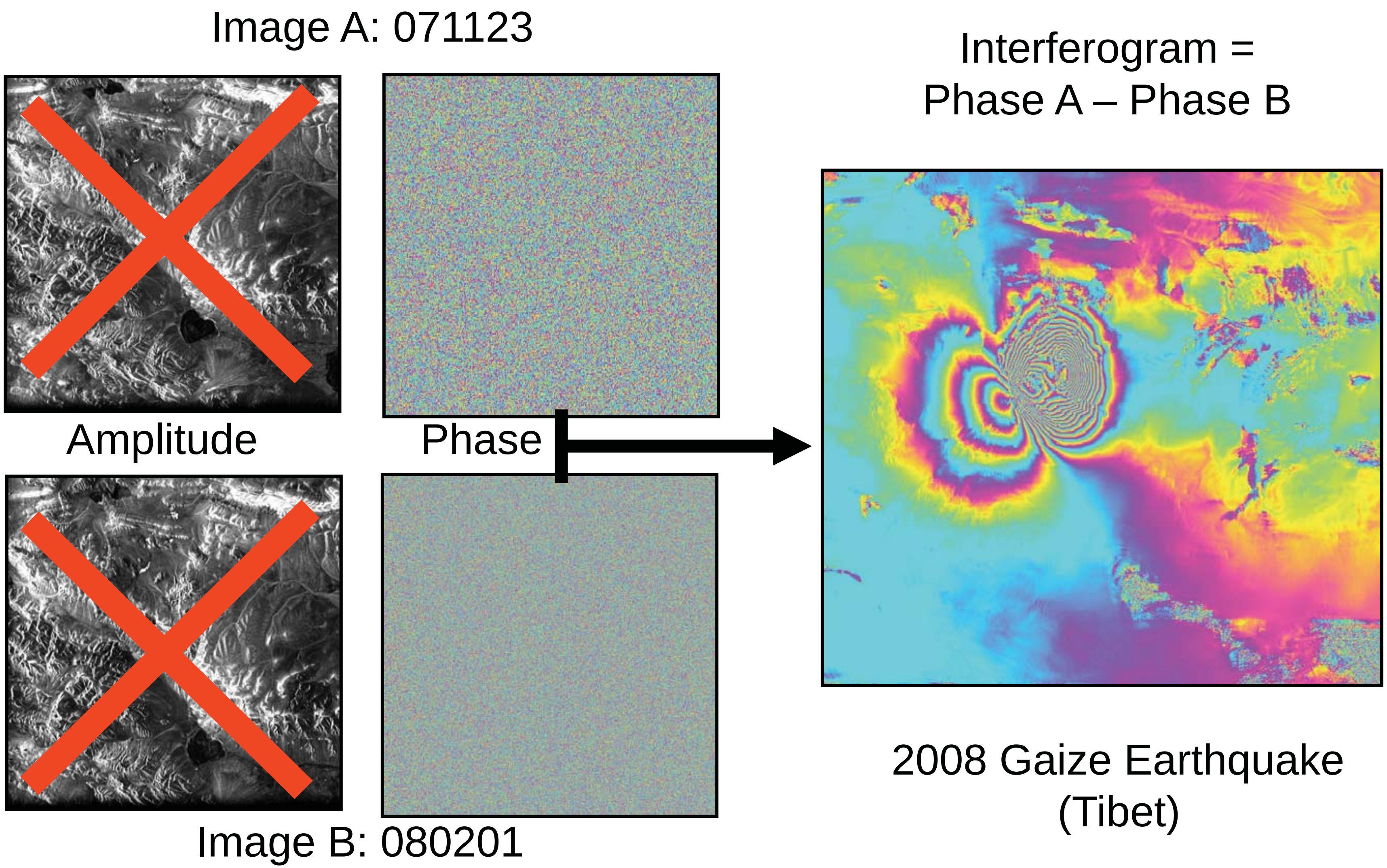
- ZWD is much smaller than ZHD
- ZWD is usually between 0-30cm.
- ZWD varies from place to place, from time to time
- ZWD is the most highly variable (both spatially and temporally) component of delay and is not easy to determine using surface measurements.
- ZWD can be determined with water vapour radiometer (WVR) and radiosondes. But both methods are expensive.

Tropospheric delays vs Elevation angles

Elevation angle (degrees)	Hydrostatic delay (m)	Wet delay (m)
90	2.3	0.2
30	4.6	0.4
10	13.2	1.2
5	26.4	2.3

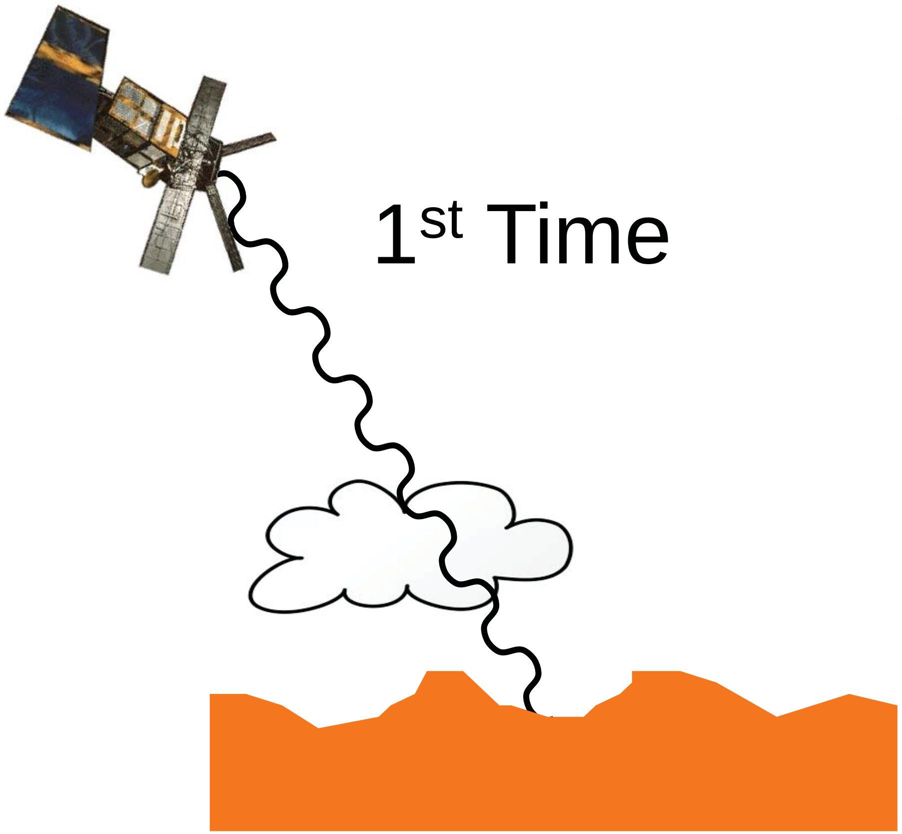
- The lower the elevation angle, the greater the delay
- Note: The table shows one-way delays only!

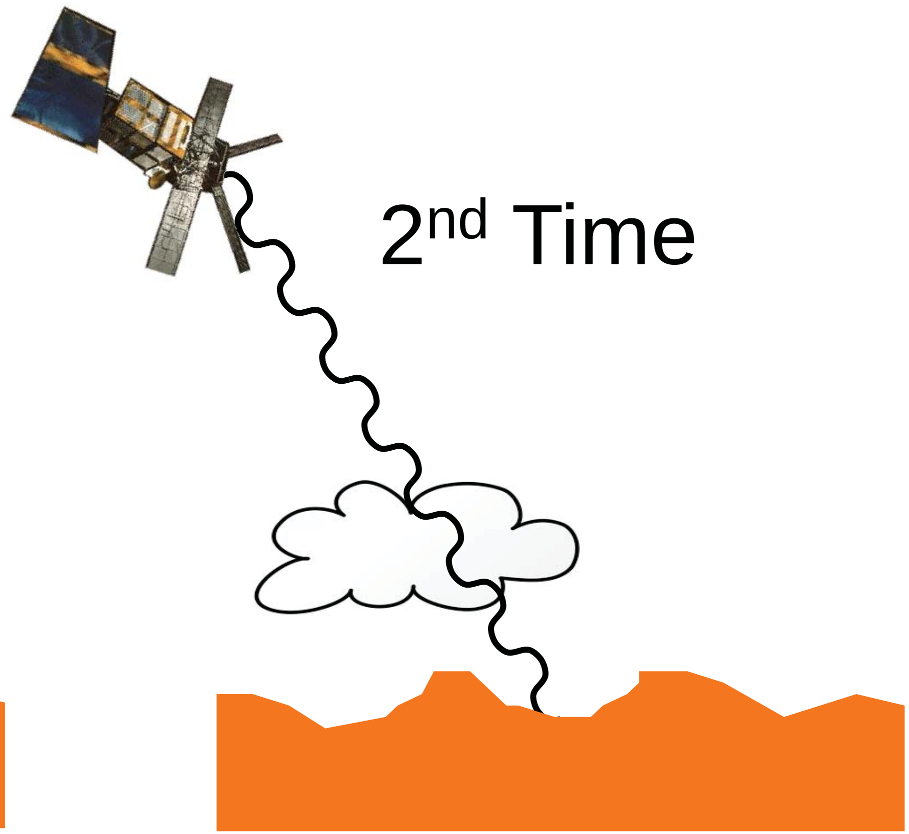
InSAR – how does it work?



InSAR – Ideal scenarios (NO atmospheric effect)

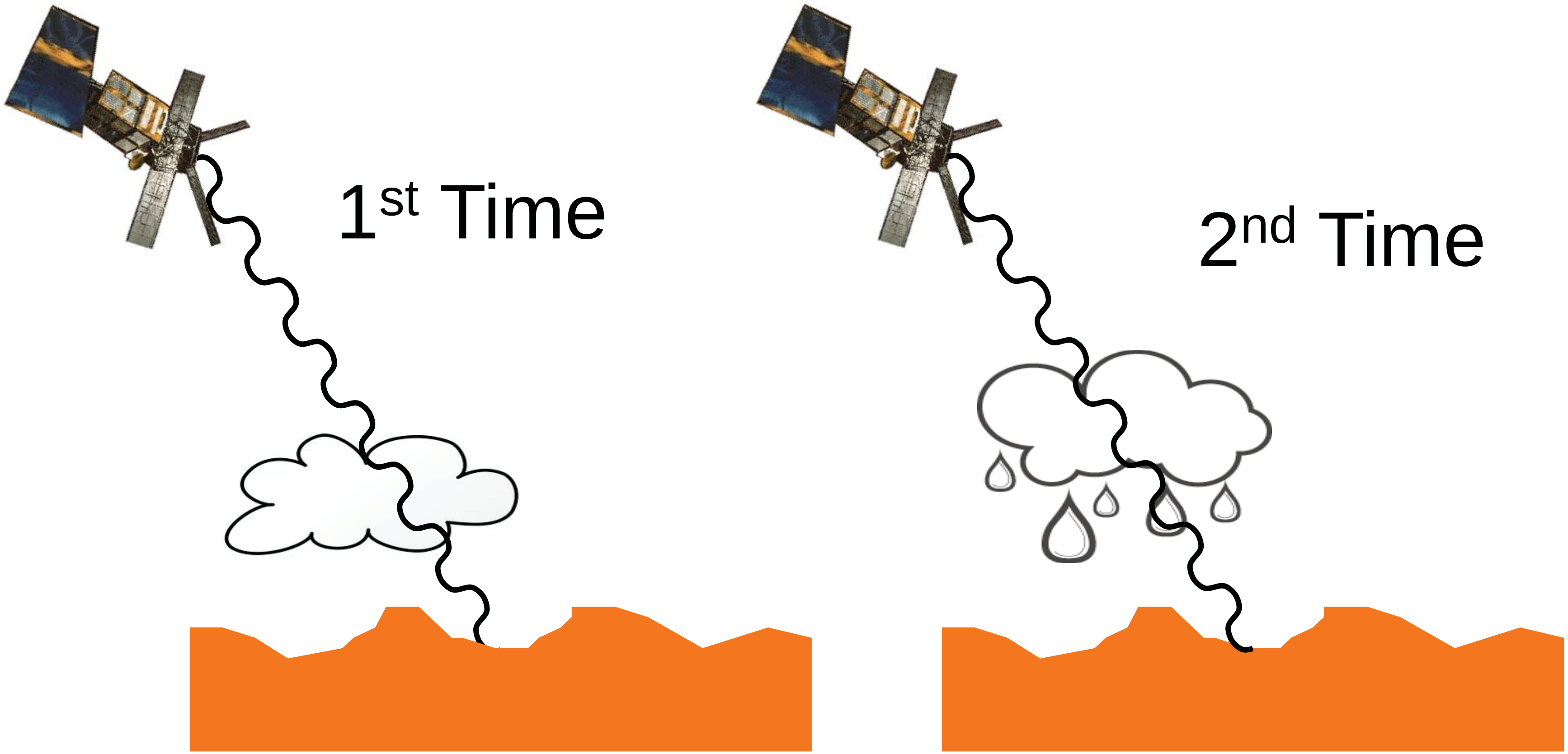
- Ideal scenarios: (1) no spatial variation; (2) no temporal variation; or (3) constant temporal change across the whole image





InSAR – atmospheric effects

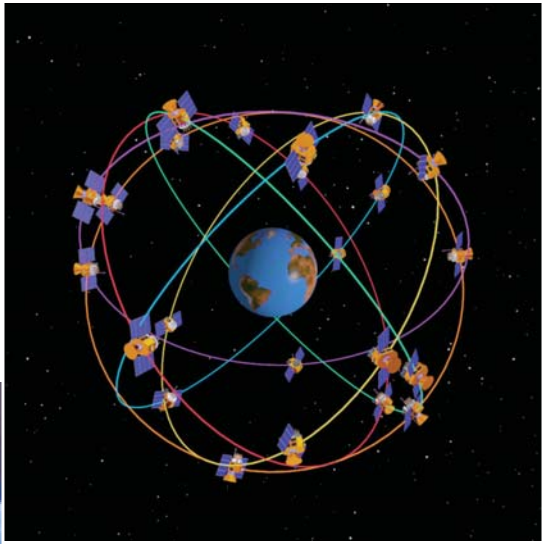
- Spatiotemporal variations in Atmosphere represent one of the major limitations of repeat-pass InSAR



Atmospheric water vapour products

- **GPS**

  (Global Positioning System)



- **MODIS**

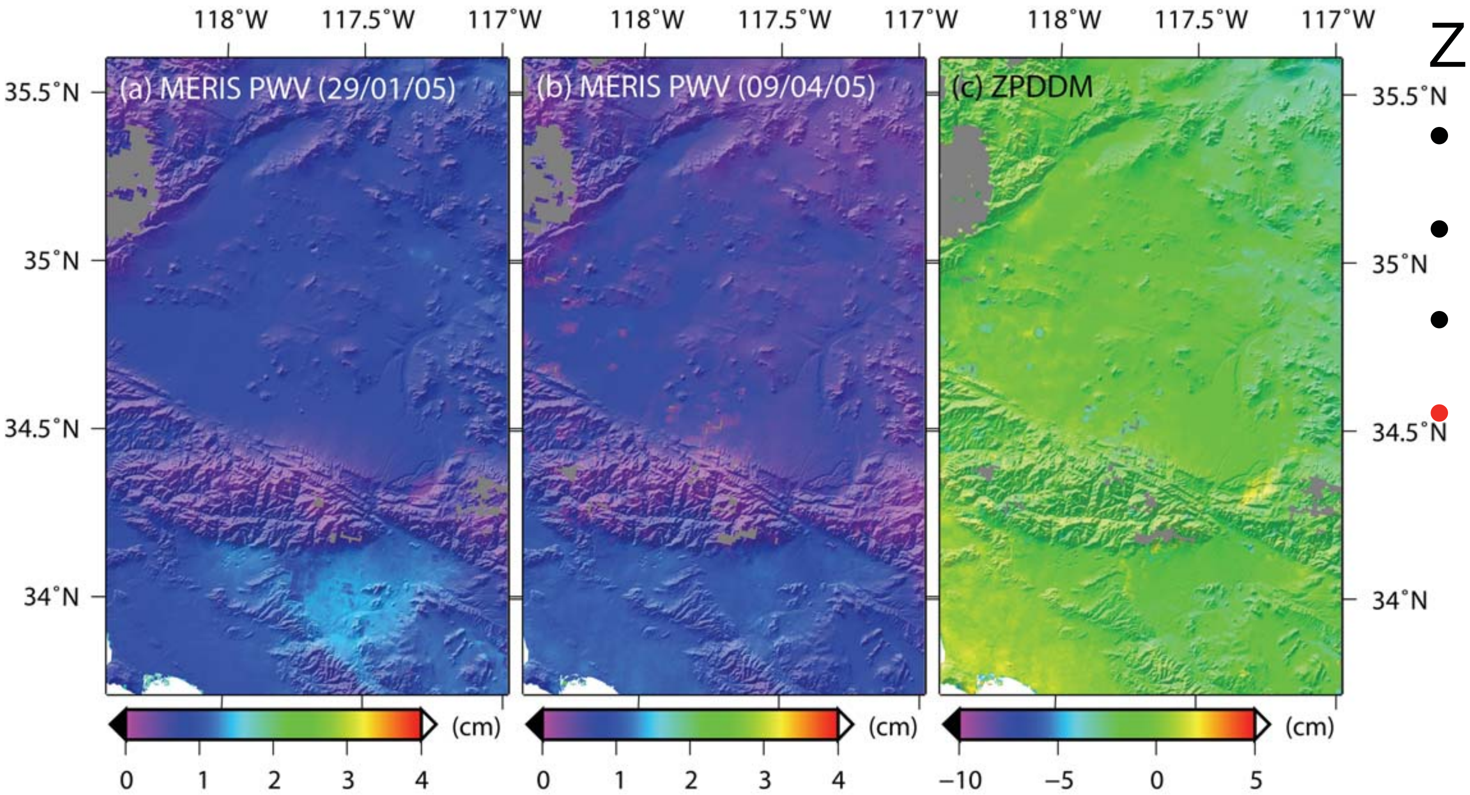
  (Moderate Resolution Imaging Spectroradiometer)

- **MERIS**

  (MEdium Resolution Imaging Spectrometer)

Atmospheric water vapour effects (limited)

Southern California (29 Jan 2005 – 09 Apr 2005)



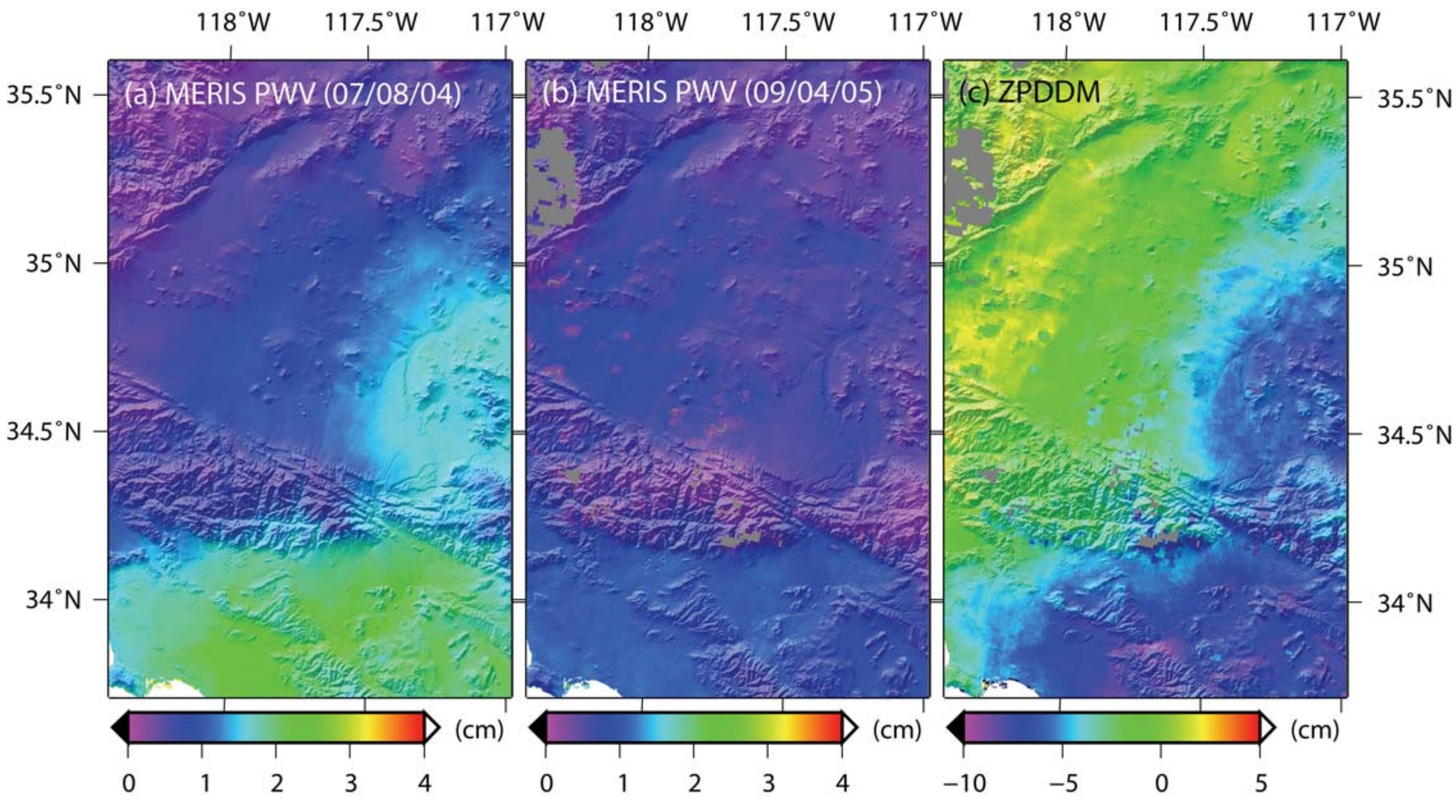
ZPDDM

- Max: 7.8 cm
- Min:-5.2 cm
- Mean: -0.9 cm
- StdDev: 1.0 cm

- 1 mm of PWV => ~6.2 mm of ZPD
- ZPDDM: Zenith Path Delay (ZPD) Difference Map

Atmospheric water vapour effects

Southern California (07 Aug 2004 – 09 Apr 2005)



ZPDDM:

Max: 2.7 cm

Min: -12.8cm

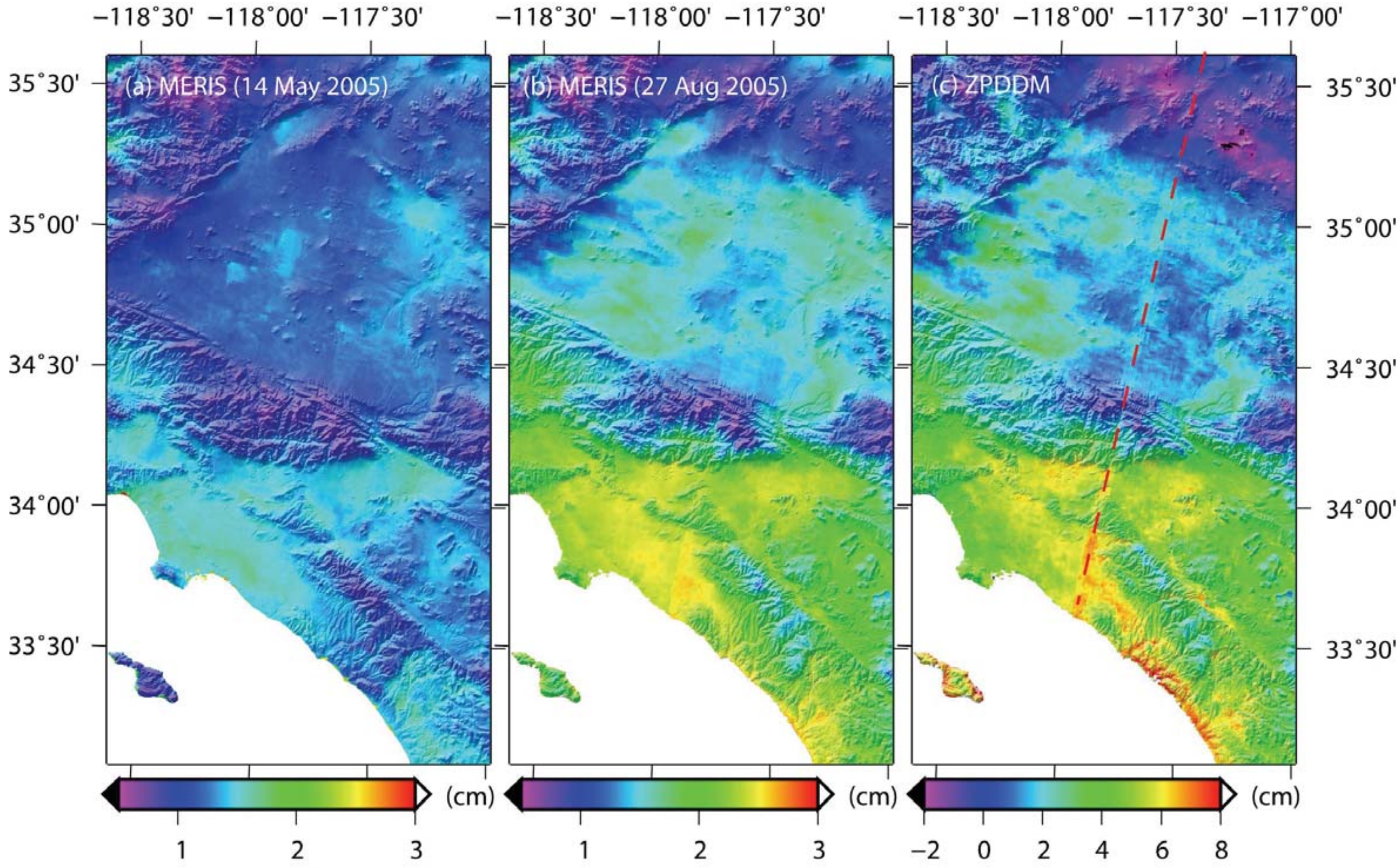
Mean: -2.9 cm

StdDev:
2.9 cm

N.B. Strong gradient in Figure (a)

Atmospheric water vapour effects

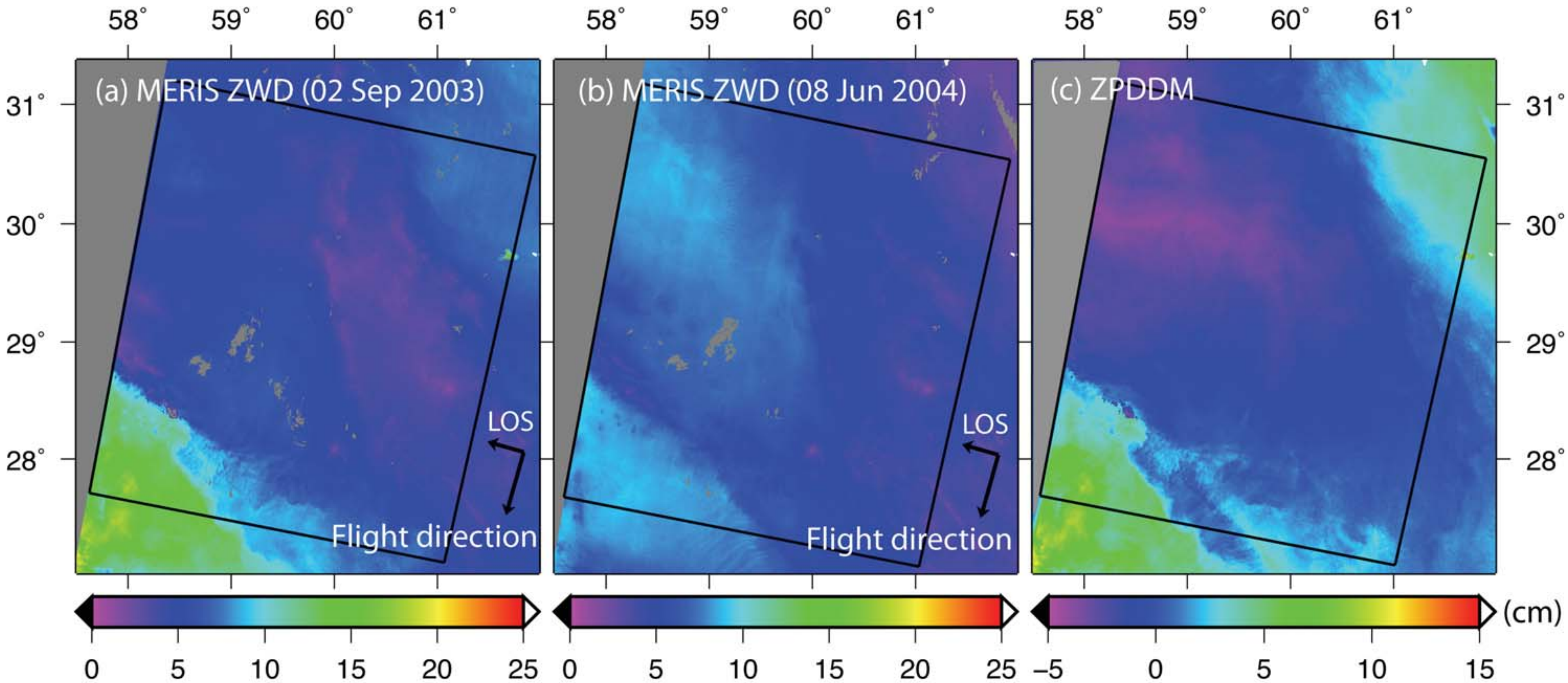
Southern California (14 May 2005 – 27 Aug 2005)



Red dashed line: MERIS camera border artefact (Camera 4)

Atmospheric water vapour effects

Bam, Iran



***ZPDDM* = *ZPD* (Day 2) - *ZPD* (Day 1)**

(Li et al., 2011, IEEE GRSL)

InSAR water vapour correction models

- Ground-based measurements (GPS)

  Li et al (2006); Onn & Zebker (2006); Xu et al (2011)

- Space-based water vapour measurements (MERIS, MODIS)

  Li et al (2005, 2006, 2009, 2011); Puysségur et al (2007)

- Numerical Weather Models (UM, MM5/WRF, ECMWF):

  Wadge et al (2002), Foster et al (2006; 2013), Puysségur et al (2007), Jolivet et al. (2011; 2013)

- JPL OSCAR

N.B. This is an incomplete list!

GPS Topography-dependent Turbulence Model (GTTM)

❖ **Underlying assumptions of GTTM:**

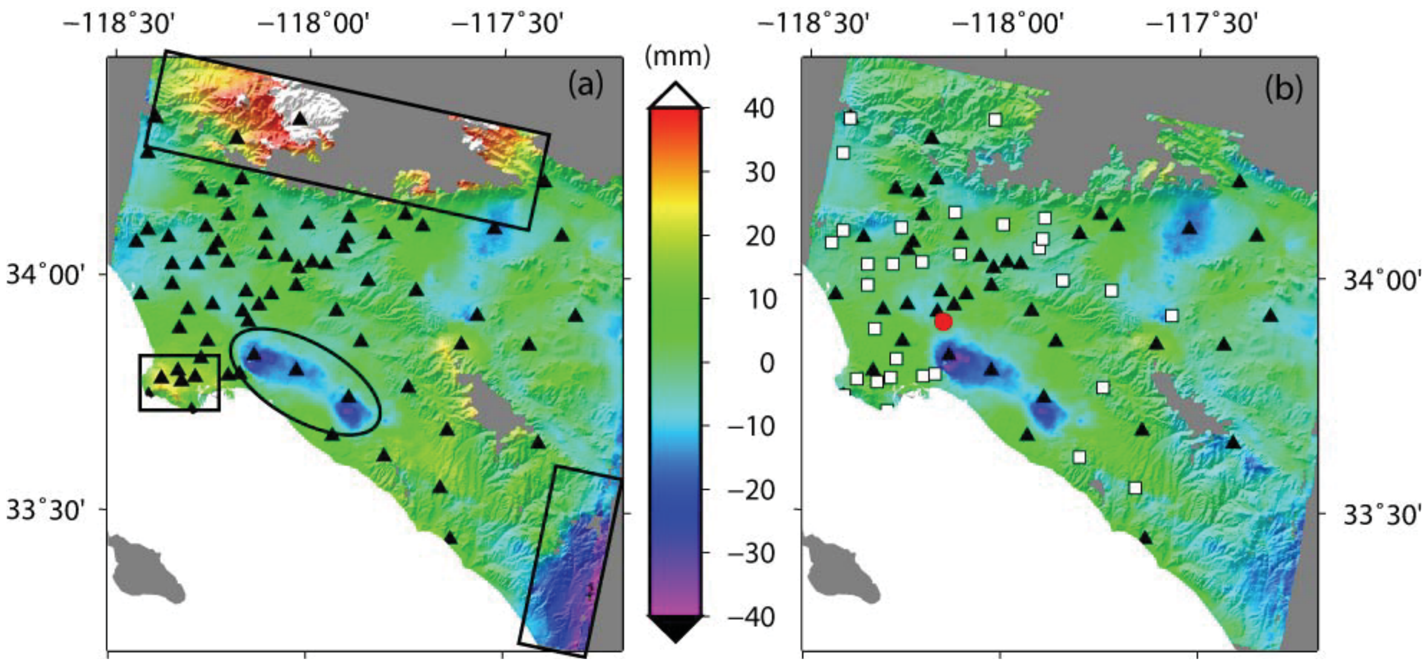
- Water vapour variations conform temporally and spatially to a statistical turbulent model;
- Water vapour distributions are correlated with topography to some extent.

◆ **Key features:**

- The reduction of topography-independent water vapor effects is limited by the spatial distribution of GPS stations
- Topography-dependent effects can be significantly reduced

(Li et al., 2006, JGR)

GPS Topography-dependent Turbulence Model (GTTM)



(Total: 77; White Square: 32; Red circle: 1)

- **Range changes: GPS vs. InSAR** **1.1cm ⇒ 0.6cm**
- **Black oval: Uplift**
- **Rectangles: water vapour signals**

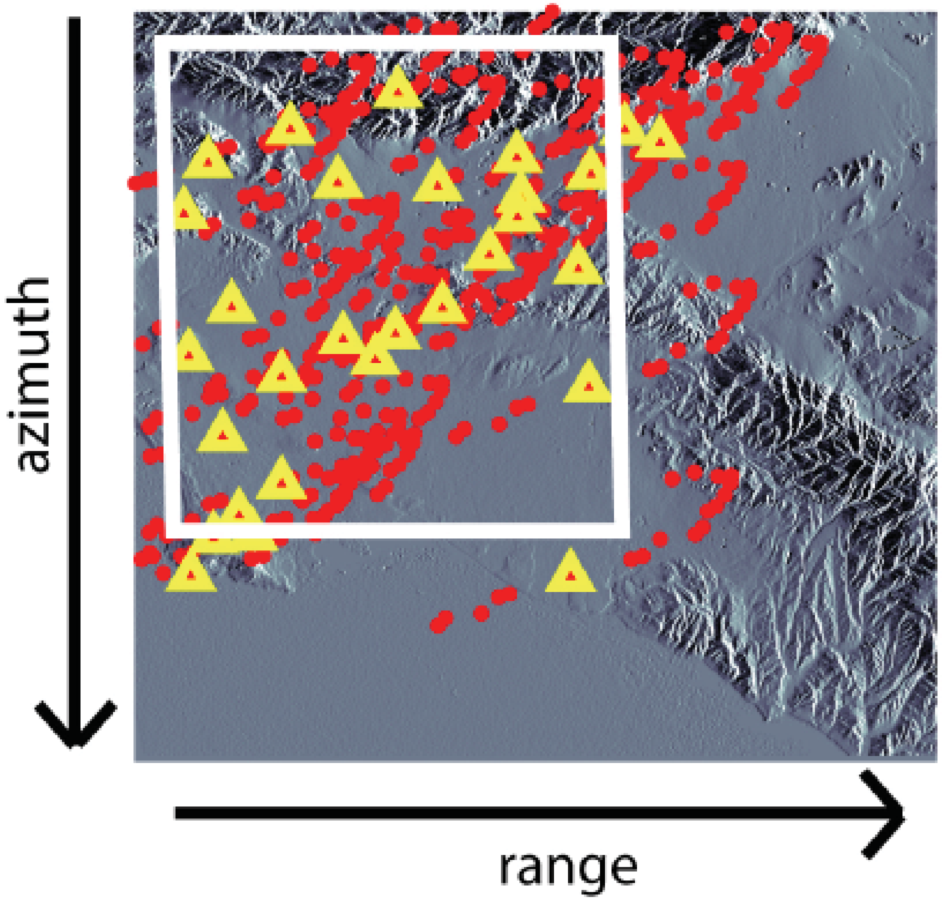
(1) black solid triangles represent GPS stations w/o changes after correction;

(2) white squares with black borders imply improvement after correction;

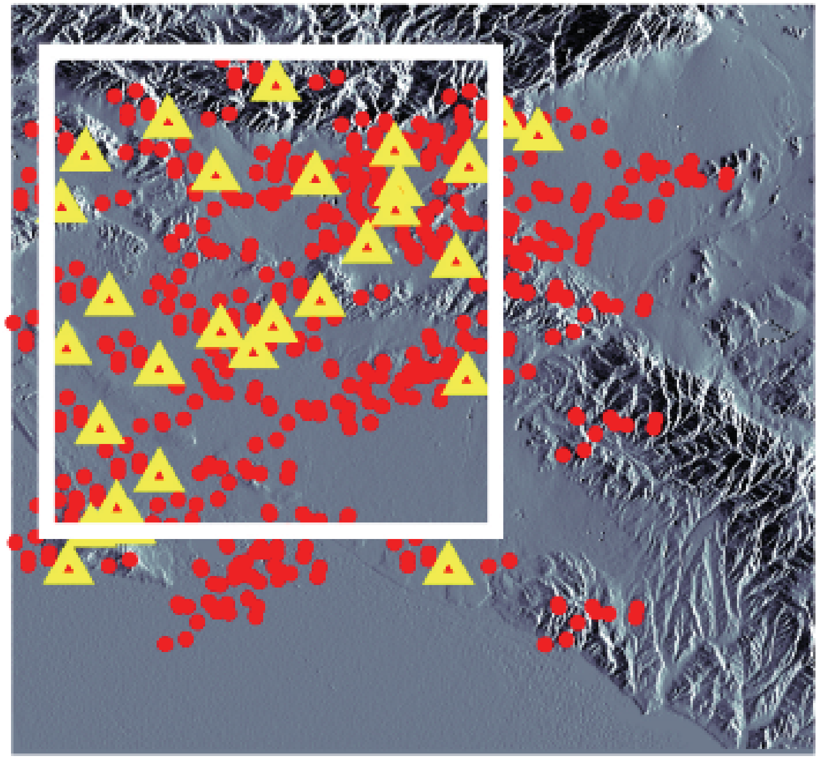
(3) red solid circles indicate deterioration after correction (Li et al., 2006, JGR)

CGPS: Frozen-flow Air

Spatial distribution of GPS ZWD on Feb 5th 2000 after application of "frozen-flow" hypothesis

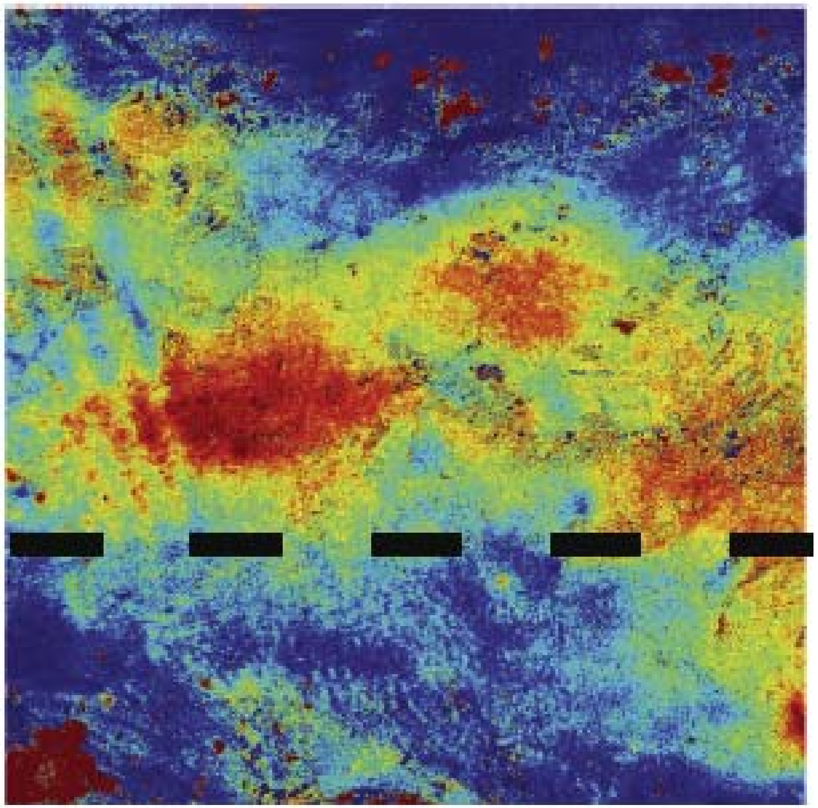


Spatial distribution of GPS ZWD on Nov 27th 1999 after application of "frozen-flow" hypothesis

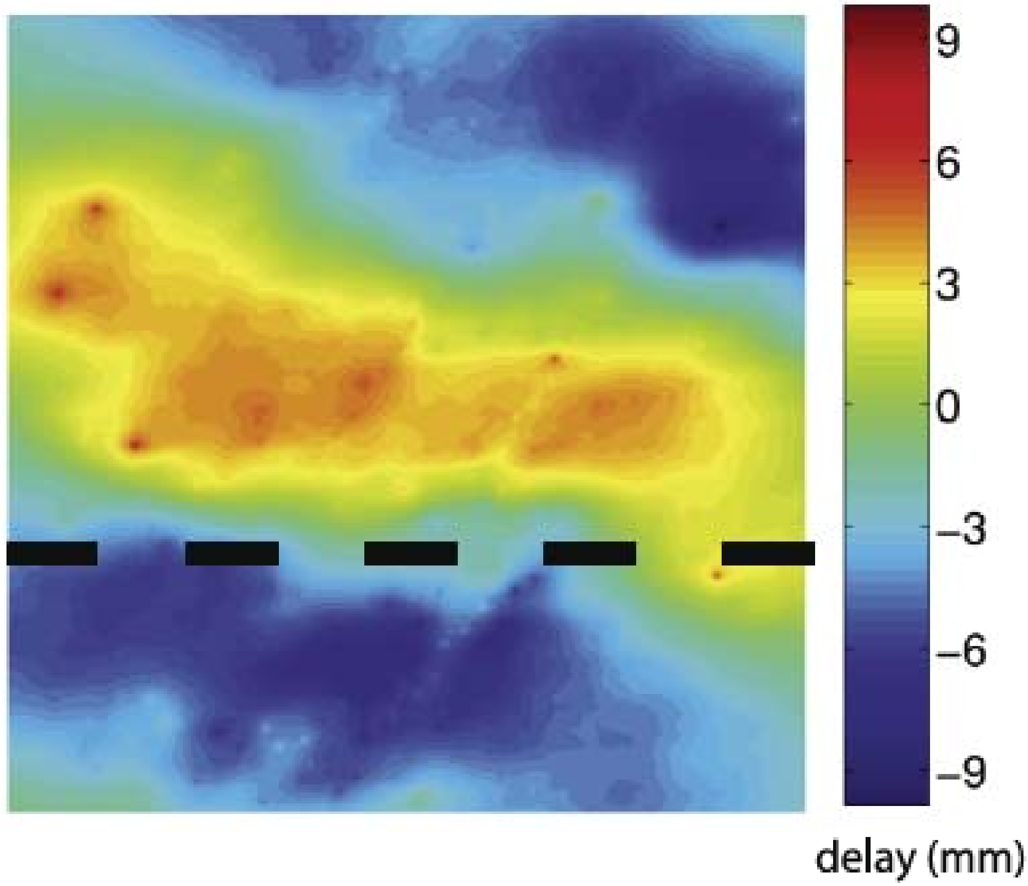


(Onn and Zebker, 2006)

CGPS: Frozen-flow Algorithm



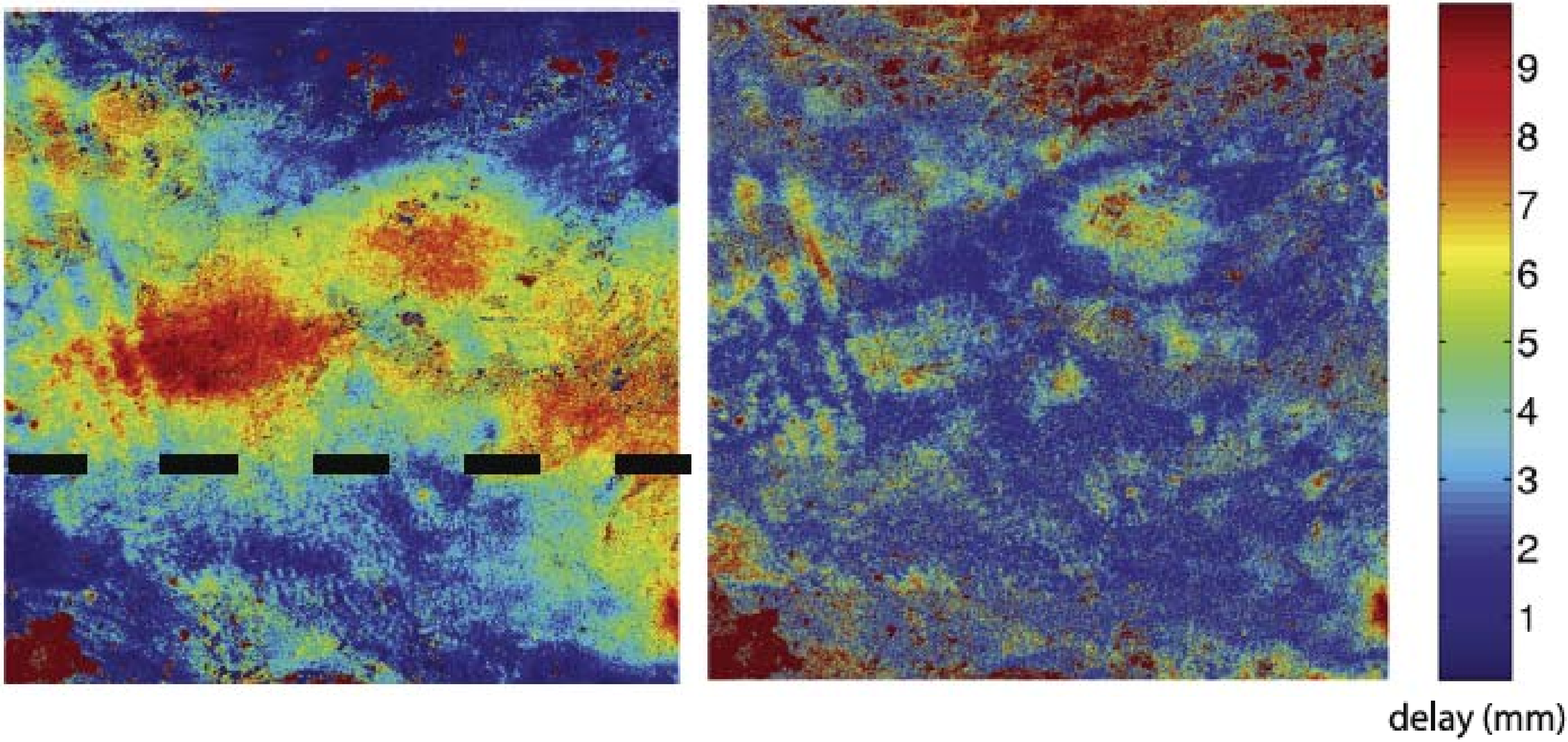
Interferogram



GPS ‘Frozen-flow’ Path Delay

(Onn and Zebker, 2006)

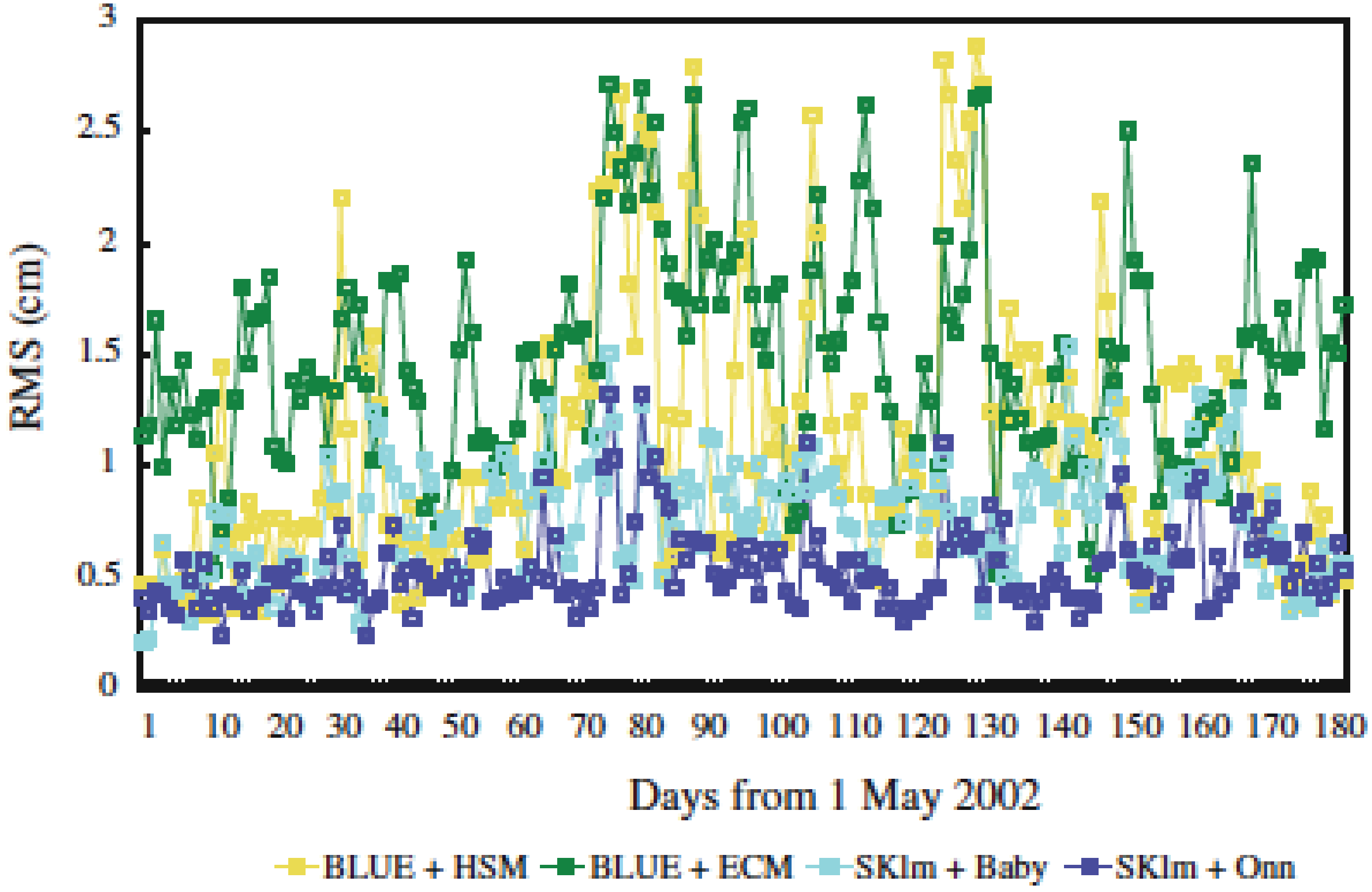
CGPS: Frozen-flow Algorithm



Interferogram Residual

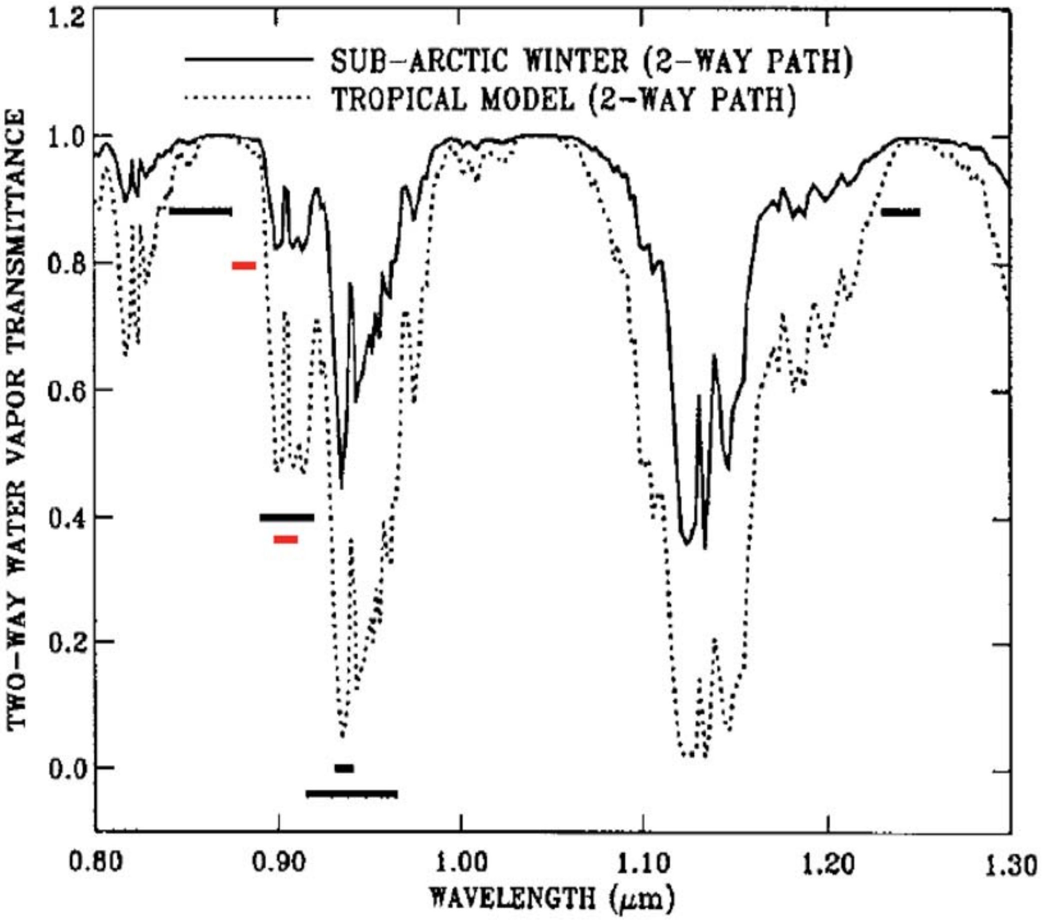
(Onn and Zebker, 2006)

CGPS: Simple Kriging + Frozen-Flow Air



(Xu et al., 2011, J. Geodesy)

MODIS/MERIS Channel Positions related with PWV



MODIS:

- **2 non-absorbing**
- **3 absorbing**

MERIS:

- **1 non-absorbing**
- **1 absorbing**

(Figure adapted from *Gao and Kaufman* [1998])

- **PWV retrievals rely on channel ratio techniques**

MODIS water vapour correction model

❖ **Basic principles:**

- There is a scale uncertainty in MODIS near-IR water vapour products (*Li et al.*, 2003, JGR)
- Only one continuous GPS station is required to calibrate MODIS scale uncertainty within a 2,030 km × 1,354 km MODIS scene
- GPS and MODIS data can be integrated to provide regional water vapour fields with a spatial resolution of 1 km × 1 km
- ~60 minute time difference between ENVISAT and MODIS

(Li et al., 2005, JGR)

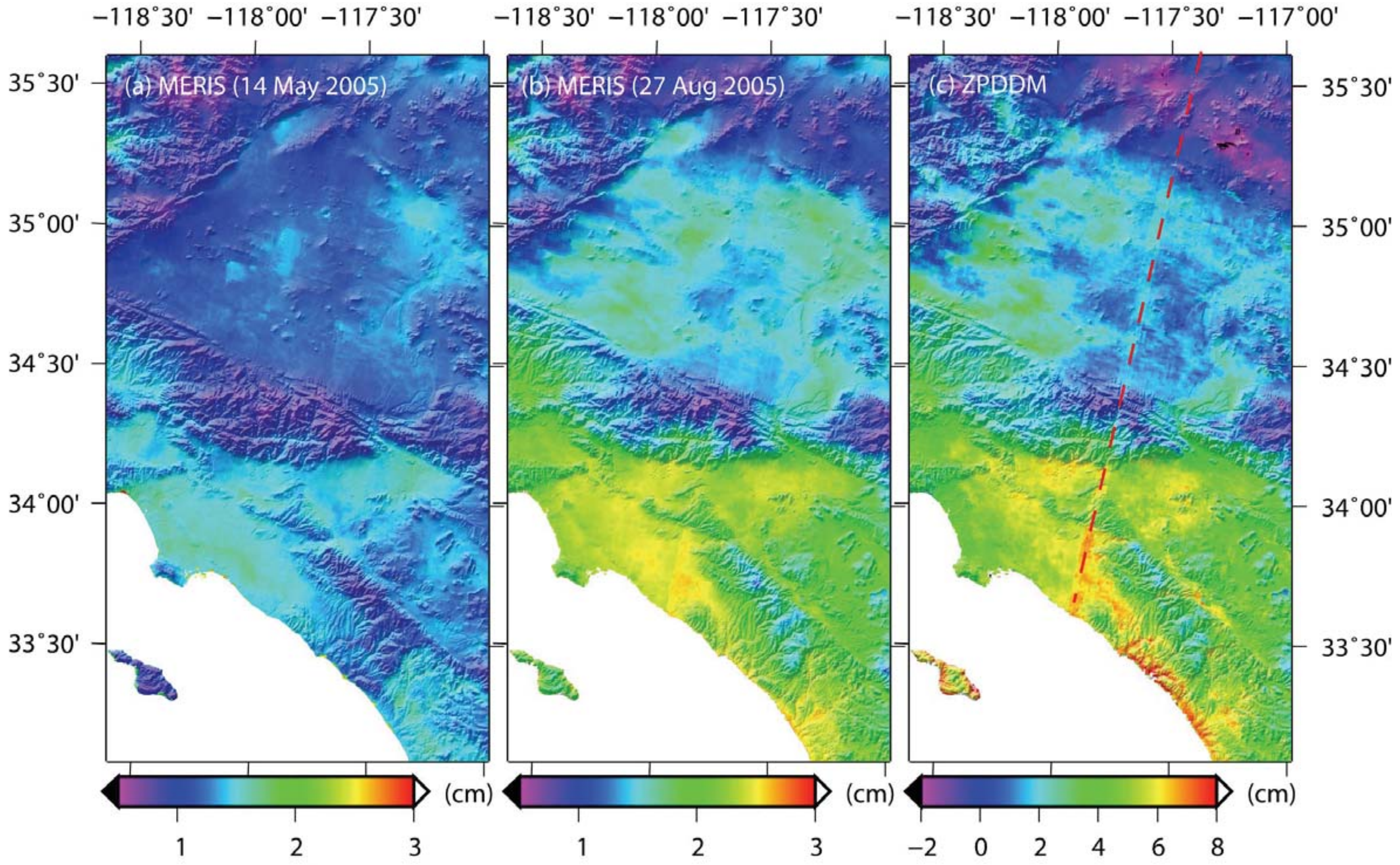
MERIS water vapour correction model

- MERIS data can be acquired at the same time as ASAR data (time differences between MODIS and SAR data: ~1 hour)
- MERIS has better spatial resolution, up to 300 m against 1km for MODIS
- MERIS near IR water vapour product agrees more closely with GPS than MODIS (though MODIS cloud mask is more robust)

(Li et al., 2006, GRL; Li et al., 2009, IJRS)

MERIS water vapour and simulated Interferogram

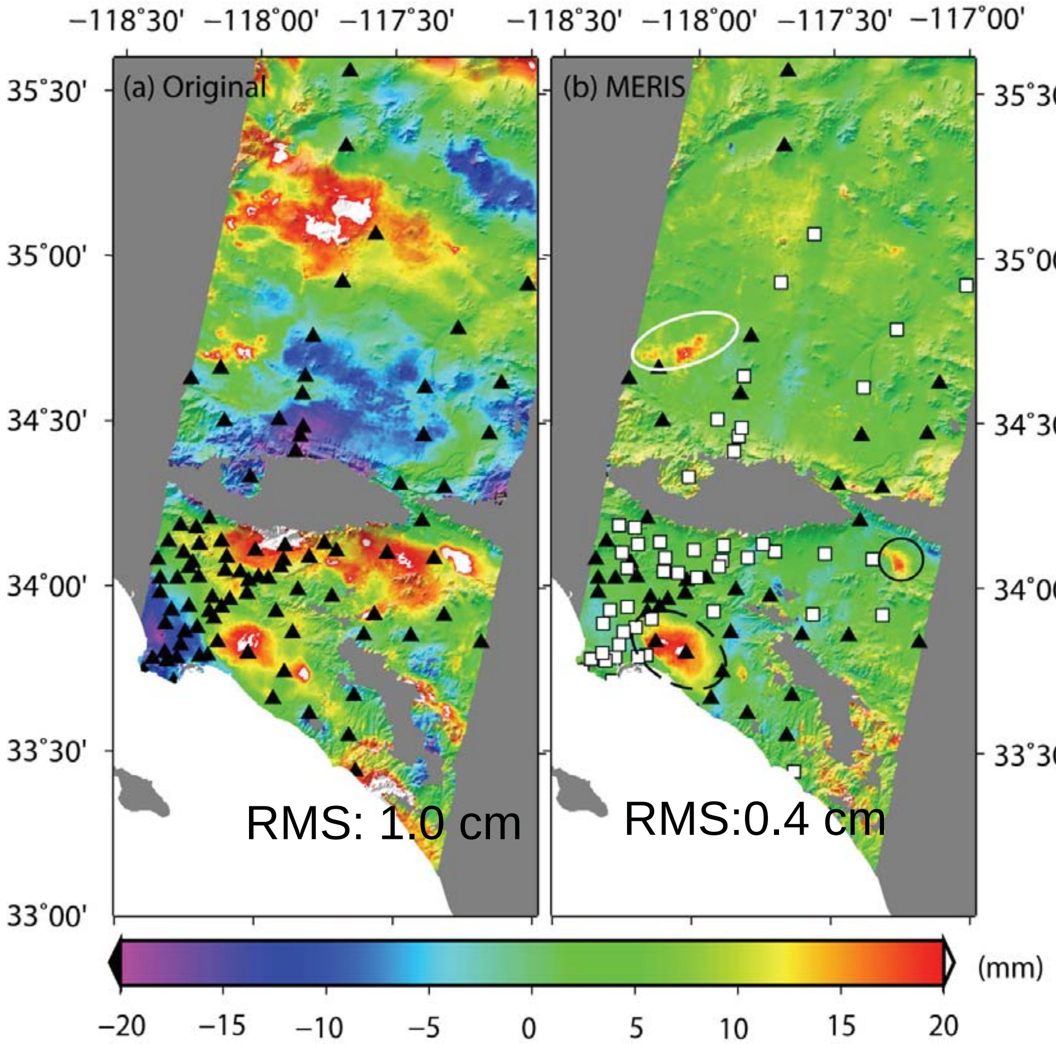
Southern California (20050514 – 20050827)



Red dashed line: MERIS camera border artefact (Camera 4)

MERIS water vapour correction model for IM ASAR

(Los Angeles: 20050514-20050827)



- **Range changes: GPS vs. InSAR** **1.0cm ⇒ 0.4cm**
- **Dashed black oval, Solid white oval, Solid black circle: Subsidence**

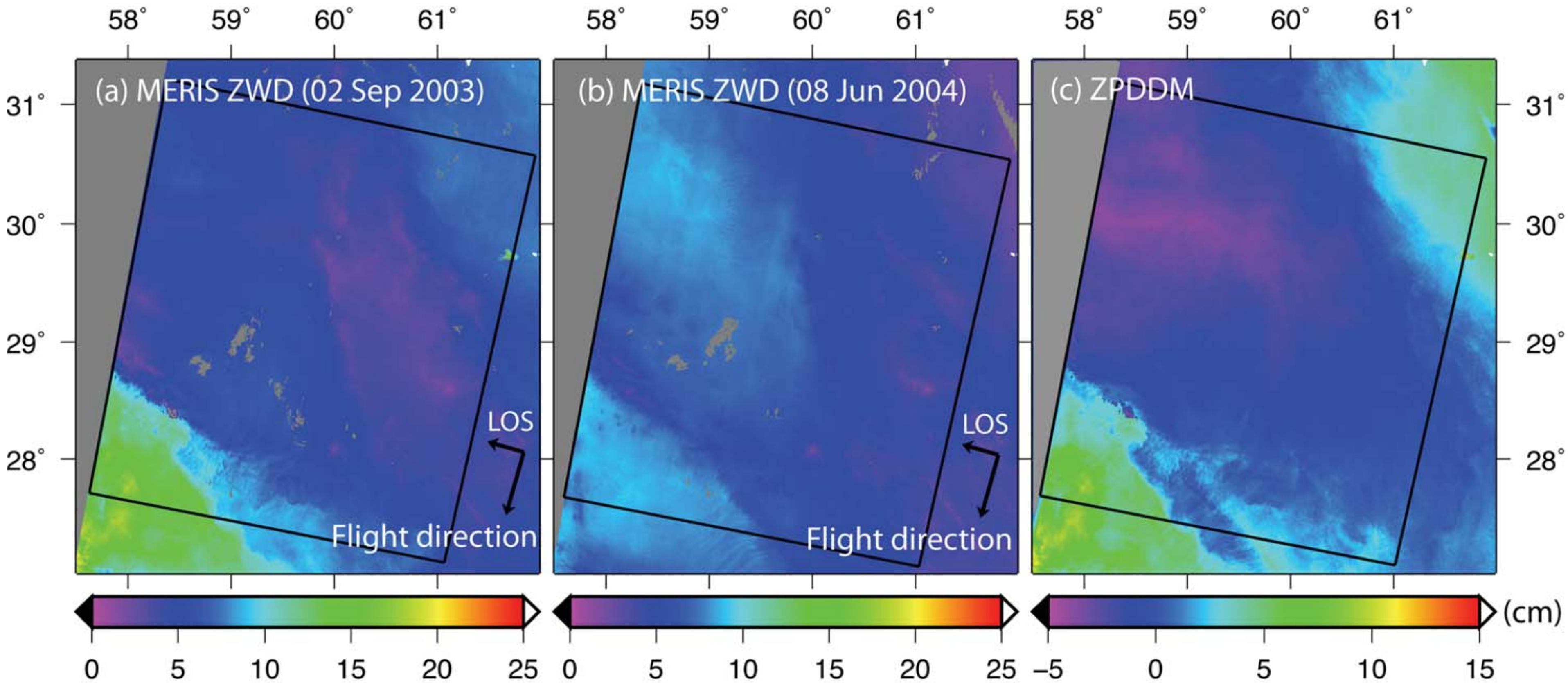
(1) black solid triangles represent GPS stations w/o changes after correction;

(2) white squares imply improvement after correction.

(Li et al., 2009, IJRS)

MERIS water vapour and simulated Interferogram

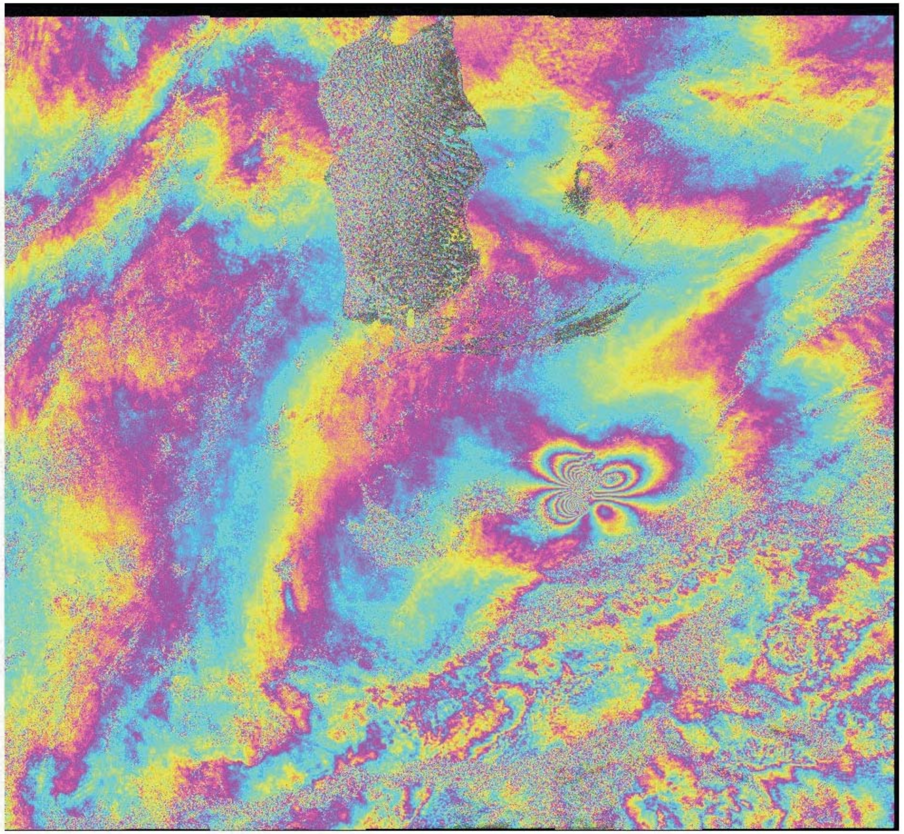
Bam, Iran



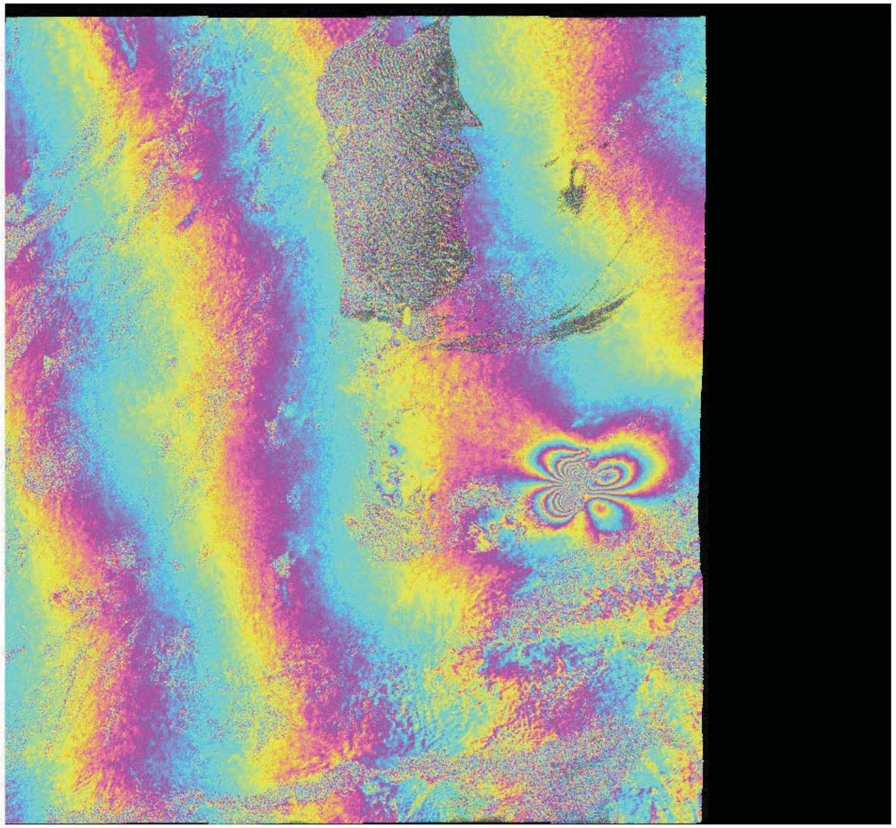
ZPDDM = ***ZPD*** *(Day 2)* - ***ZPD*** *(Day 1)*

(Li et al., 2011, IEEE GRSL)

MERIS water vapour correction model for WS ASAR (Bam)



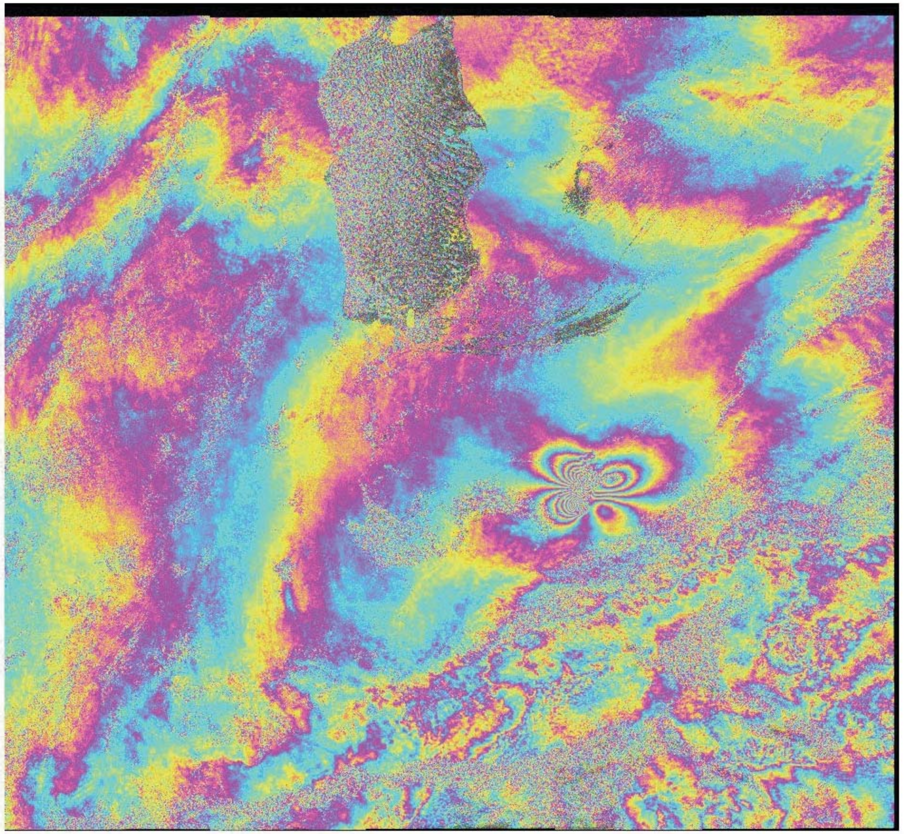
Original Interferogram



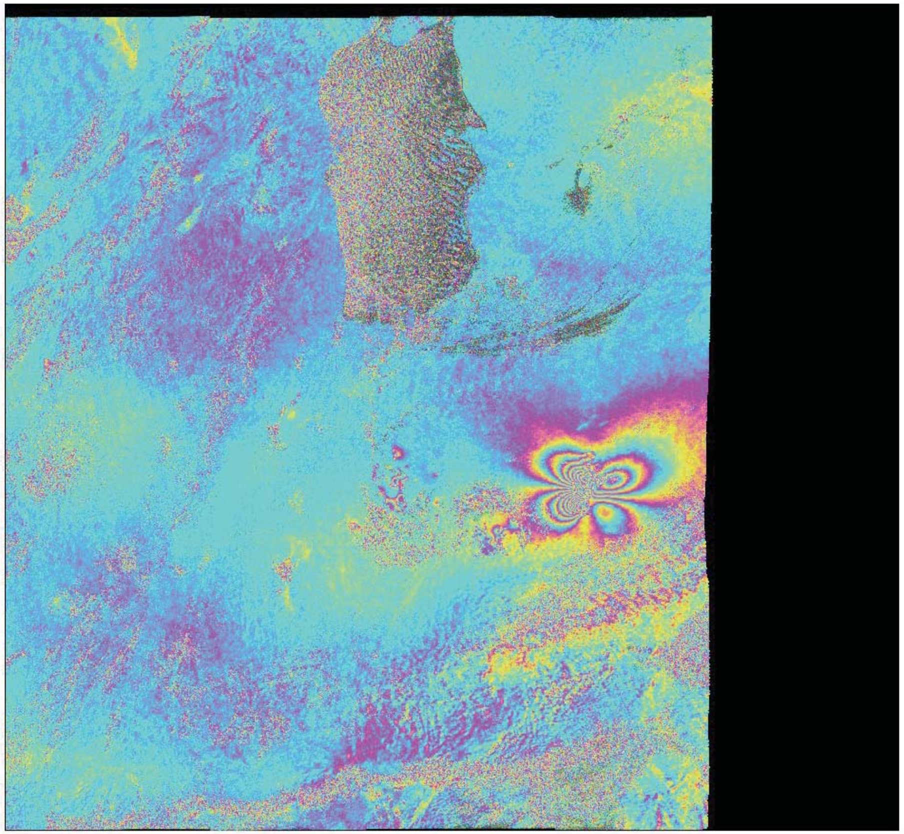
After MERIS water vapour correction

(Li et al., 2011, IEEE GRSL)

MERIS water vapour correction model for WS ASAR (Bam)



Original Interferogram



After orbital ramp removal

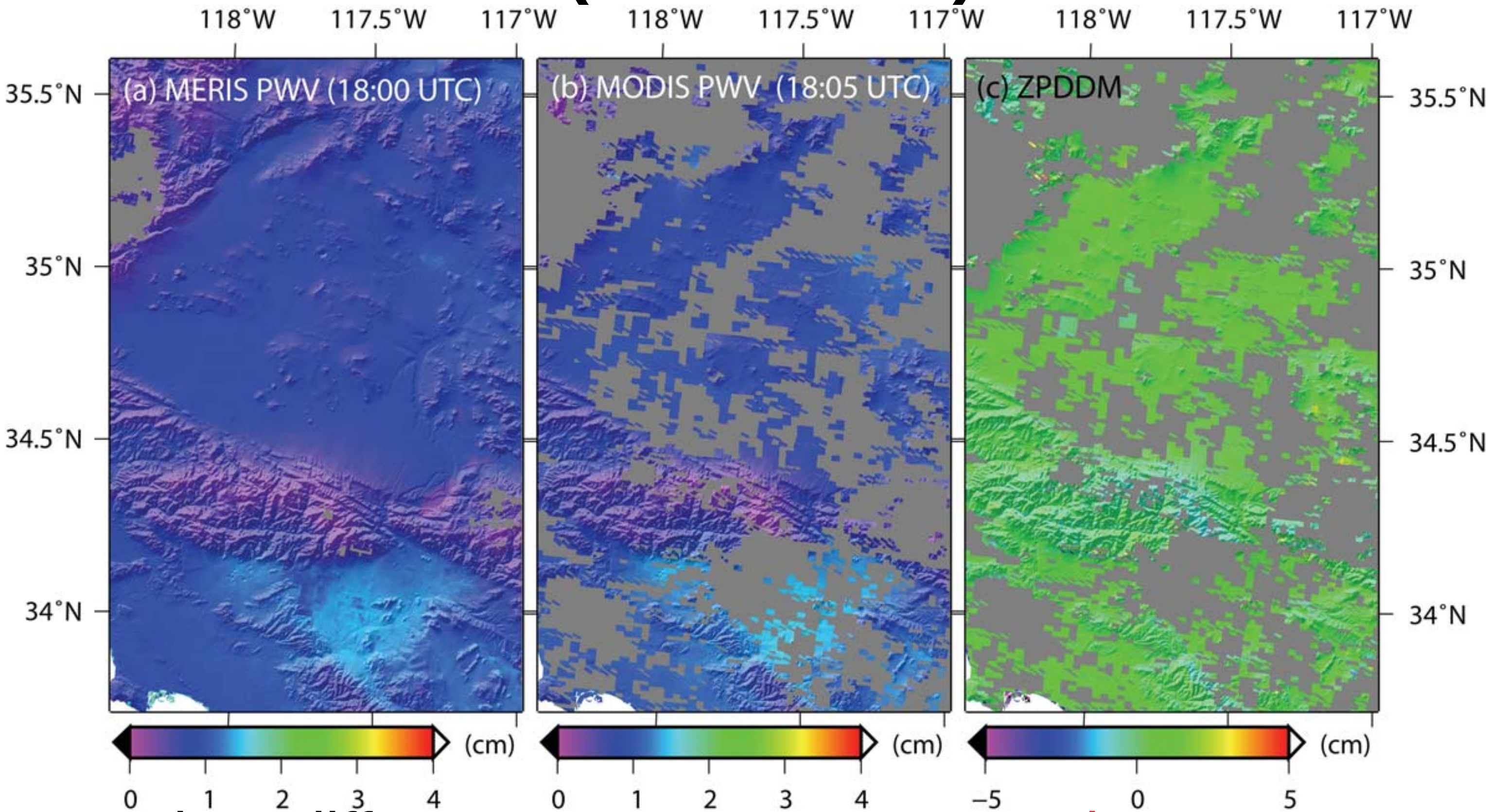
(Li et al., 2011, IEEE GRSL)

Time differences between MODIS and ERS/Envisat

- Terra MODIS descending node: 10:30 am (local time)
- ERS-2 descending node: 10:30 am (local time)
- ENVISAT descending node: 10:00 am (local time)
- MODIS-ERS time difference: <60 min (usually)
- MODIS-ASAR time difference: 30~60 min (normally)

Impact of time differences

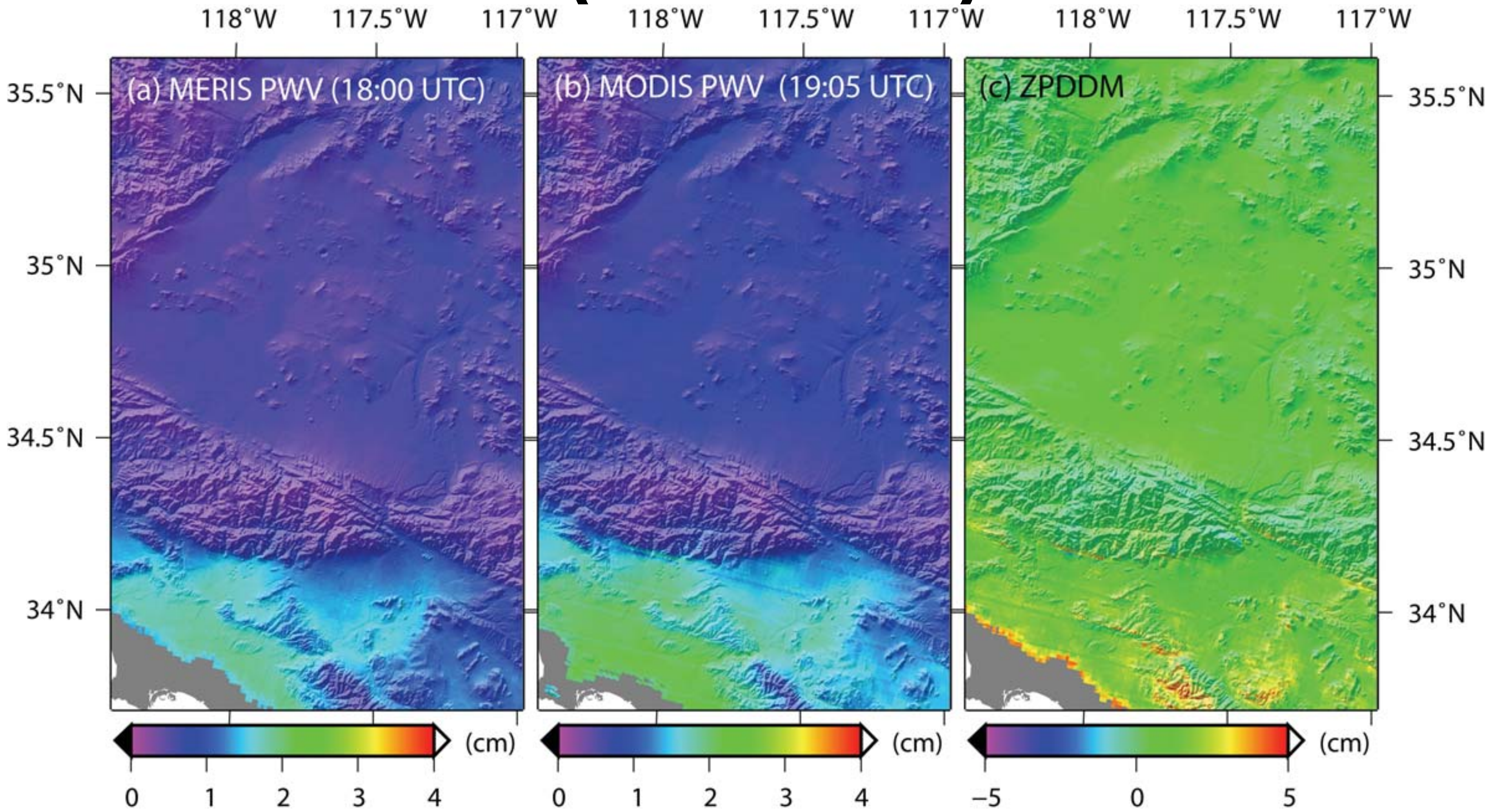
(2005/01/29)



- Time difference across scene: 5 min
- Little water vapour variation

Impact of time differences

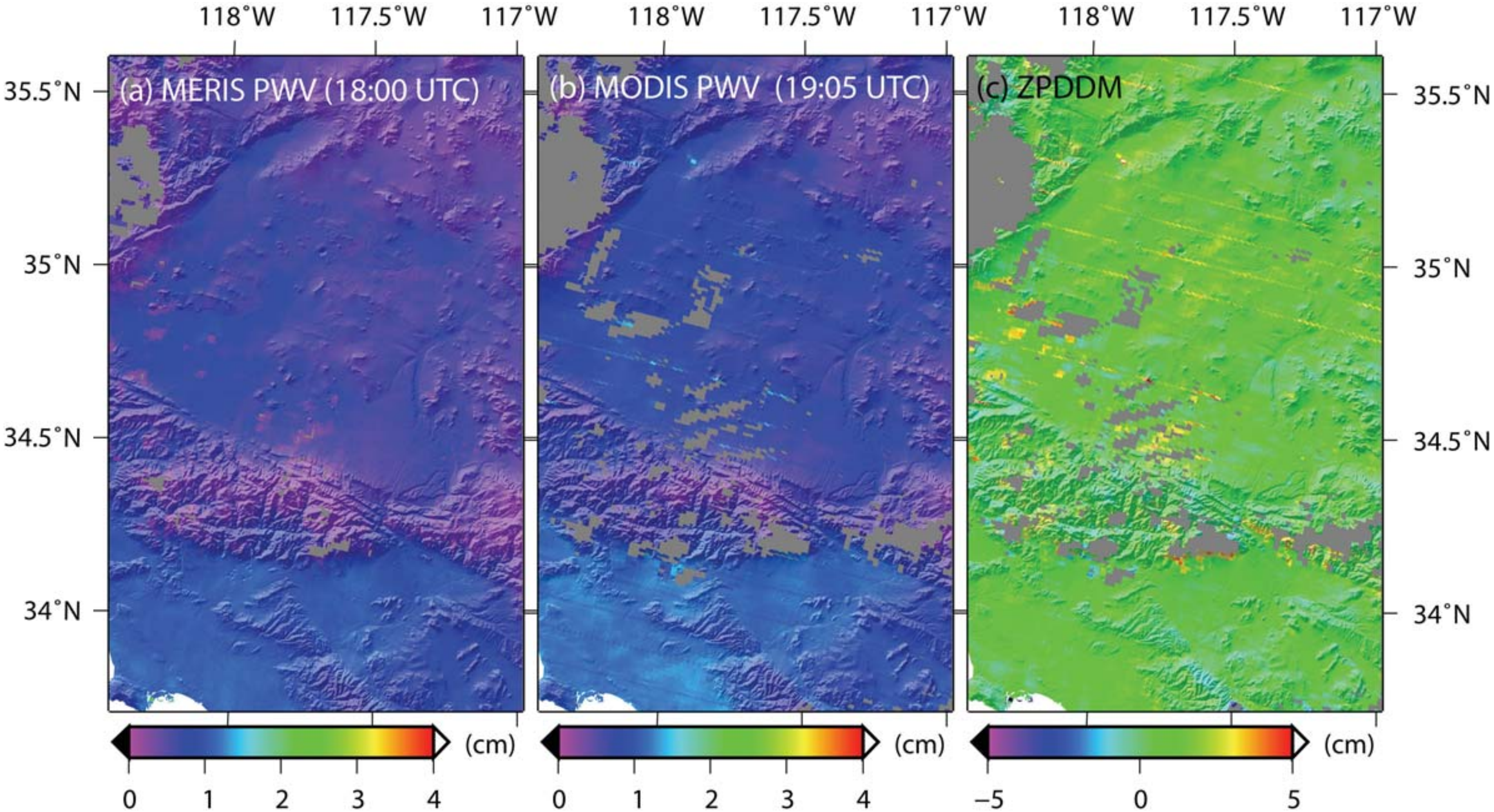
(2003/09/27)



- Time difference across scene: 65 min
- Little water vapour variation

Impact of time differences

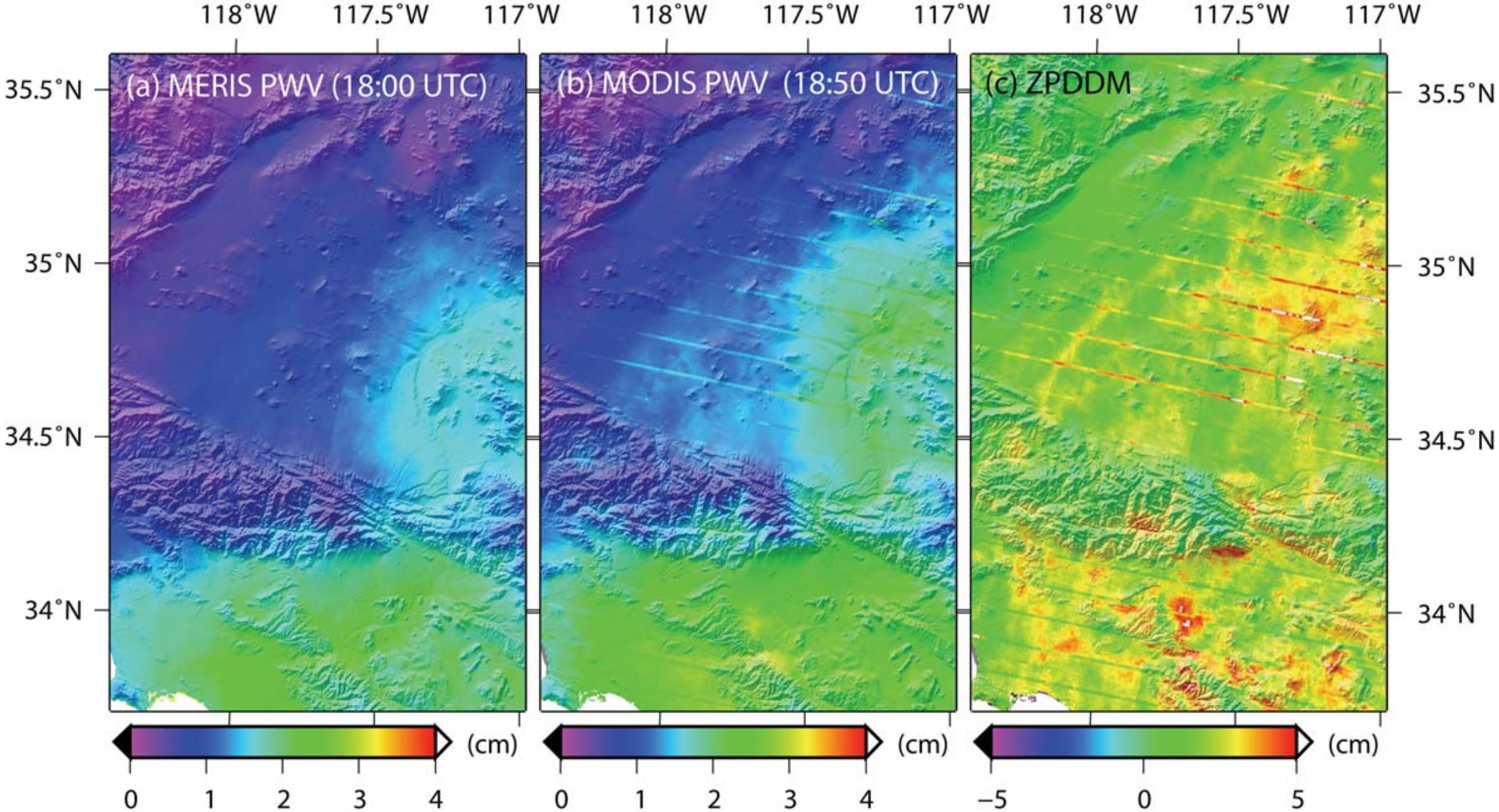
(2005/04/09)



- Time difference across scene: 65 min
- Little water vapour variation

Impact of time differences

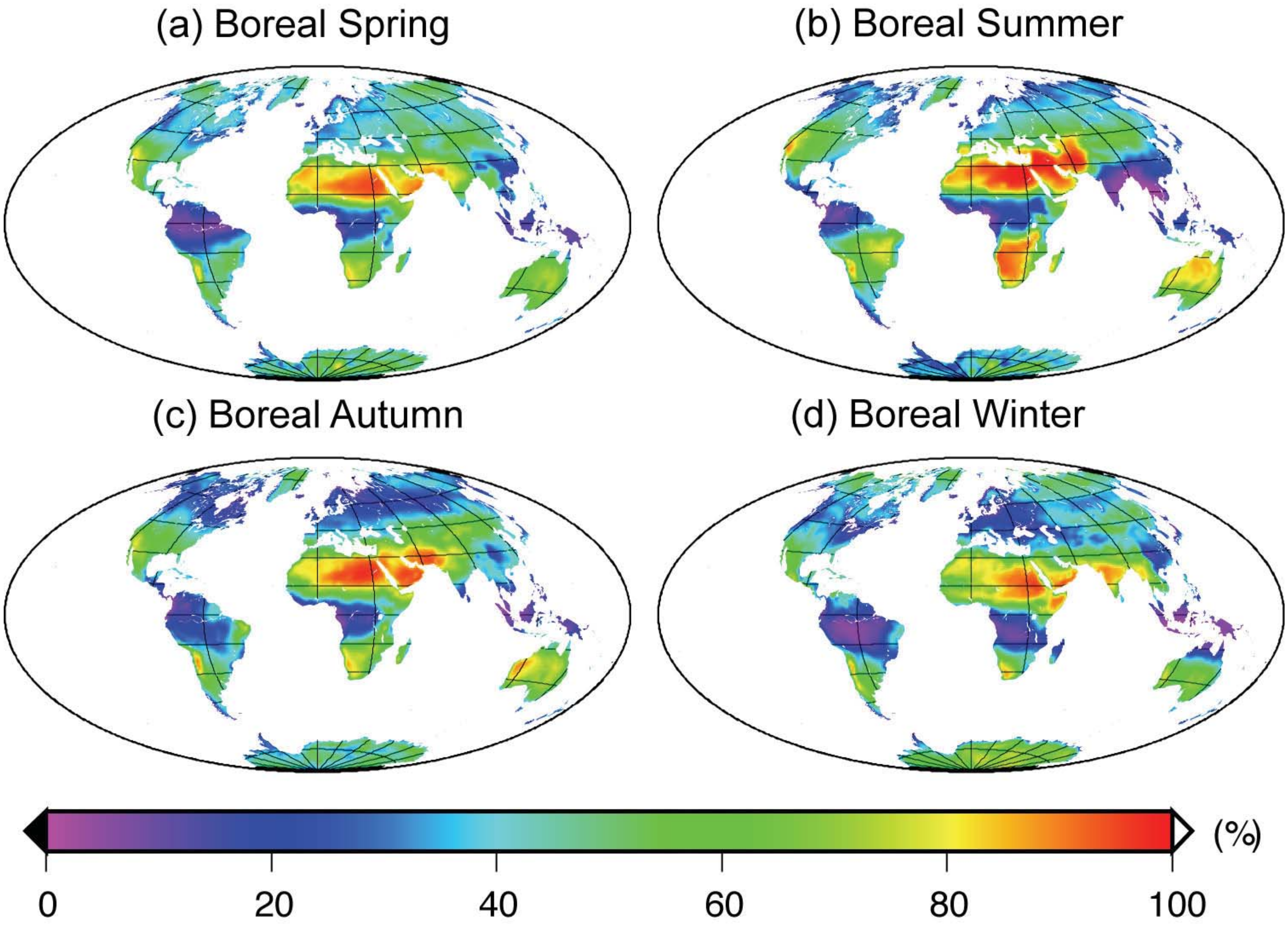
(2004/08/07)



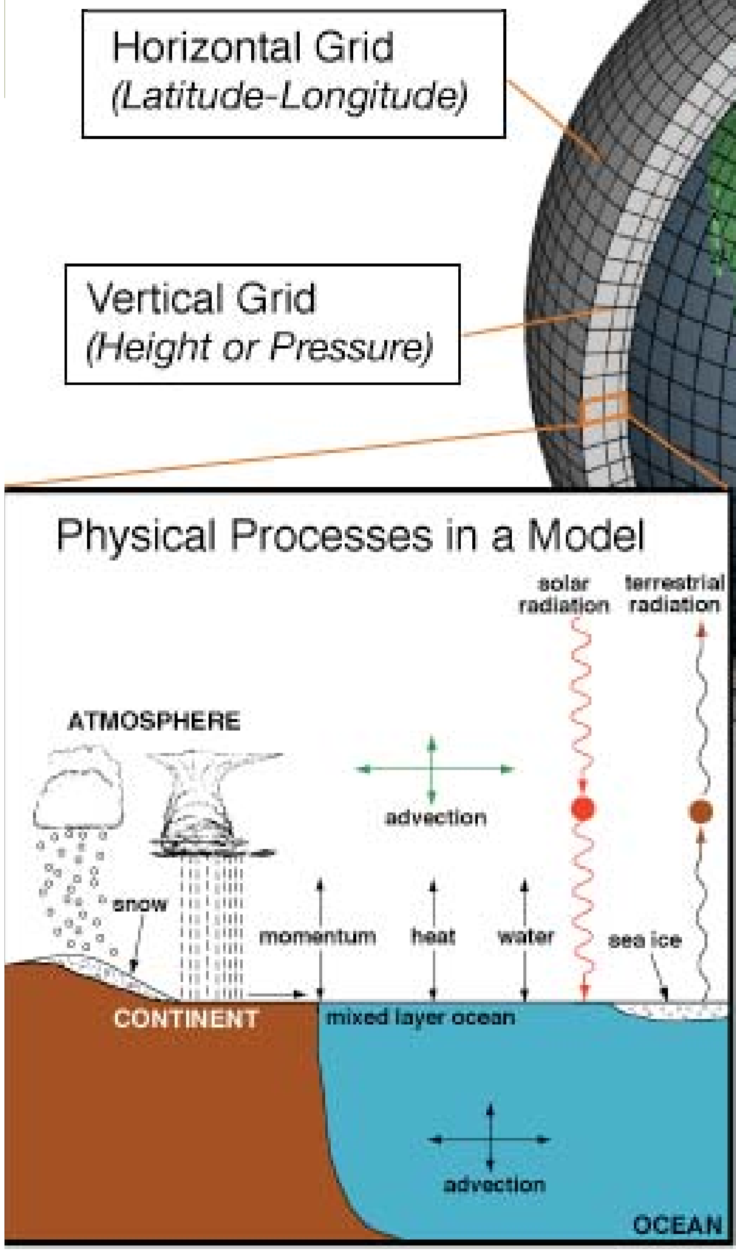
- Time difference across scene: 50 min
- Strong local water vapour variation

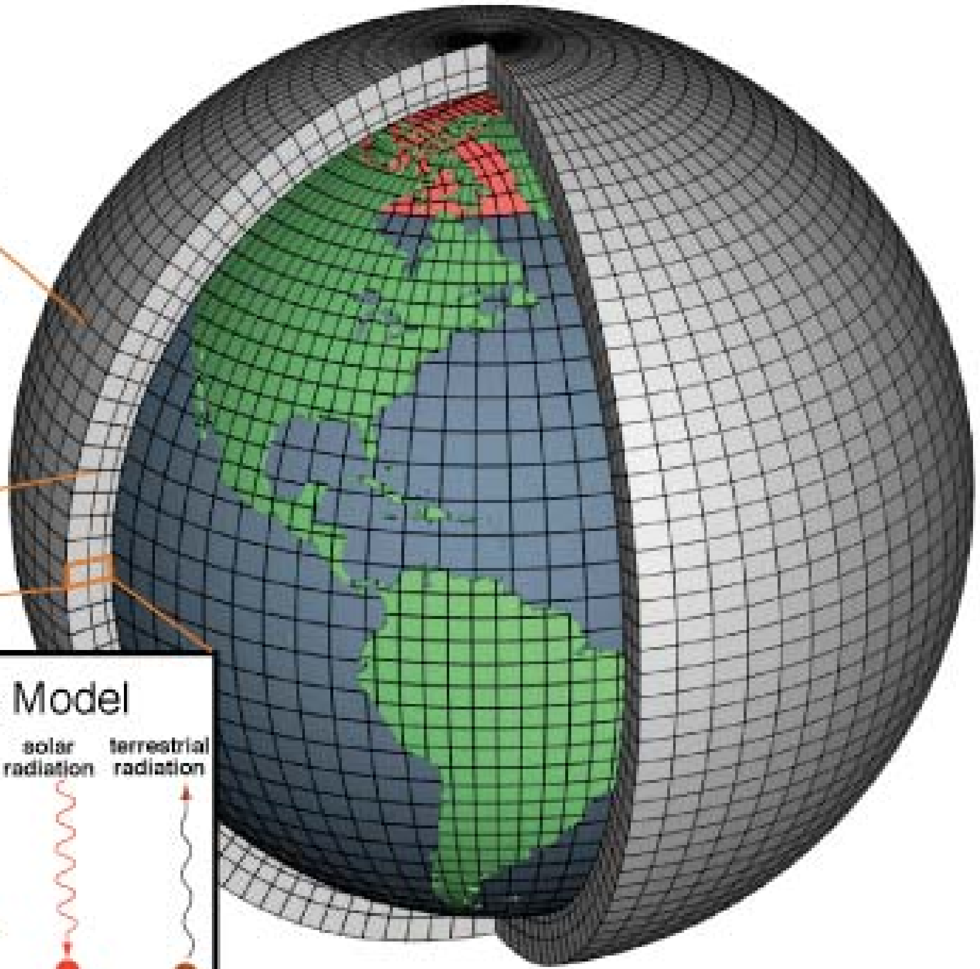
NB: Stripes are due to radiometric calibration errors in MODIS sensors.

Seasonal Frequencies of cloud free conditions



Numerical Weather Models

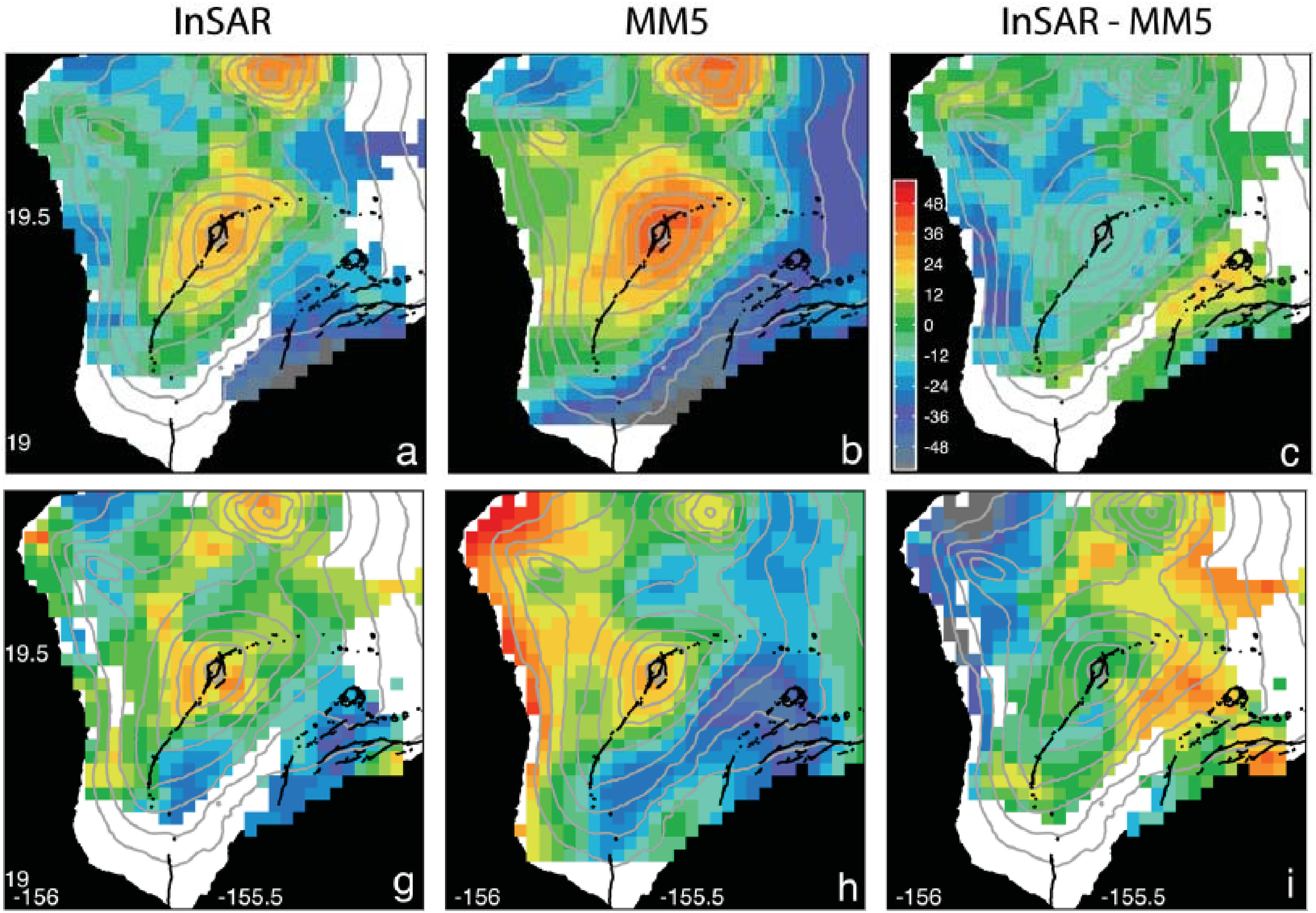




- Global/regional/local coverage
- High-resolution
- Continuous
- Insensitive to the presence of clouds

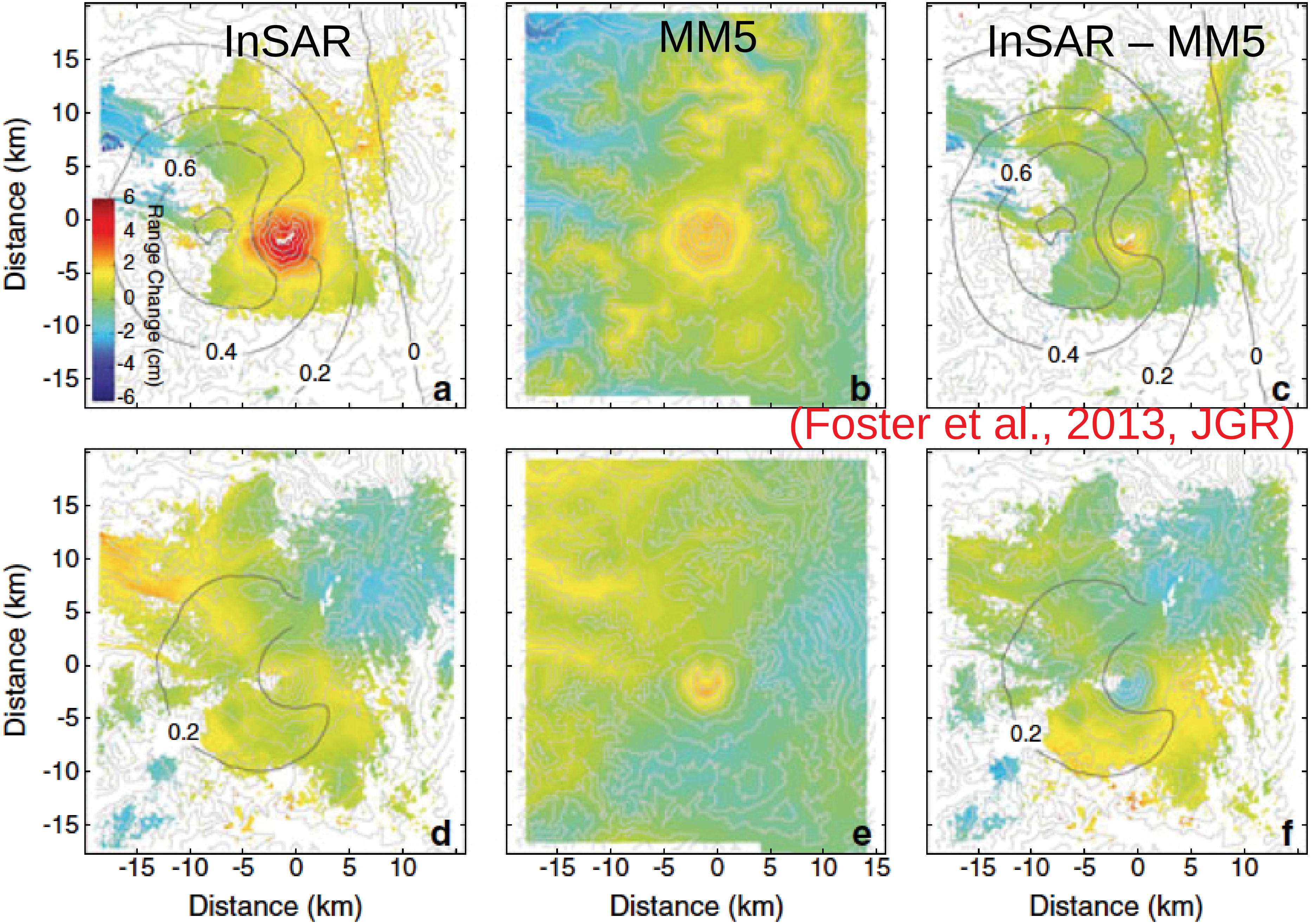
http://upload.wikimedia.org/wikipedia/commons/7/73/AtmosphericModelSchematic.png

MM5: case studies



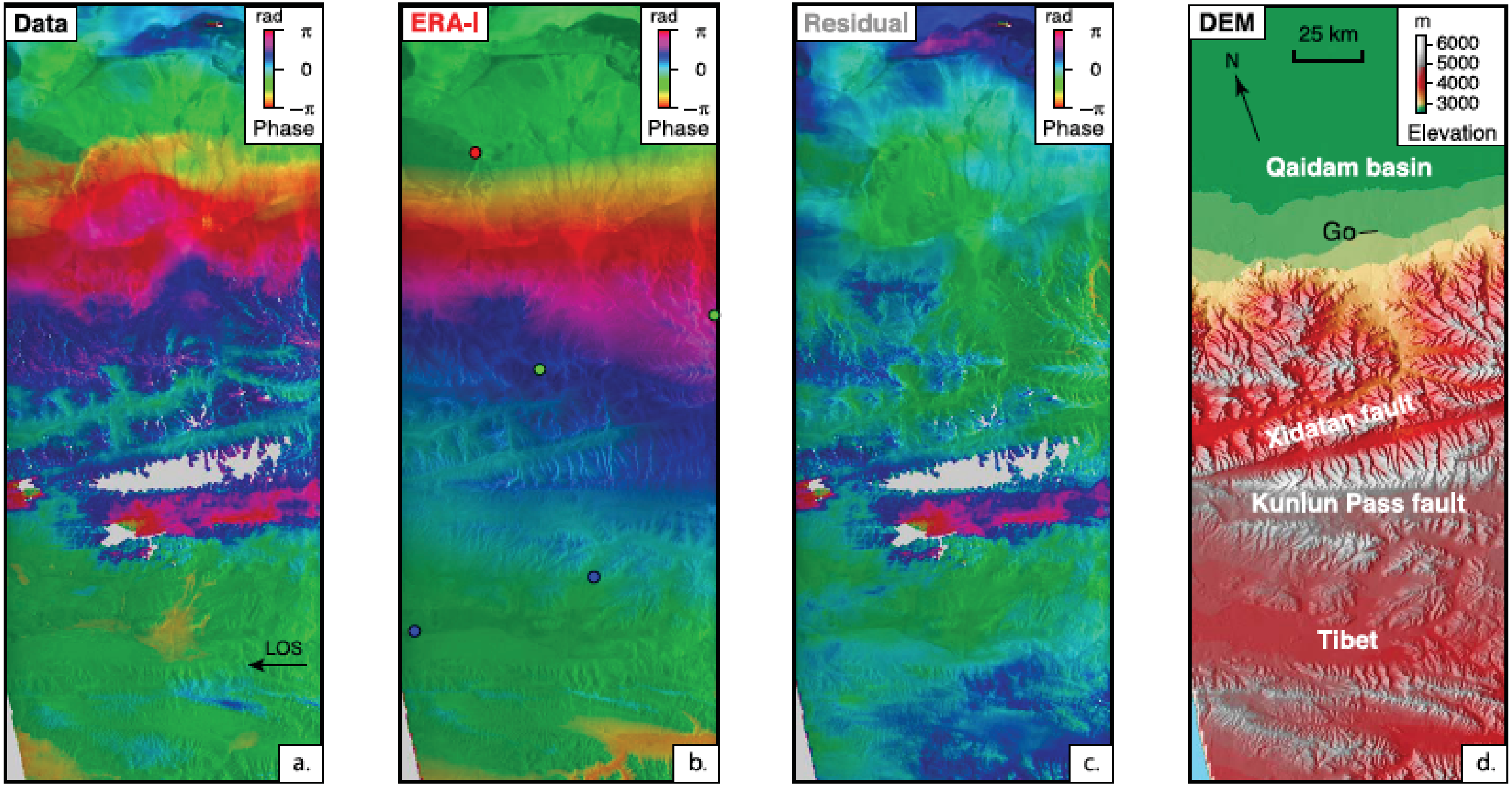
(Foster et al., 2006, GRL)

MM5 Assimilation: case studies



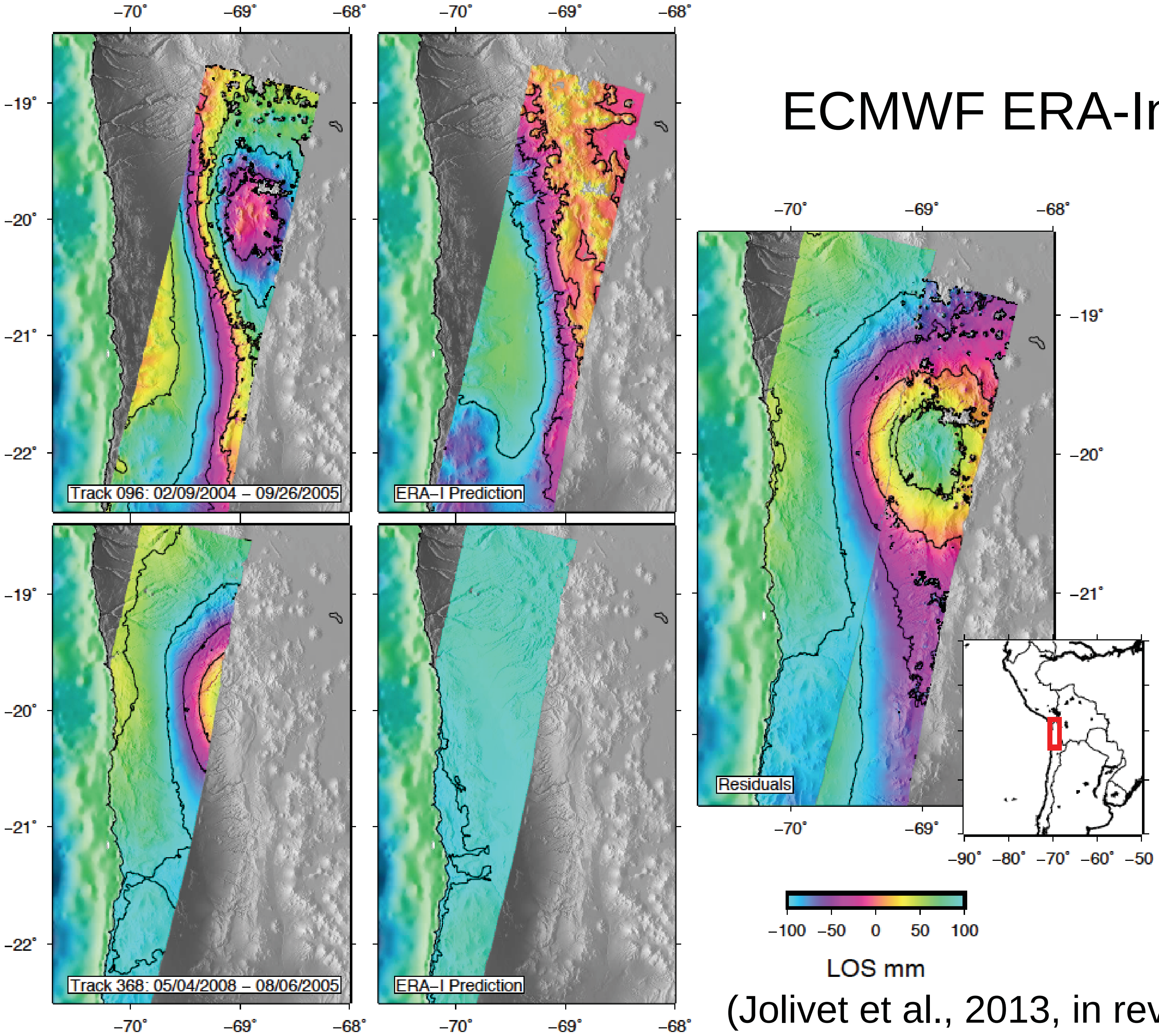
(Foster et al., 2013, JGR)

ECMWF ERA-Interim



(Jolivet et al., 2011, GRL)

ECMWF ERA-Interim



(Jolivet et al., 2013, in review for JGR)

OSCAR: Online Services for Correcting Atmosphere in Radar

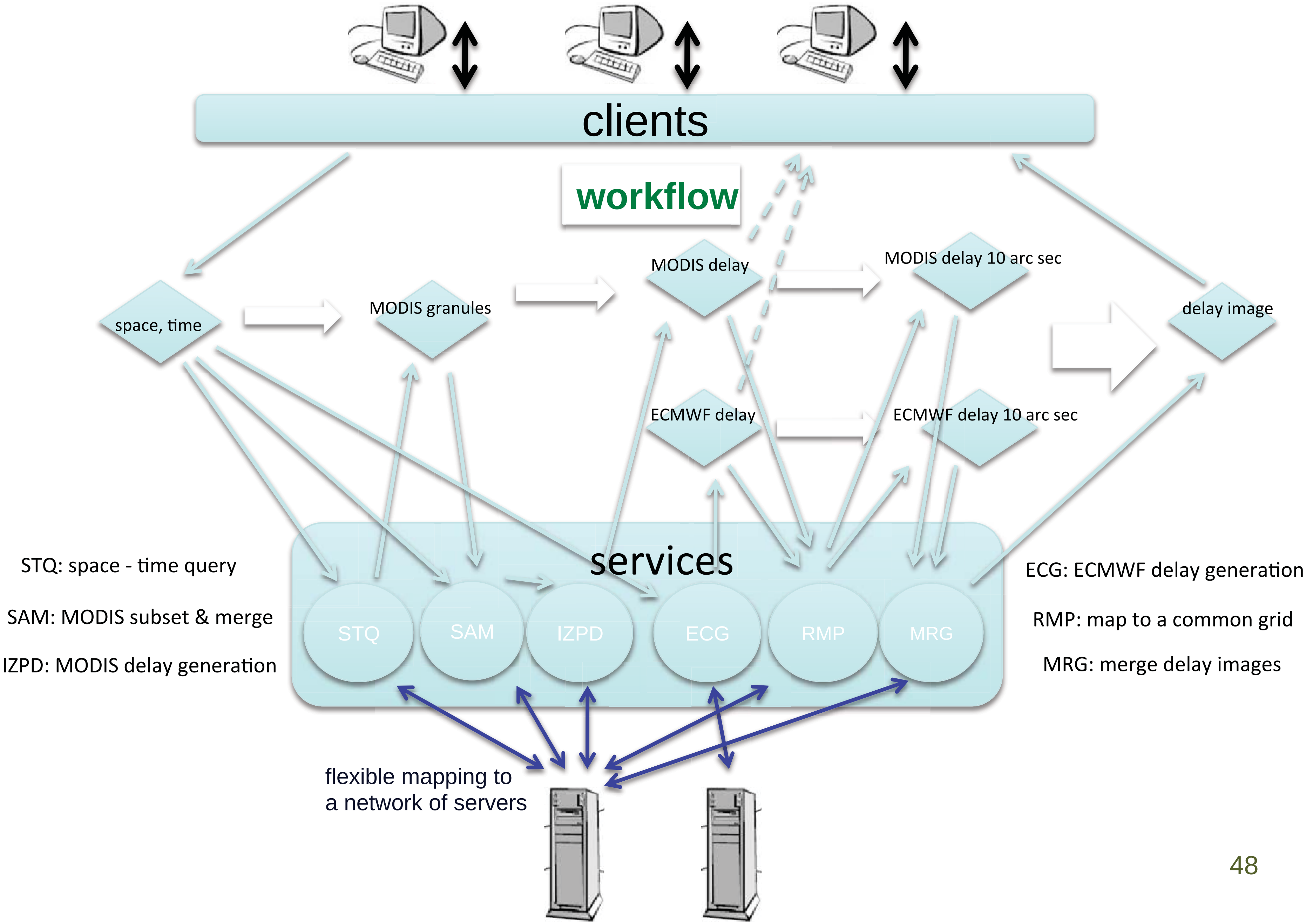
University of Glasgow

• Time series filtering or estimation • Correlation of phase with topography	InSAR Derived
• CGPS (Continuous Global Positioning System) zenith wet delay interpolated spatially and temporally	Ground-Based
• Total column water vapor from absorption of reflected near IR (MODIS and MERIS) • Water vapor measurements (profiling and total column) from thermal IR and MW (AIRS, MODIS, AMSU)	Remote-Sensed
• European Center for Medium Range Weather Forecasting (ECMWF) • NOAA NCEP North American Mesoscale Model (NAM)	Numerical Weather Forecast Models

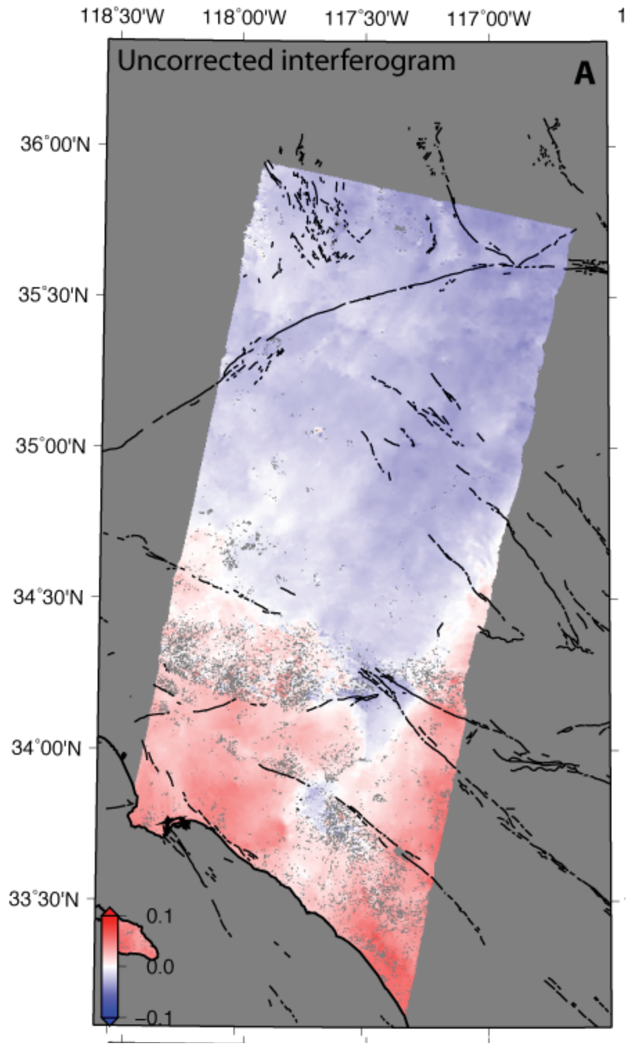
OSCAR is a web service that locates, retrieves, and merges these data sets to derive an optimal, best estimate of tropospheric delay

Investigators: **Paul von Allmen** Eric Fielding, Evan Fishbein, Zhangfan Xing, Lei Pan, and Martin Lo, JPL; Zhenhong Li, University of Glasgow

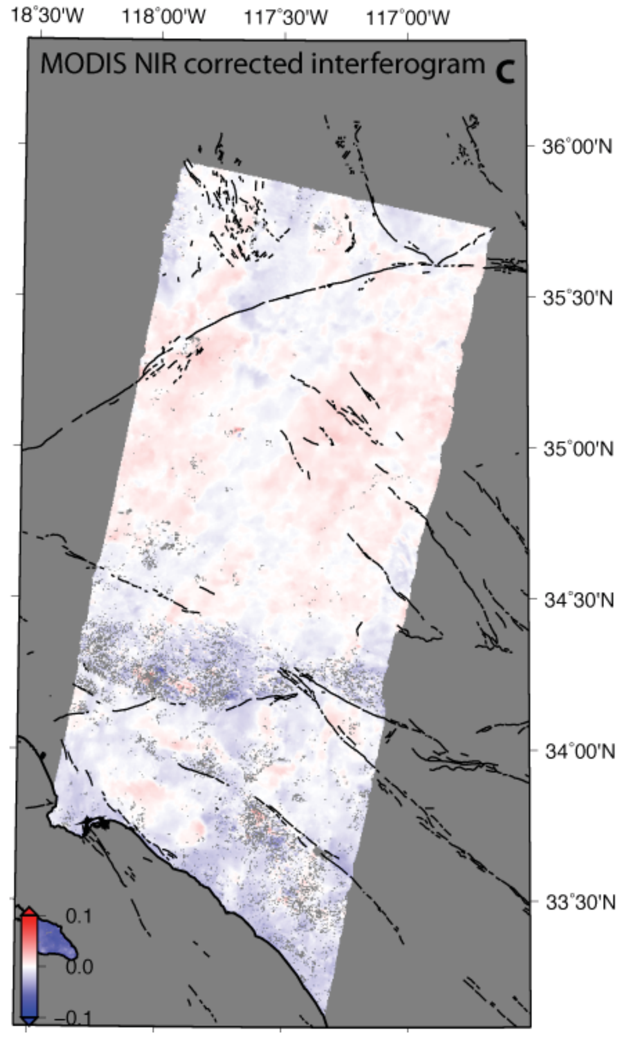
Functional Architecture Diagram



Example of OSCAR MODIS correction

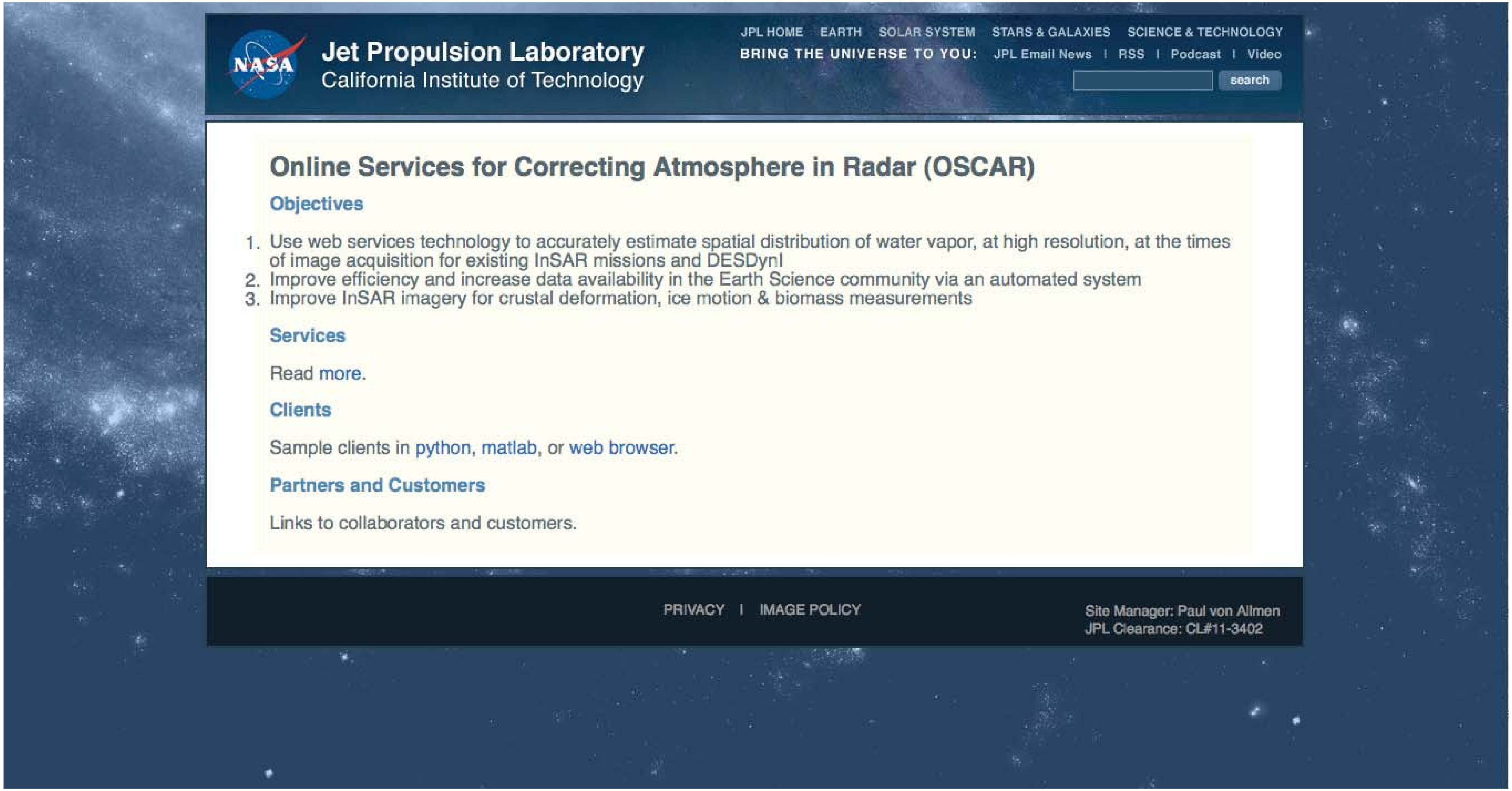


Original interferogram



MODIS-corrected interferogram

JPL OSCAR



(http://oscar.jpl.nasa.gov)

Comparions: InSAR correction models

Models	GPS	MERIS/MODIS	NWM
Coverage	Regional/Local	Global	Global
Observation period	Day and Night	Day (Near IR)	Day and Night
Spatial resolution	A few to tens of km	0.3 – 1.2 km	Up to 100s metres
Temporal resolution	Almost continuous (e.g. 5 min)	Up to 4 times a day	Often 6 hours
Sensitivity to clouds	NO	YES	NO
PWV accuracy	~1 mm	1.6-2.0 mm	~2 mm (WRF; Gonzalez et al., 2013)
InSAR accuracy	5-10 mm	5-10 mm	???

NWM-based InSAR correction models: Remaining questions

- Uncertainties in PWV from different Numerical Weather Models (ECMWF, UM, MM5 or WRF) in different places at different times?
- Which NWM is the best for InSAR correction? Why? When? Where?
- What is the optimal procedure to use NWM for InSAR correction? For individual interferograms? For time series analysis?
- In the cases without ground truth, how to ensure the usability of NWM-based correction models?

Thank you !

OSCAR: Online Services for Correcting Atmosphere in Radar

- **Time series filtering or estimation**
- **Correlation of phase with topography**

InSAR Derived

- **CGPS (Continuous Global Positioning System) zenith wet delay interpolated spatially and temporally**

Ground-Based

- **Total column water vapor from absorption of reflected near IR (MODIS and MERIS)**
- **Water vapor measurements (profiling and total column) from thermal IR and MW (AIRS, MODIS, AMSU)**

Remote-Sensed

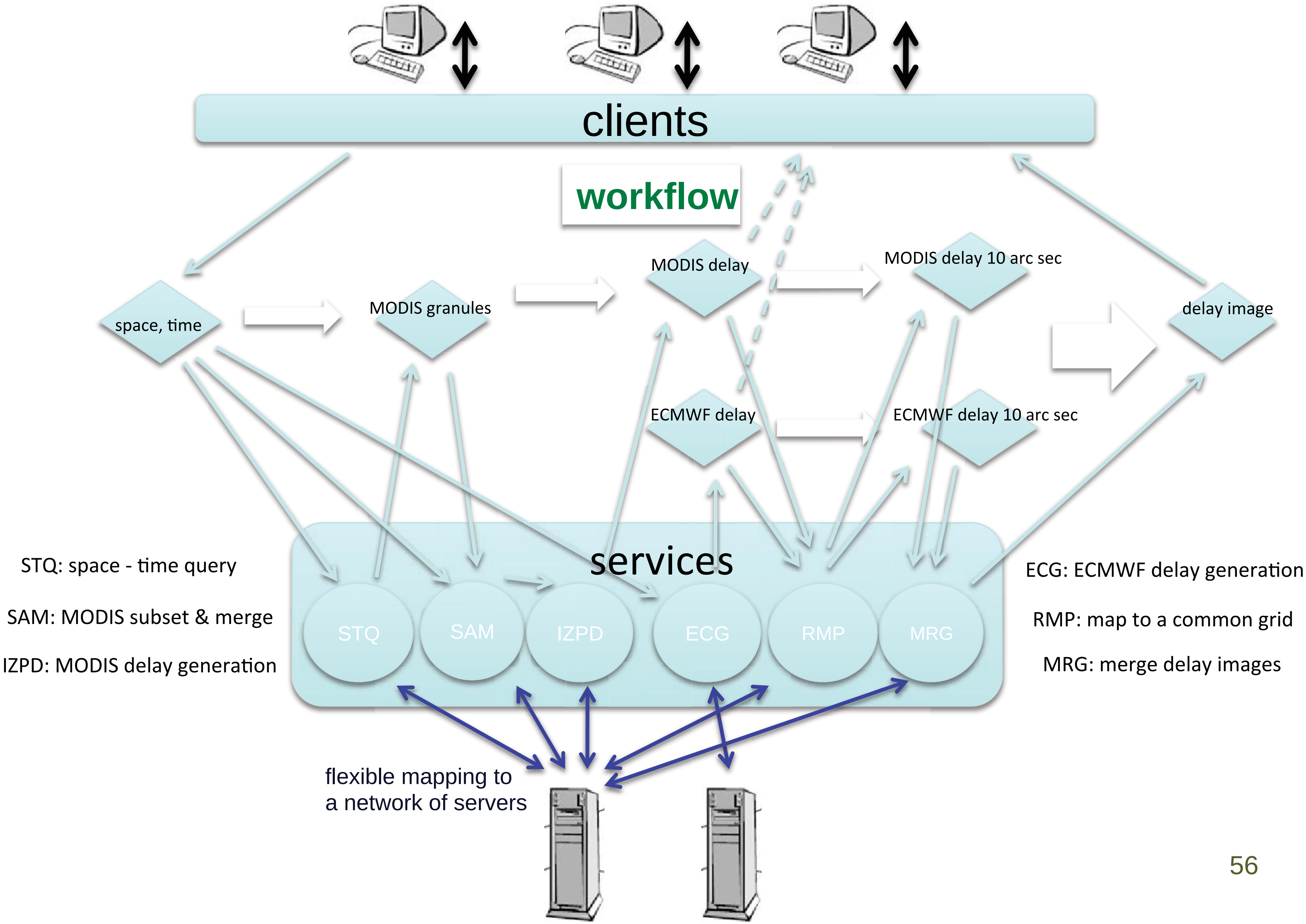
- **European Center for Medium Range Weather Forecasting (ECMWF)**
- **NOAA NCEP North American Mesoscale Model (NAM)**

Numerical Weather Forecast Models

OSCAR is a web service that locates, retrieves, and merges these data sets to derive an optimal, best estimate of tropospheric delay

Investigators: **Paul von Allmen** Eric Fielding, Evan Fishbein, Zhangfan Xing, Lei Pan, and Martin Lo, JPL; Zhenhong Li, University of Glasgow

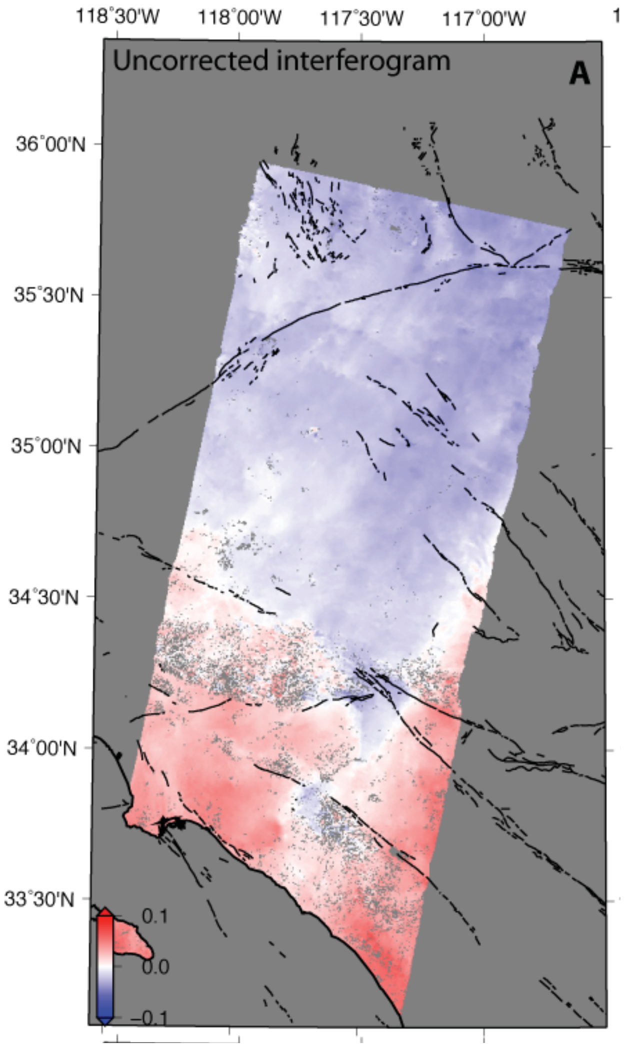
Functional Architecture Diagram



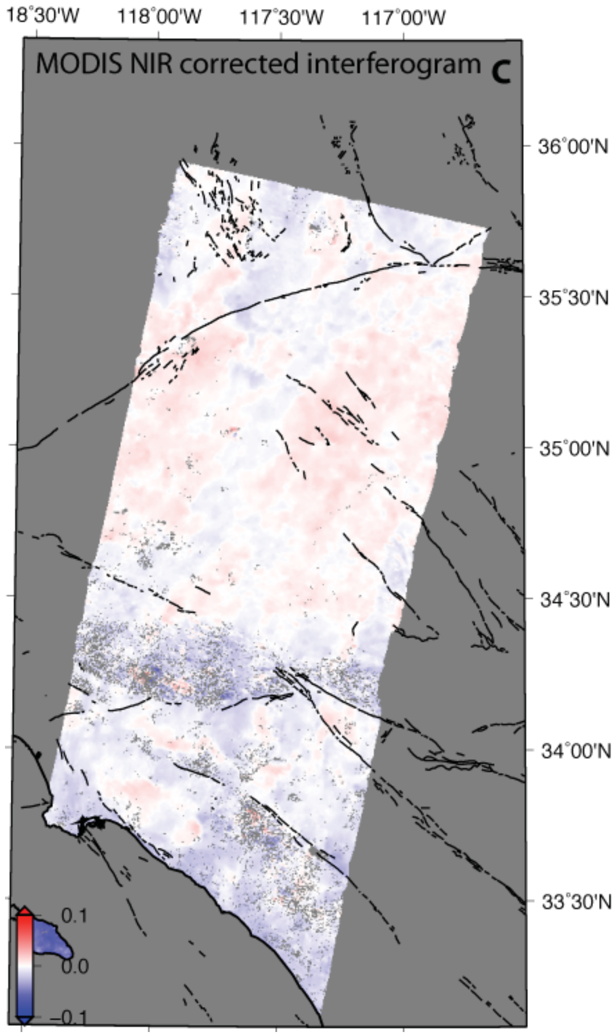
JPL OSCAR: Use Case

1. User selects InSAR scenes, where OSCAR will compute tropospheric delays
2. User selects data to use for corrections (MODIS, MERIS, AIRS, ECMWF, NAM)
3. User provides OSCAR client with spatial bound box and temporal constraints
4. OSCAR retrieves the URL of data granules corresponding to spatio-temporal constraints
5. OSCAR merges granules and subsets the data
6. OSCAR returns the delays on a latitude-longitude grid
7. User applies gridded delays to InSAR scenes in data processing package (e.g., ROI_PAC)
8. User retrieves scientific analysis from InSAR package (ROI_PAC or ISCE)

Example of OSCAR MODIS correction



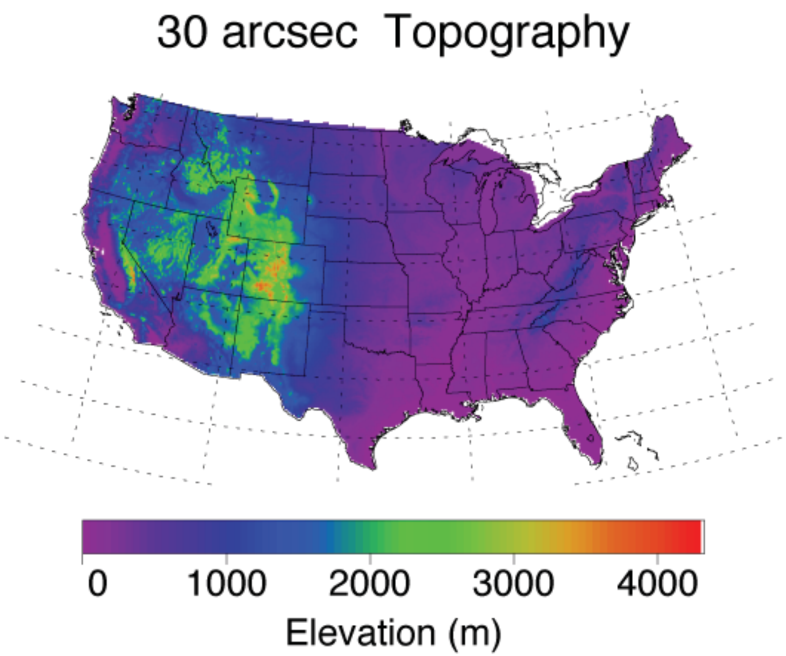
Original interferogram

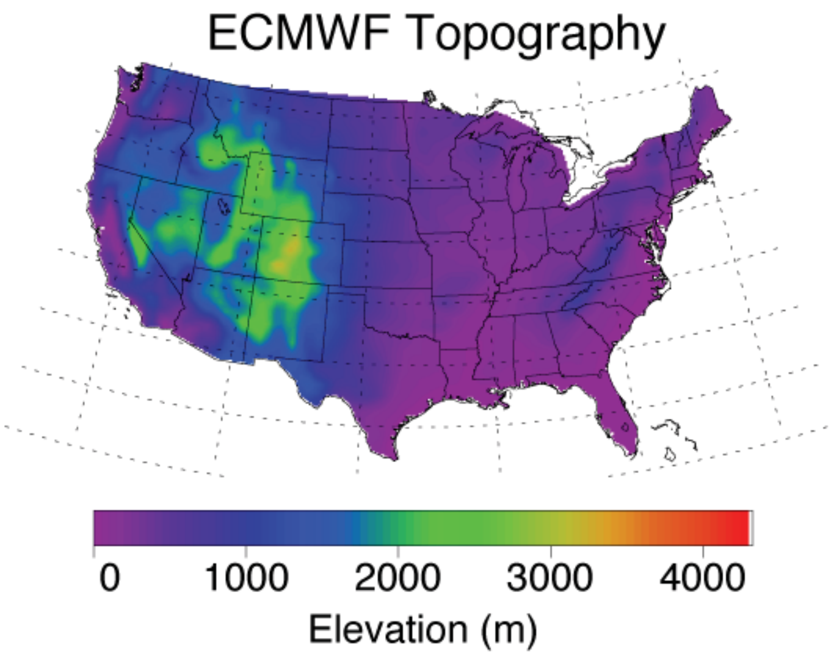


MODIS-corrected interferogram

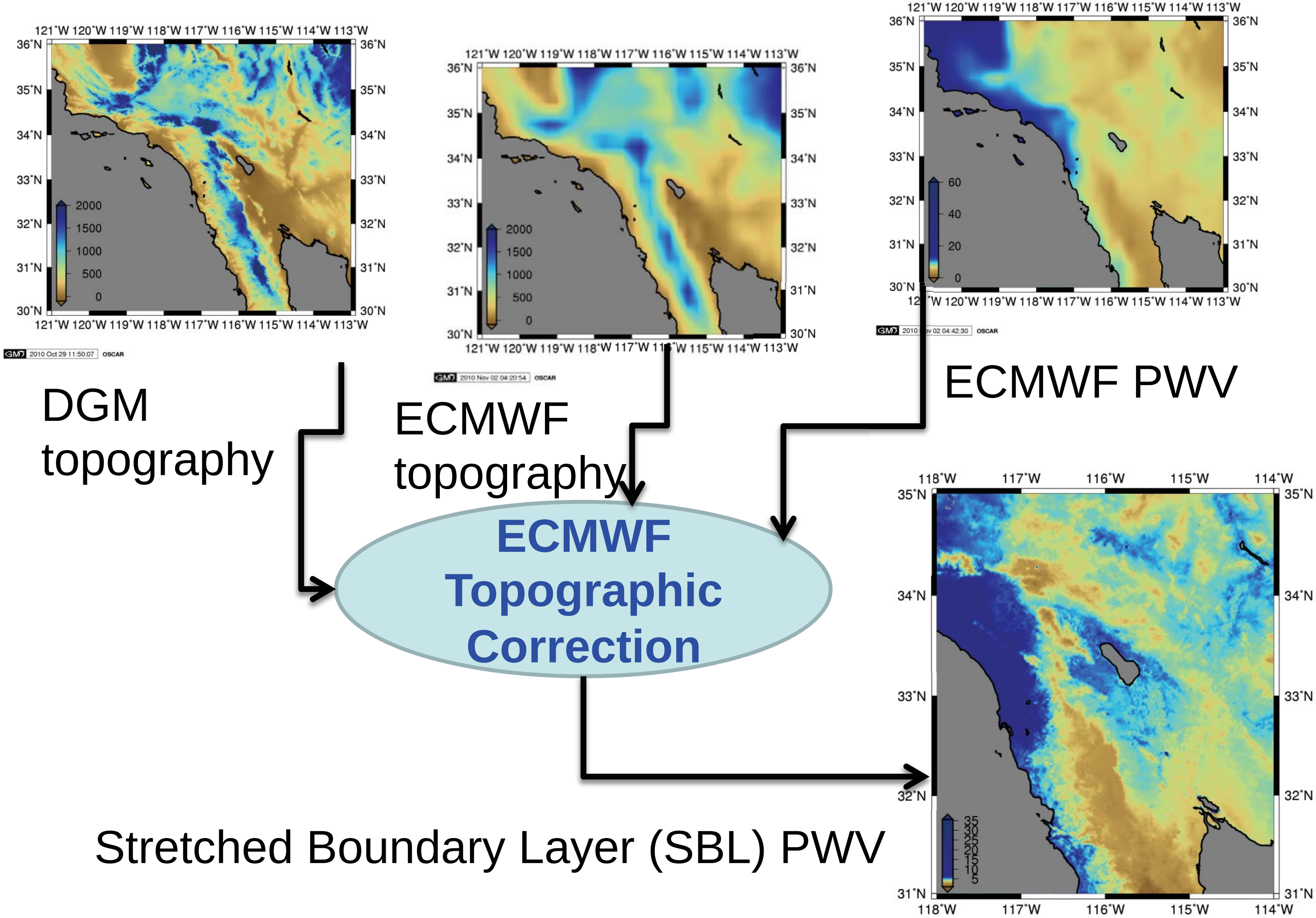
ECMWF Topographic Corrections

- Coarse spatial resolution of ECMWF topography introduces errors in local water vapor which can be corrected through a local topography correction.

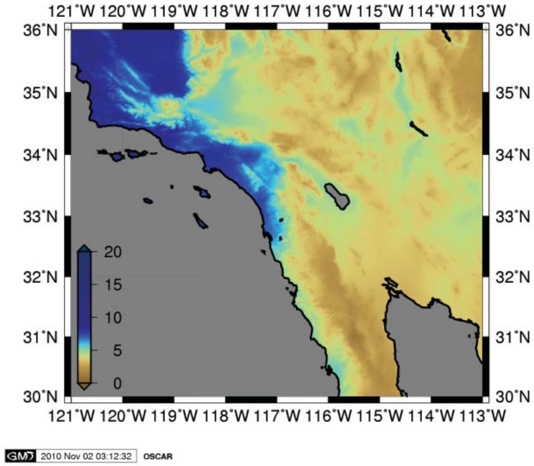




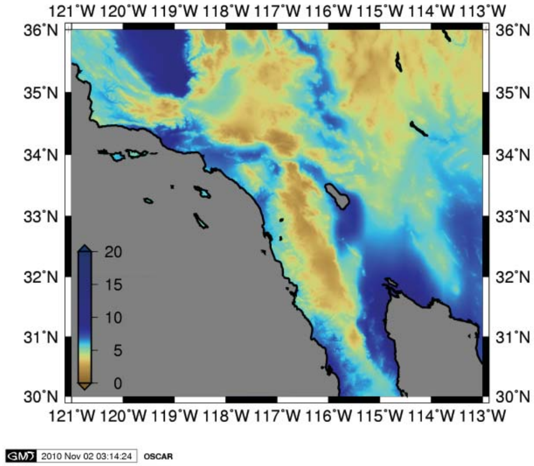
Data Flow


DGM topography
ECMWF topography
ECMWF PWV
ECMWF Topographic Correction
Stretched Boundary Layer (SBL) PWV

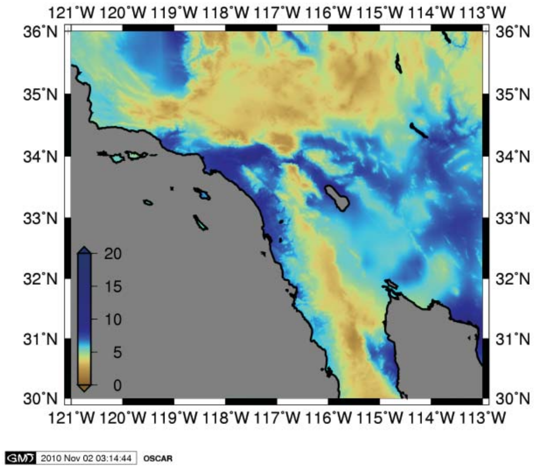
Examples of ECMWF SBL output



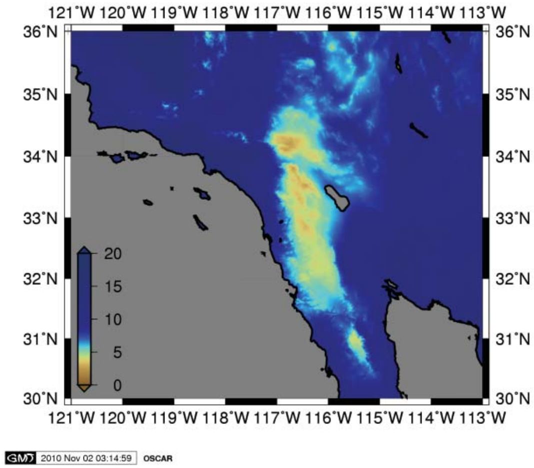
12 Mar 2010



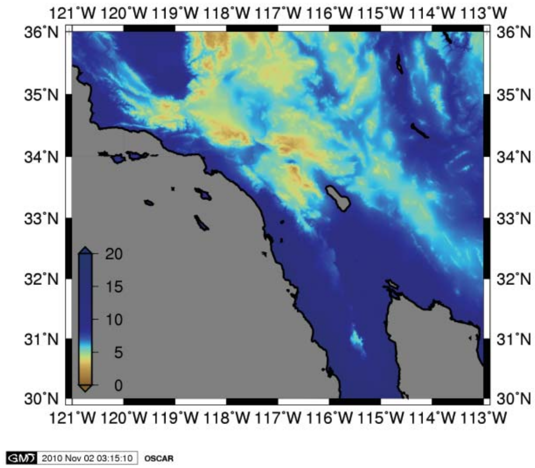
16 Apr 2010



21 May 2010



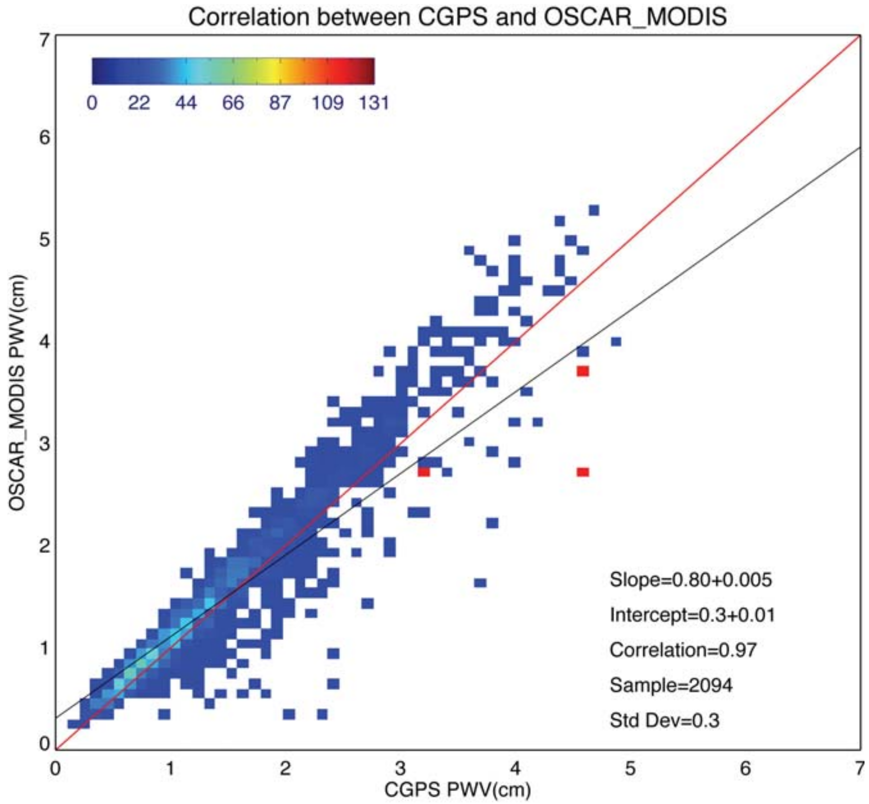
25 Jun 2010



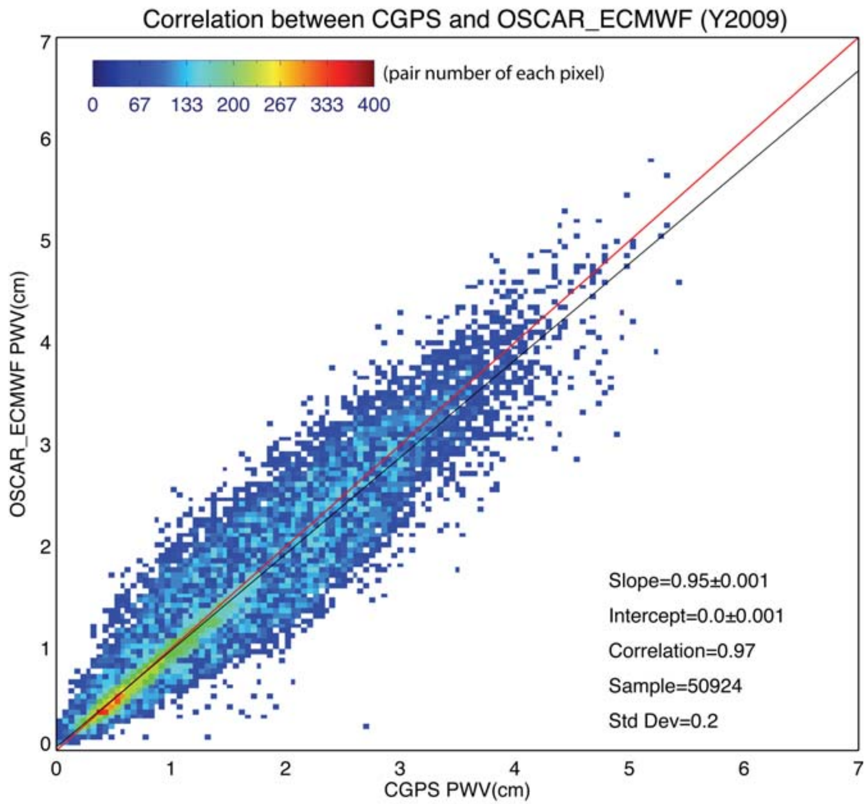
3 Sep 2010

Validation of OSCAR products

MODIS
Std dev = 3 mm path delay

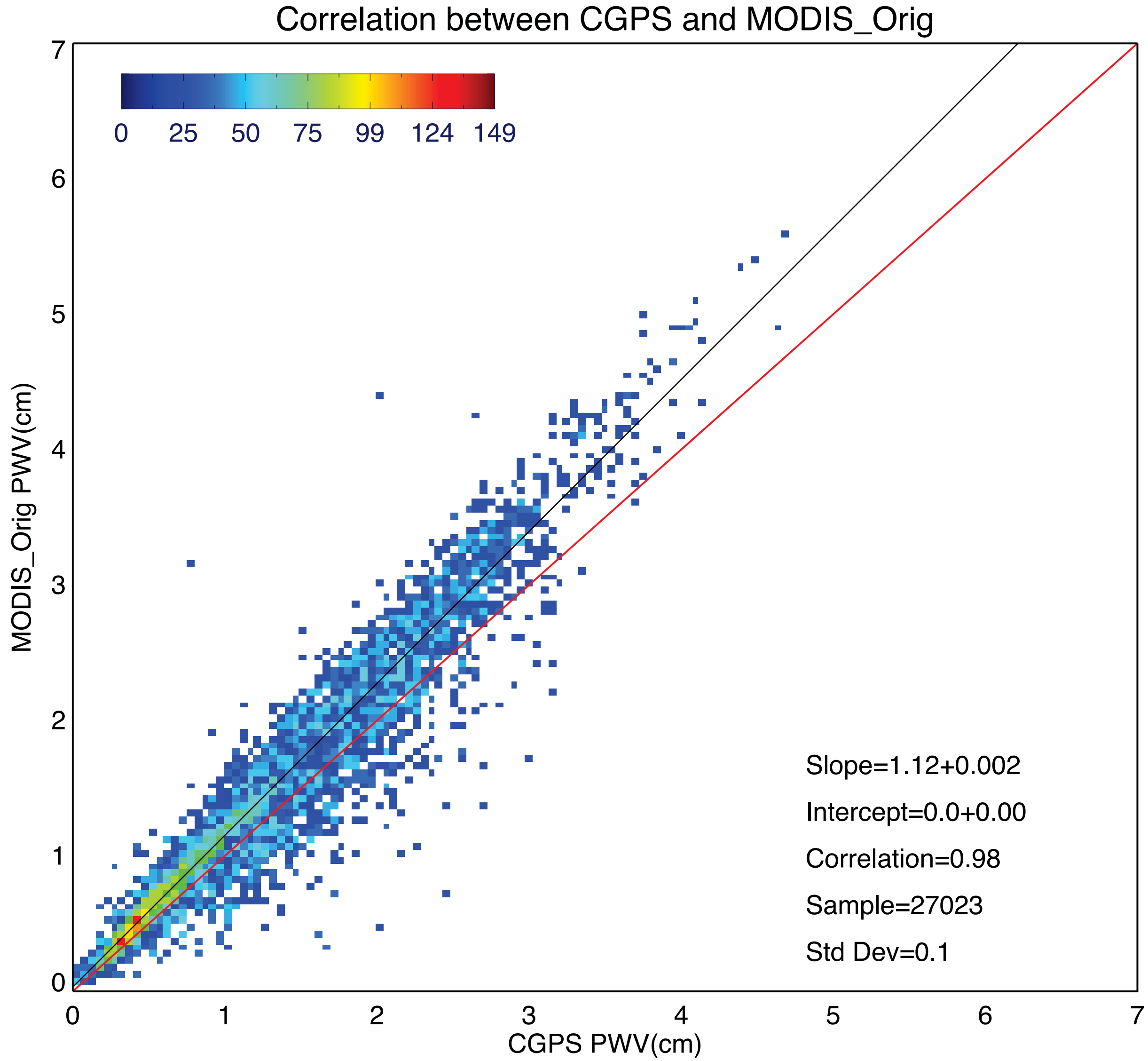


ECMWF
Std dev = 2 mm path delay



Comparing MODIS and ECMWF delay with GPS delay for Year 2009 in Southern California

GPS vs Original MODIS



(1) Original MODIS: PWV extracted using IDL codes

(2) High correlation and small RMS, which is similar to our previous studies

(3) Higher scale factor than Li et al. (2005)

Reported to the OSCAR team in December 2010.

MODIS_SAMI developed in 2012.