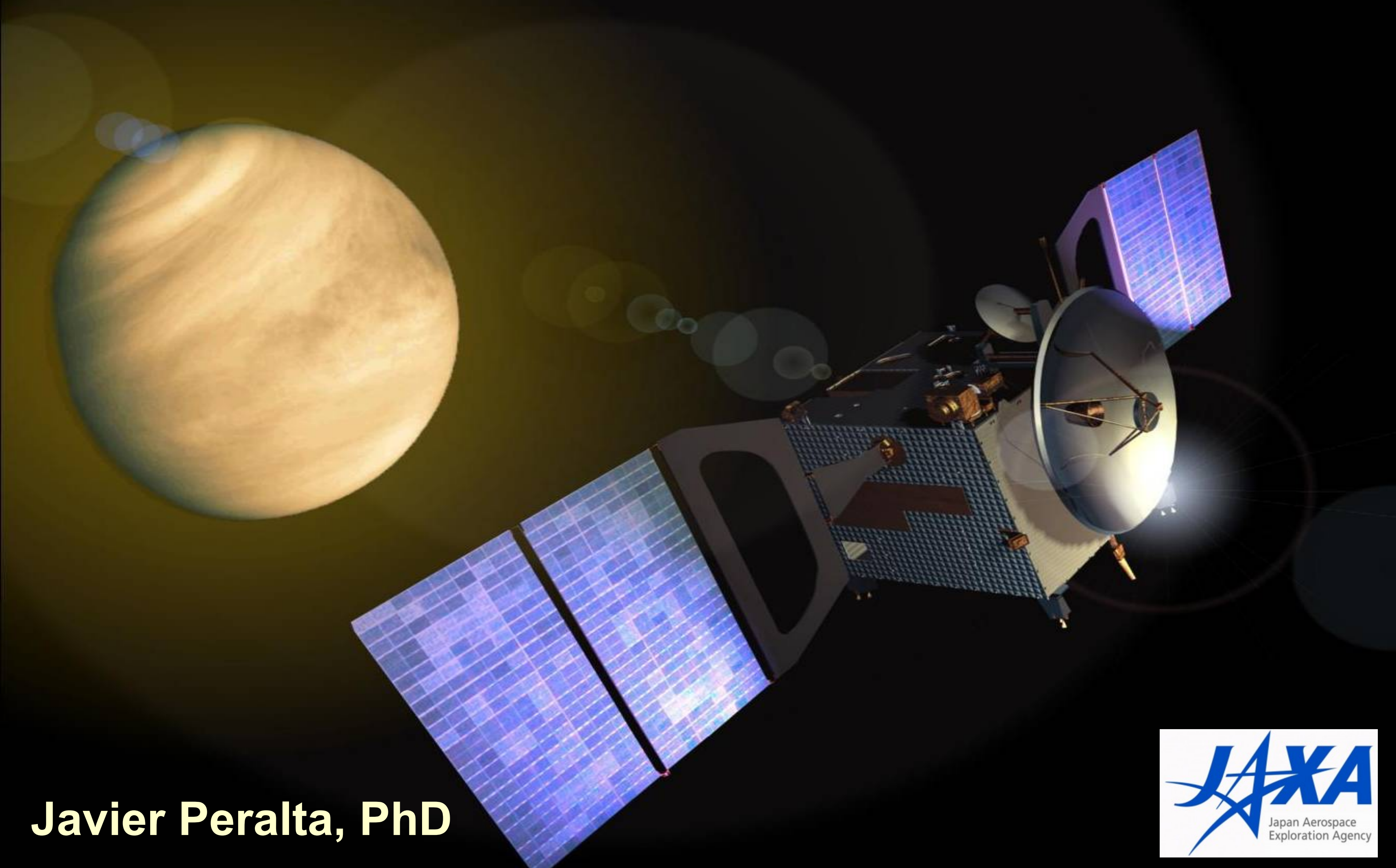
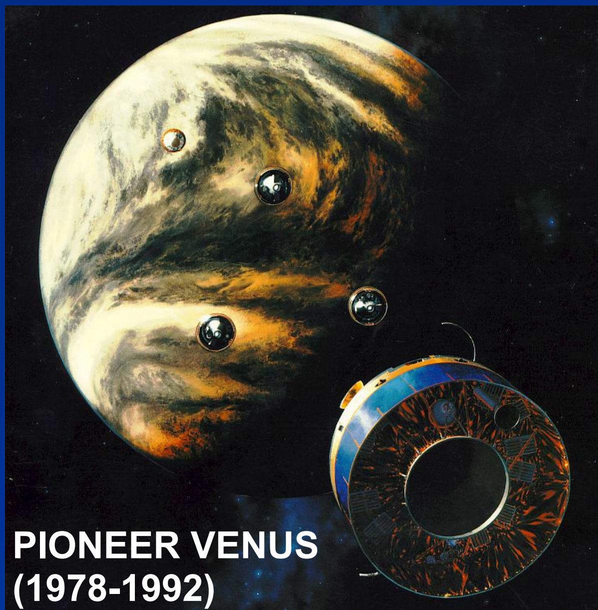
IR Cloud Tracking in Venus

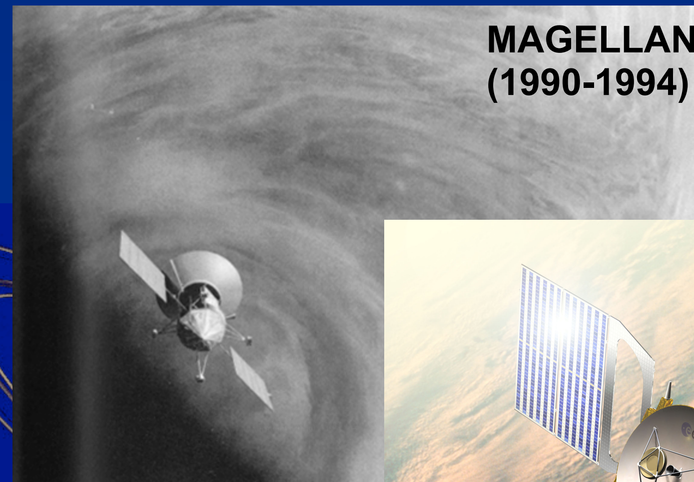


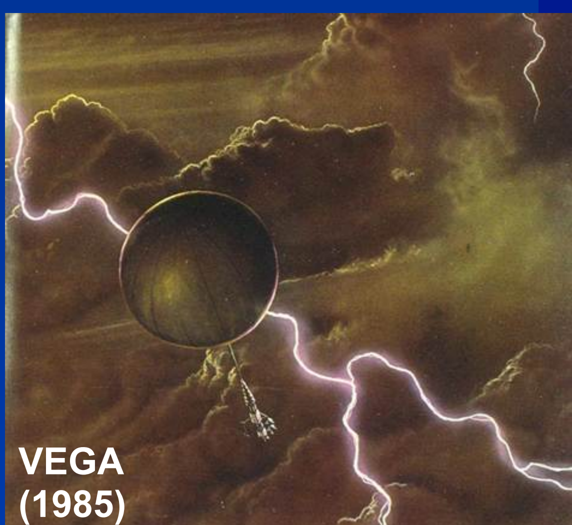
Javier Peralta, PhD

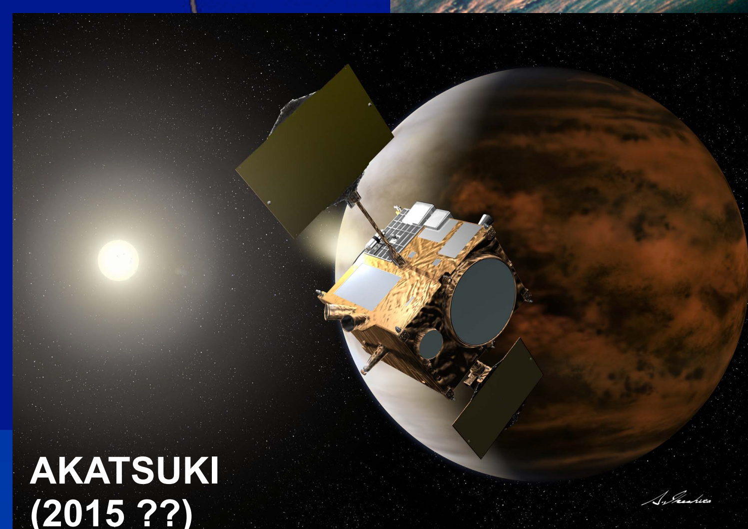
JAXA
Japan Aerospace Exploration Agency

Spatial missions to Venus

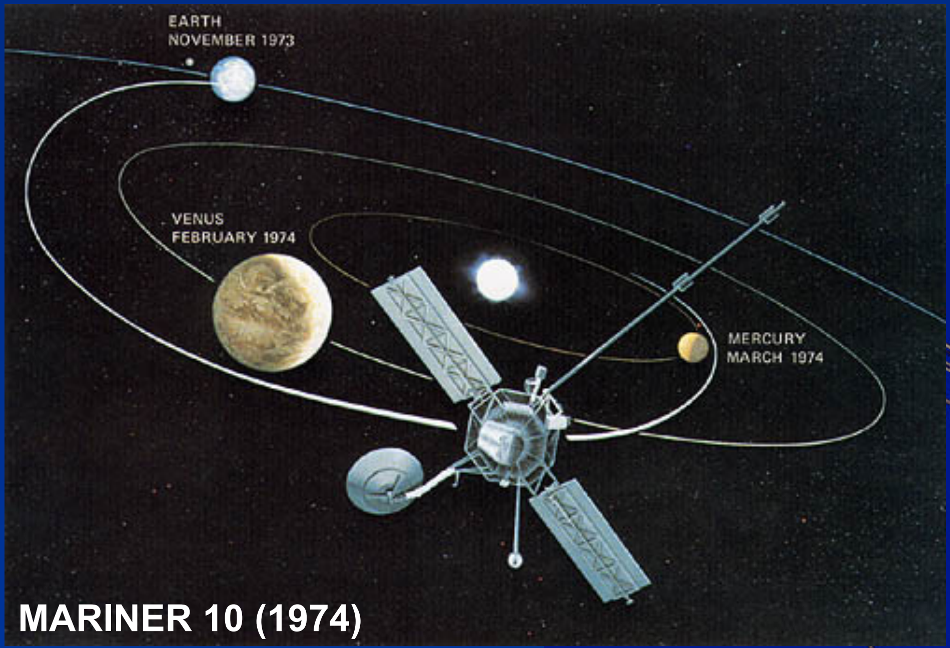


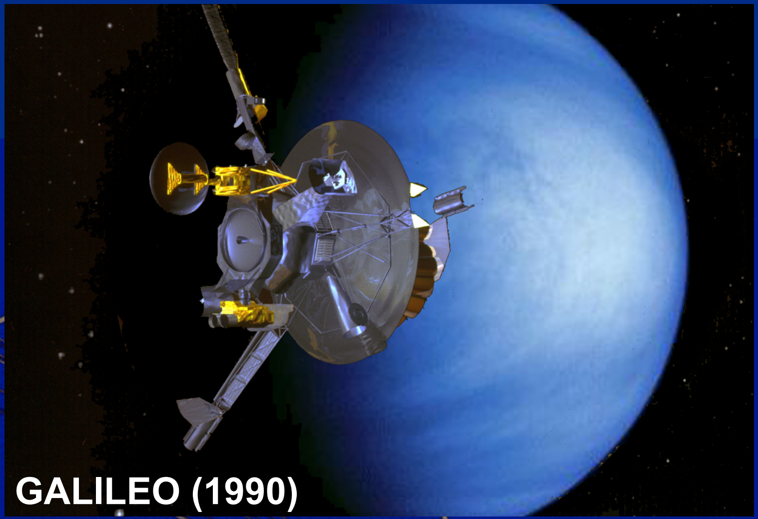


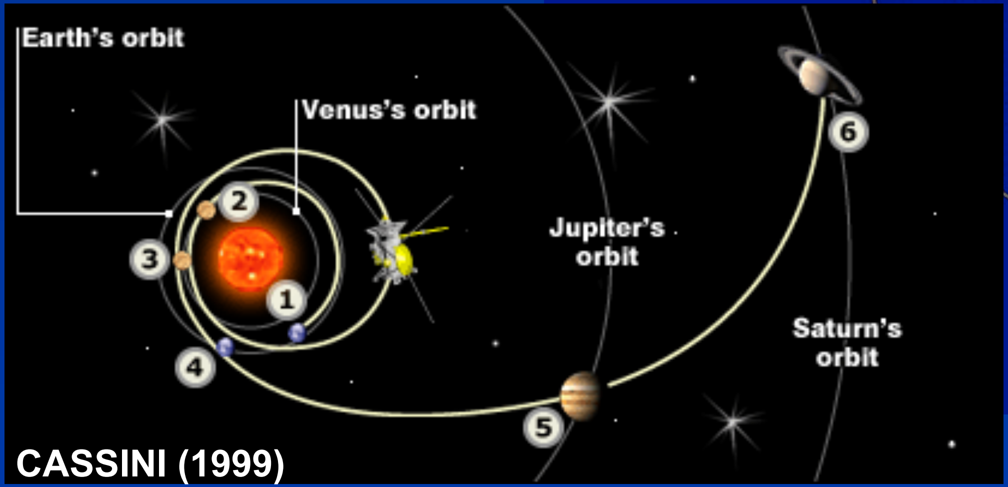




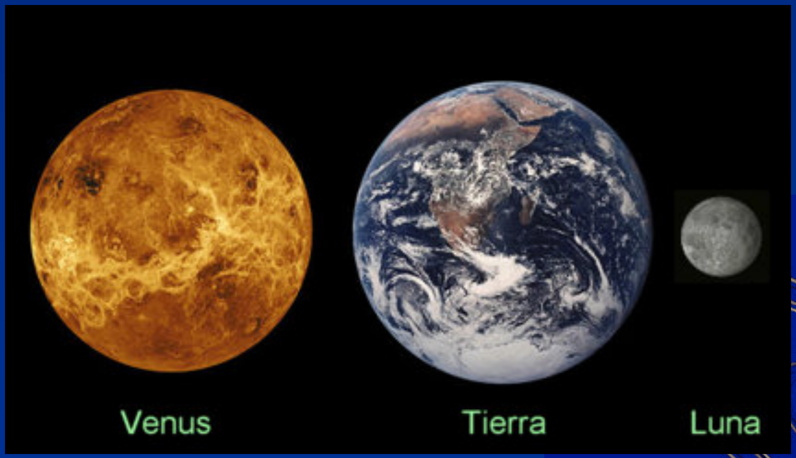
Venus flybys towards other planets

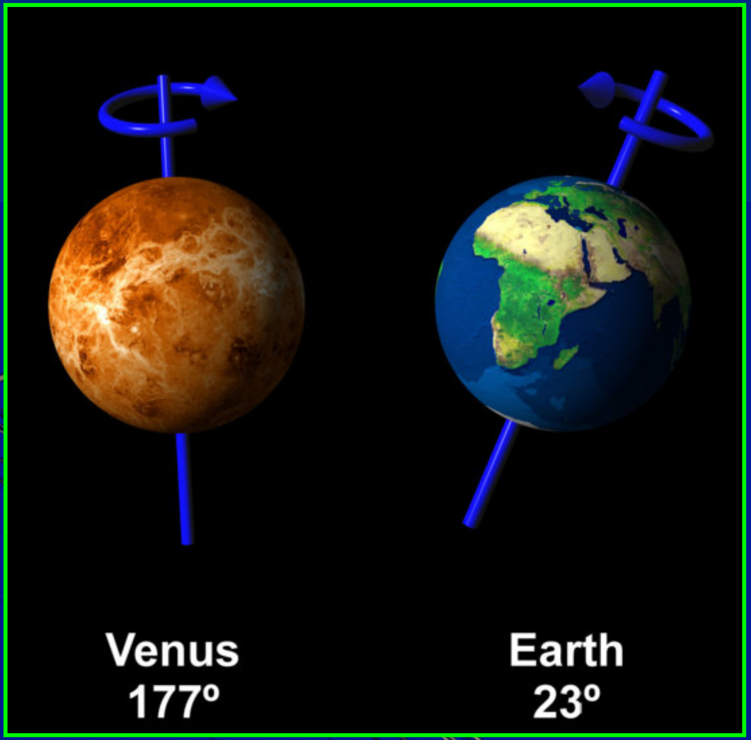


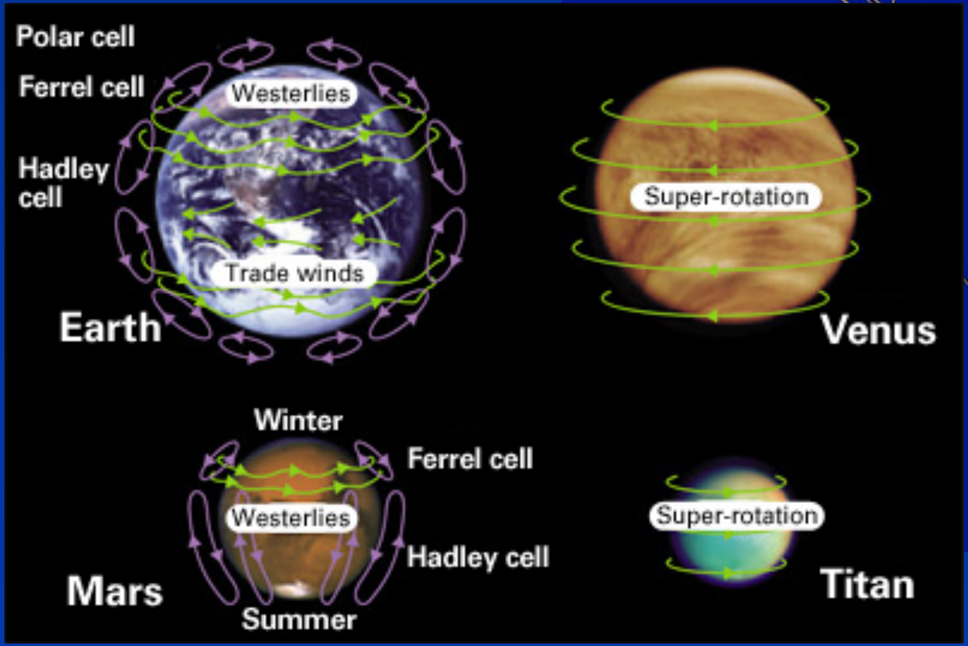




Venus: slow/*fast* planet/*atmosphere* rotation

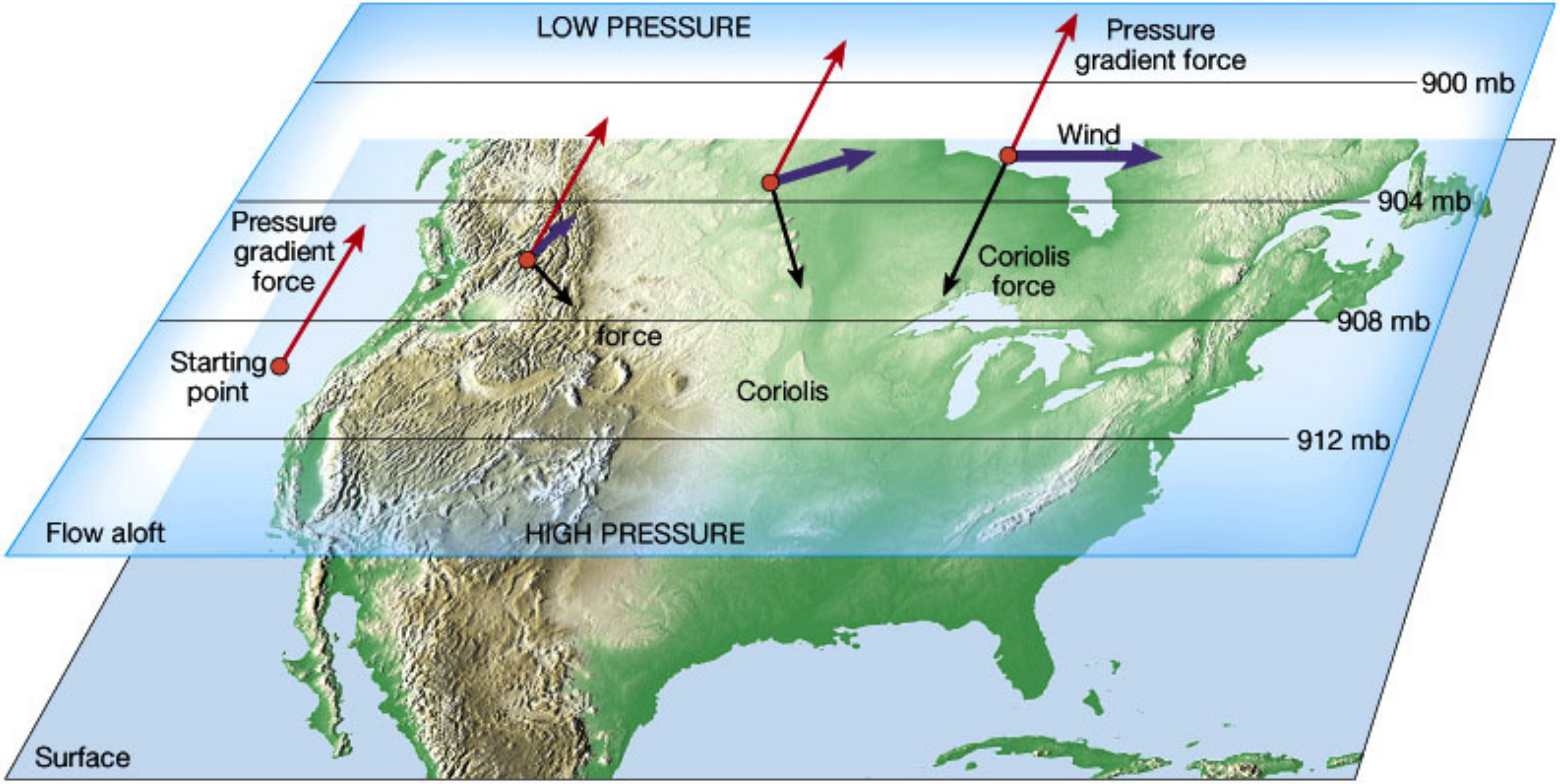






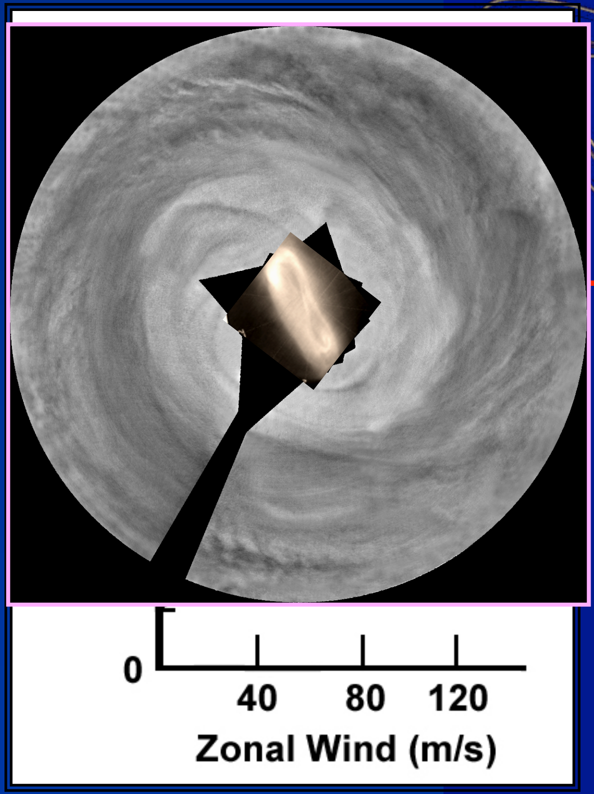
Equations for quickly/slowly rotating planets

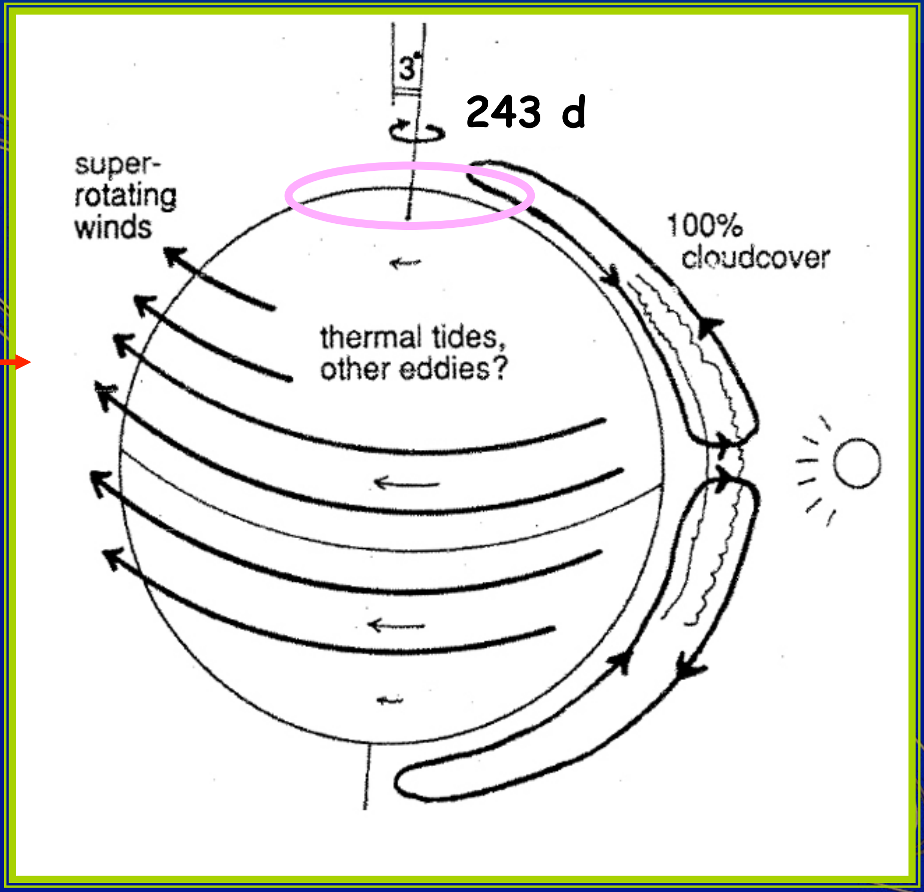
Earth Momentum equations:



Zonal Circulation of Venus Atmosphere

Venus is dominated by strong westward winds, which are 60 times faster than the solid planet at the clouds' tops.

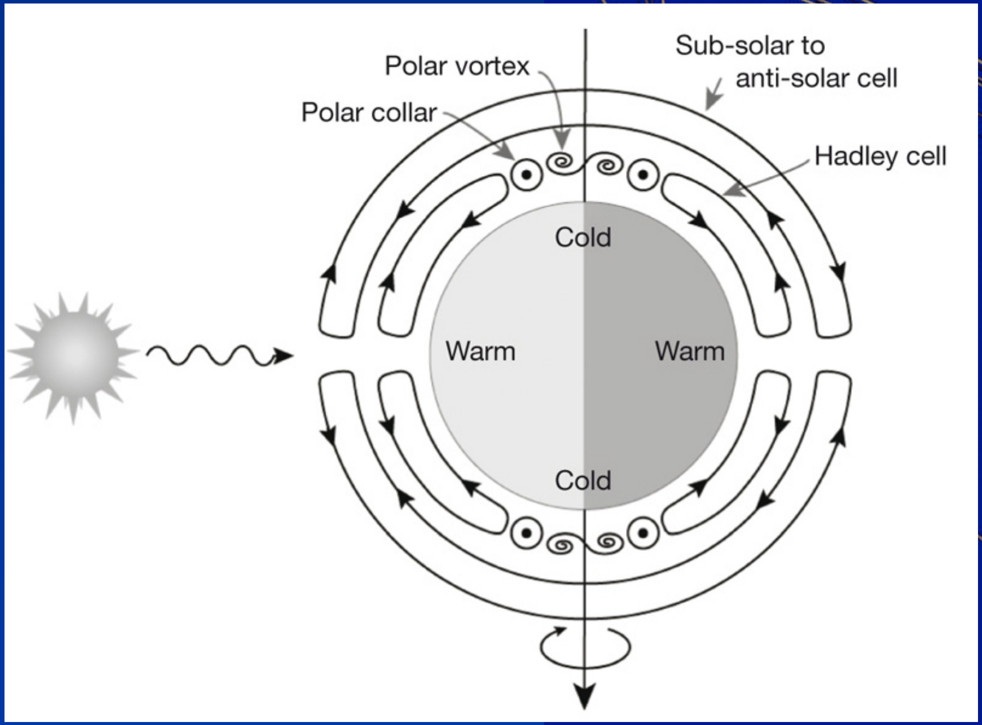


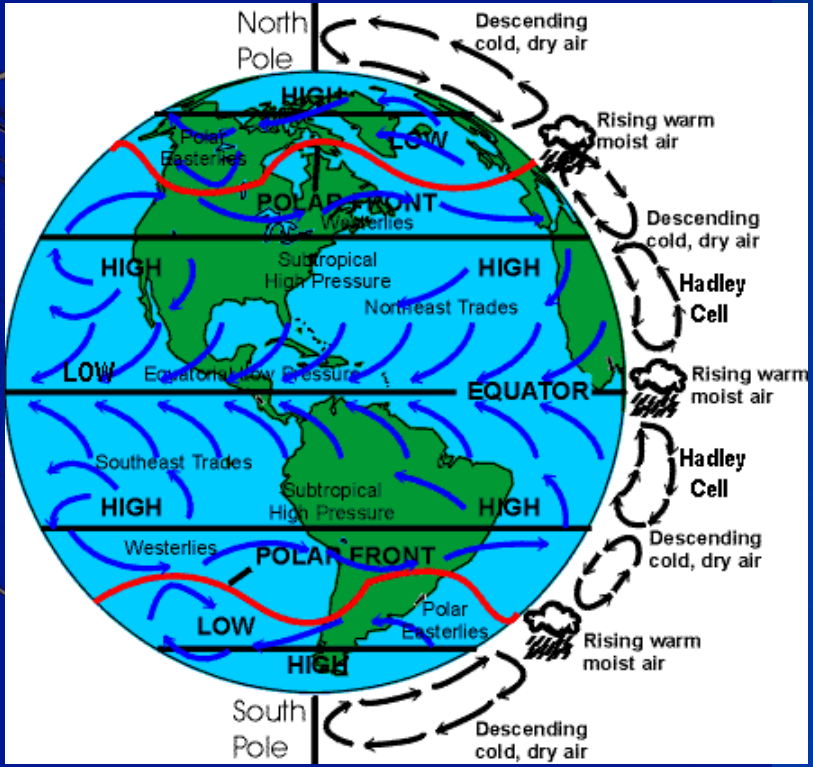


Meridional Circulation of Venus Atmosphere

Venus's *troposhere* "seems" to consist in a Hadley-cell circulation interrupted by the polar vortices at both poles.

Venus's *mesosphere* is dominated by Subsolar-to-Antisolar (SSAA) circulation.





Unsolved issues of Venus atmospheric circulation

How is superrotation generated/maintained?

How is energy transported?

Surface torque? Solar tides? Eddies? Waves?

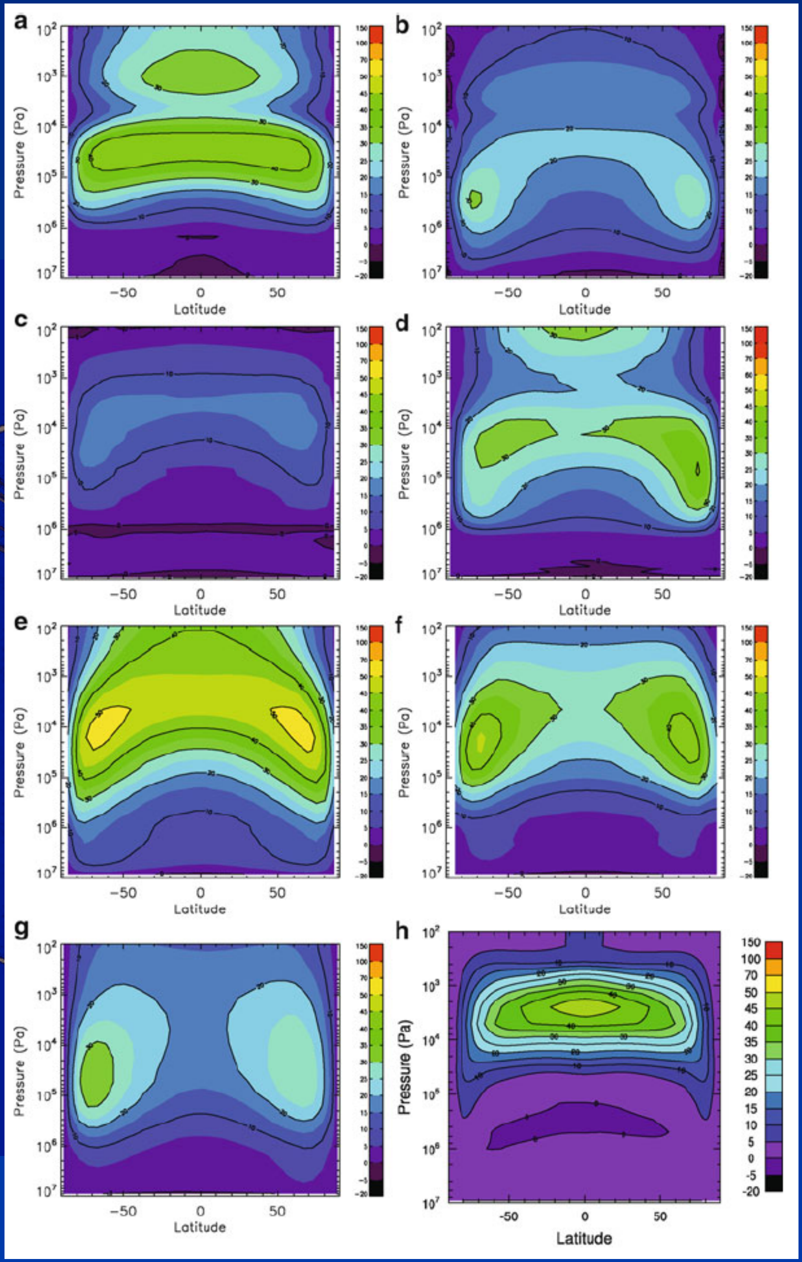
After decades of research, no Venus GCM works properly yet !!

First Column: **Spectral models**

Second Column: **Finite Difference models**

Different results are also obtained depending on:

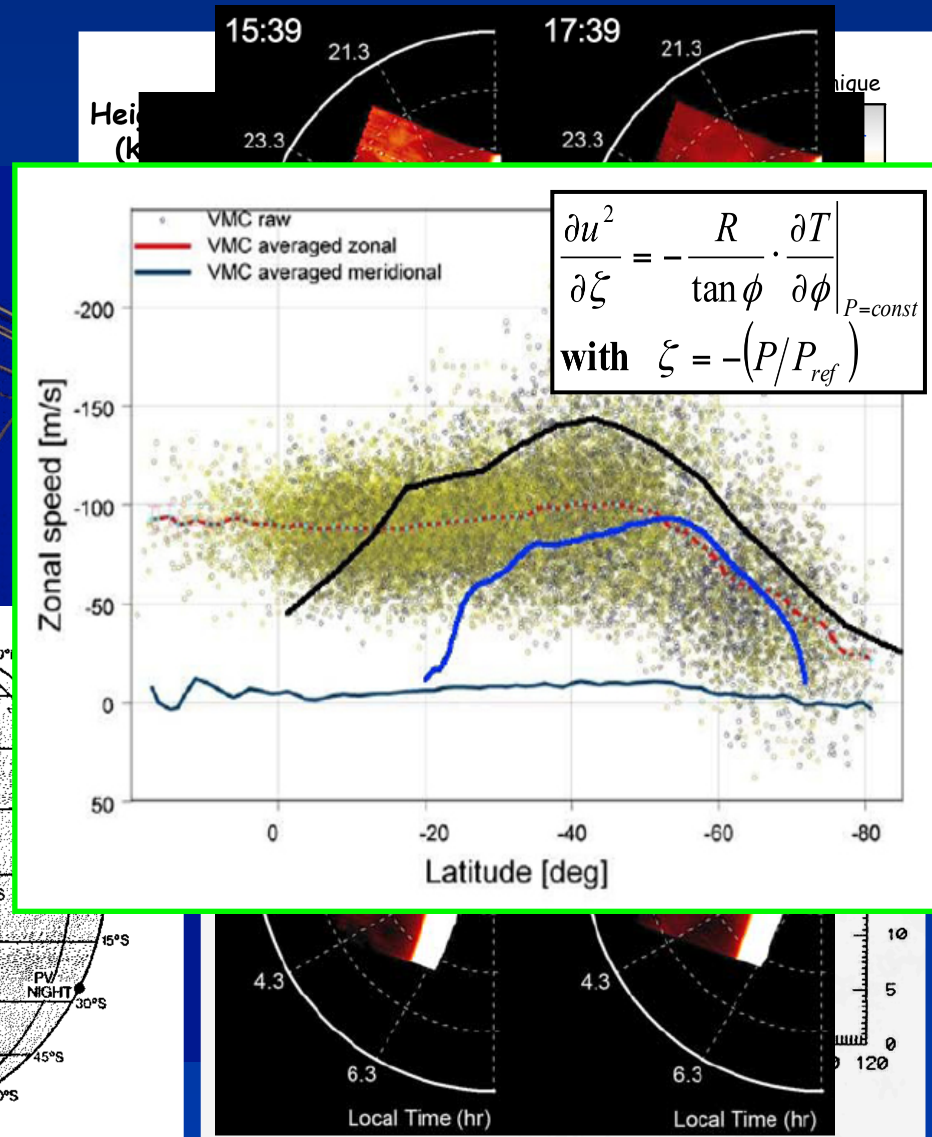
- Horizontal/Vertical resolution
- Topography
- Upper boundary layer
- Initial conditions

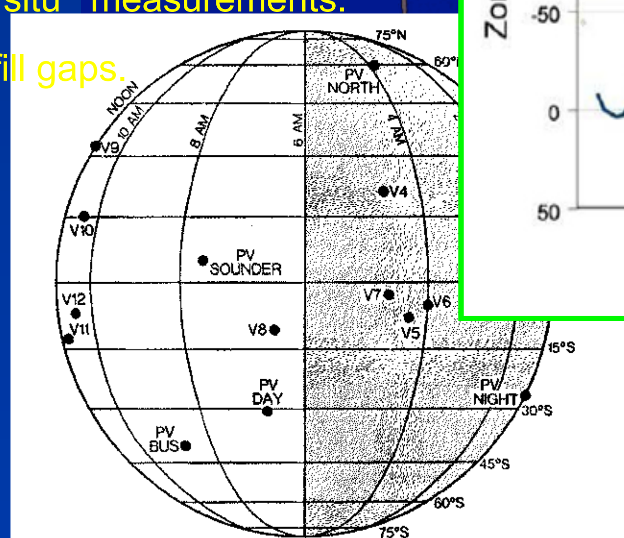


Unsolved issues of Venus atmospheric circulation

ZONAL WINDS

- **Vertical profiles only for several entry coordinates.**
- **A few vertical levels allow cloud tracking.**
- **Cloud levels sense variable altitude.**
- **Above clouds:**
  - Doppler measurements are sparse.
  - Radiation times difficult tracking of features.
  - Does Venus thermal wind equation really work?
- **Below clouds:** only "in situ" measurements.
- **GCMs:** not trustable to fill gaps.

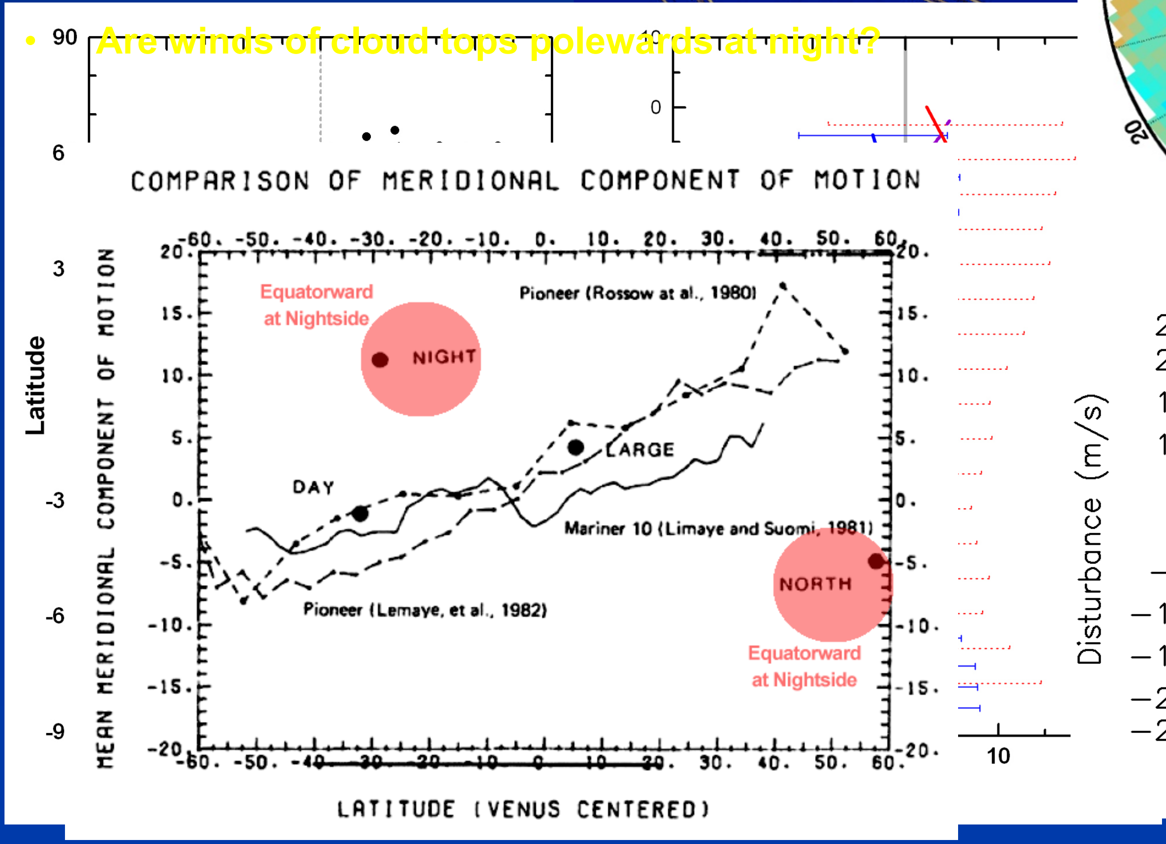


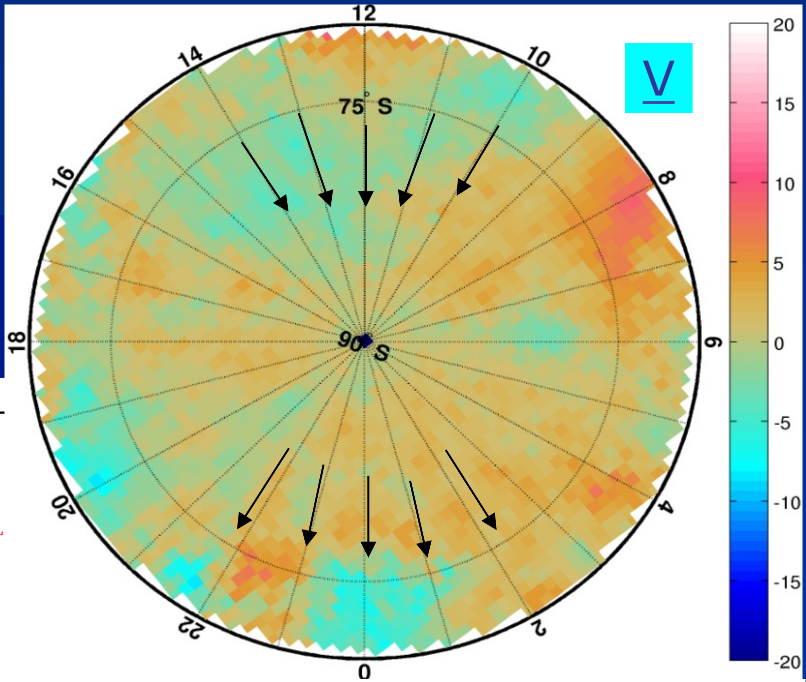


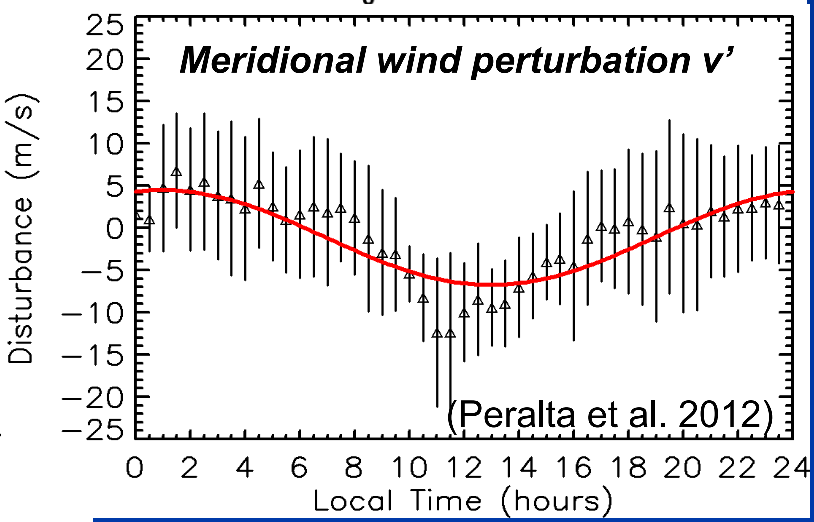
Unsolved issues of Venus atmospheric circulation

MERIDIONAL WINDS

- **Same restrictions as with zonal wind.**
- **Upper branch of Hadley cell at cloud tops?**
- **Solar Tides affect Latitudes 70º-85º:**
  - Poleward Wind in Dayside.
  - Equatorward Wind in Nightside.
- **Are winds of cloud tops polewards at night?**







Unsolved issues of Venus atmospheric circulation

VERTICAL WINDS

- **Only "in situ" (probes and VEGA balloons).**
- **Too small to be measured with Doppler. Expected to be higher at poles.**
- **We have not *indirect methods* as the ones used for geostrophic regimes (*Omega* equation).**
- **Strongest Divergence is found at cloud tops, tropical latitudes and between 13h-14h.**
- **Recently suggested that the "Y" feature causes strong vertical acceleration at height where zonal wind peaks (Peralta, 2015).**

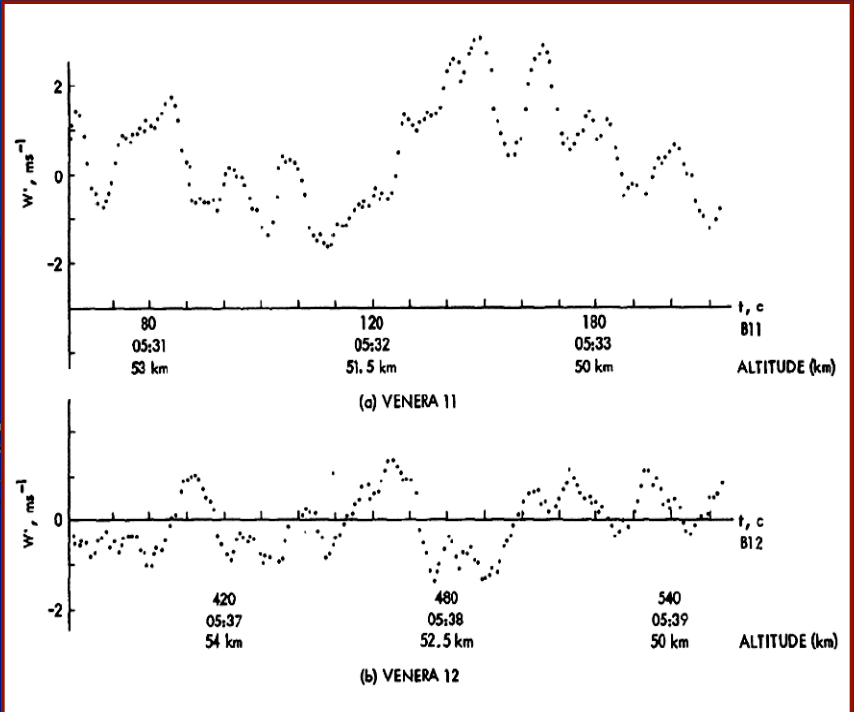
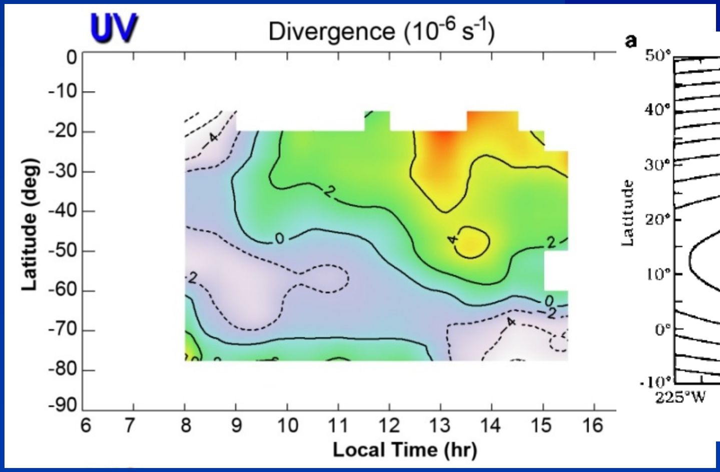
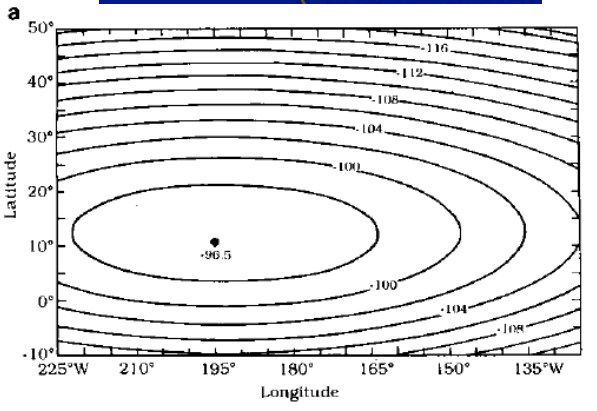
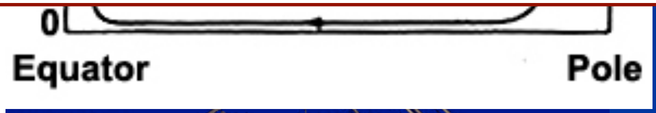


Figure 2-5. An Example of Observed Vertical Component of Motion from Venera 11 and Venera 12 Probes



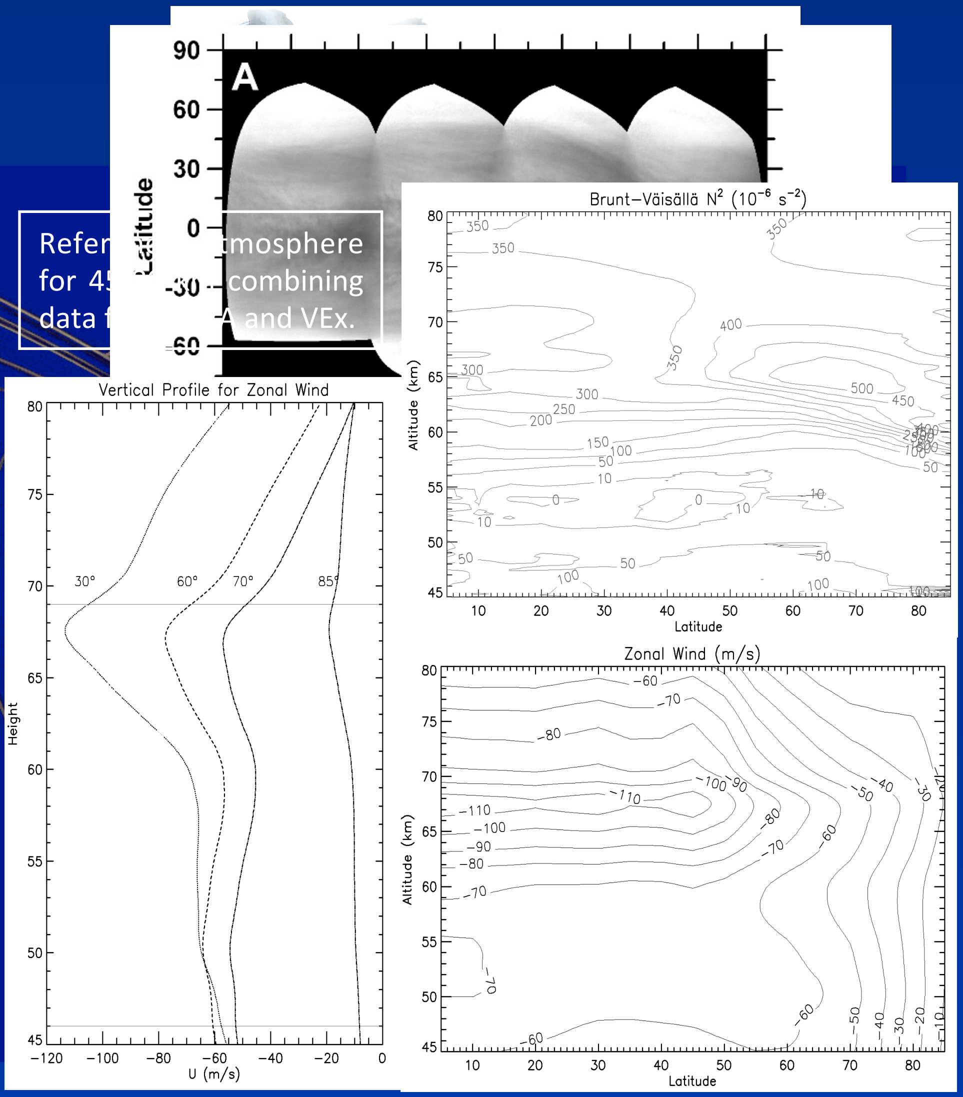




Unsolved issues of Venus atmospheric circulation

MECHANISMS FOR CREATING/TRASPORTING/ DISSIPATING MOMENTUM & ENERGY:

- **Planetary and Mesoscale waves** are frequently apparent in Venus images and must be tracked to characterize them.
- **High-precision winds** need to be obtained in order to decompose measurements into these components:
  - Solar Tides
  - Transient Waves (if any)
  - Eddies/Turbulence
- A complete **Reference Atmosphere** for Venus **Winds** is yet to be done (crucial for GCMs).



The more we know about the polar vortex, the less…

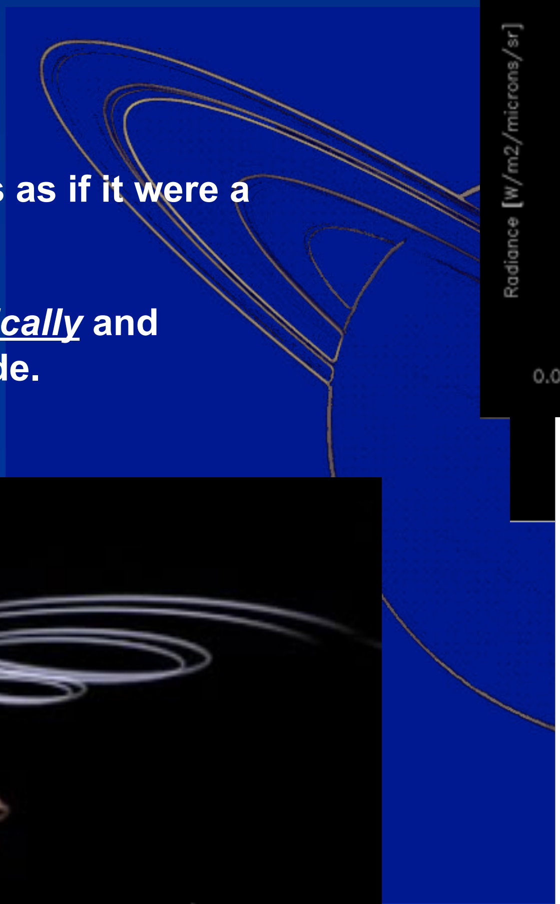
- **Rapidly changing Morphology ...**

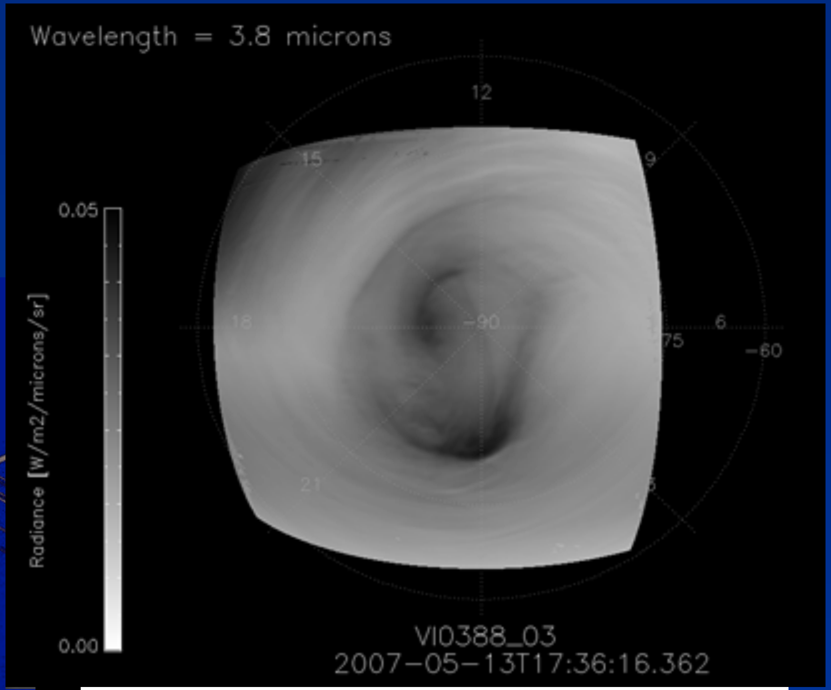
- **Morphology and Dynamics *uncoupled*?**

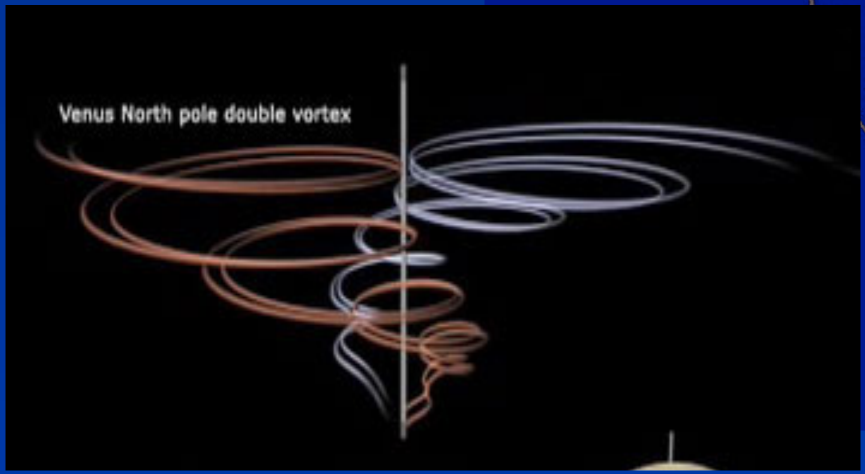
- **Polar circulation can be:**
    - *Solenoid*
    - *Convergent/Divergent*

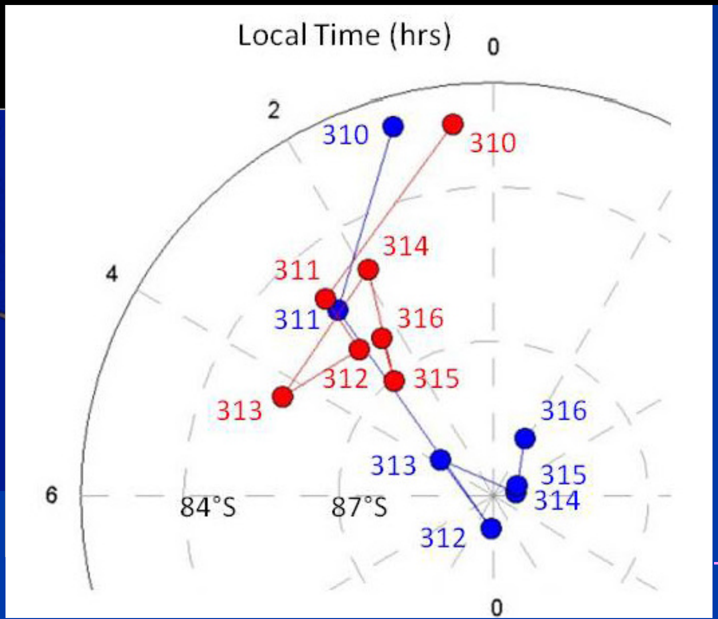
- **Sometimes, the vortex moves as if it were a *merry-go-round* …**

- **… and others it moves *chaotically* and apparently uncoupled in altitude.**



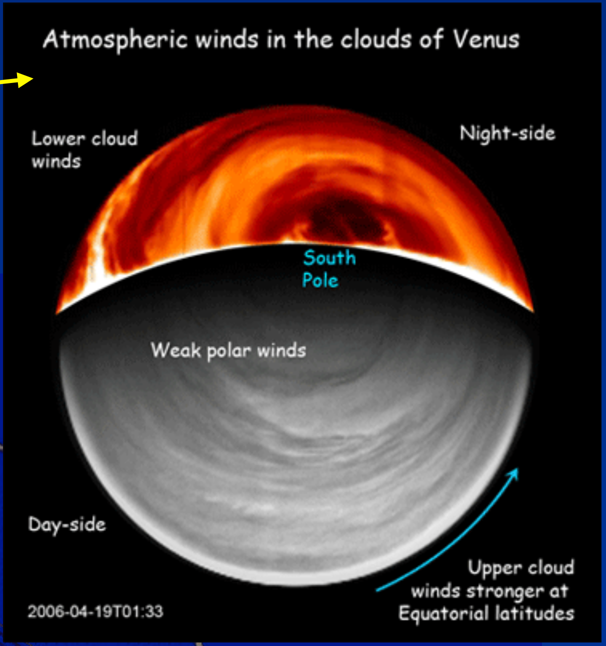




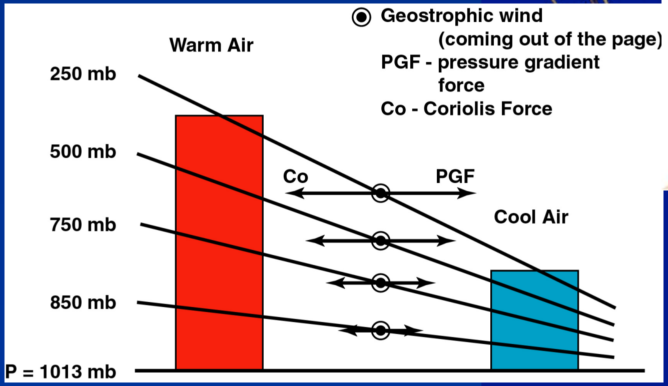


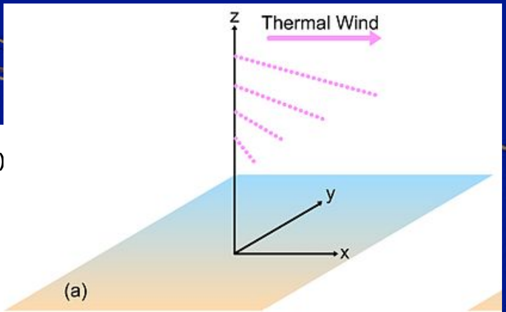
How can we measure the winds on Venus?

1. ***Tracking the features*** seen in remote-sensing images.

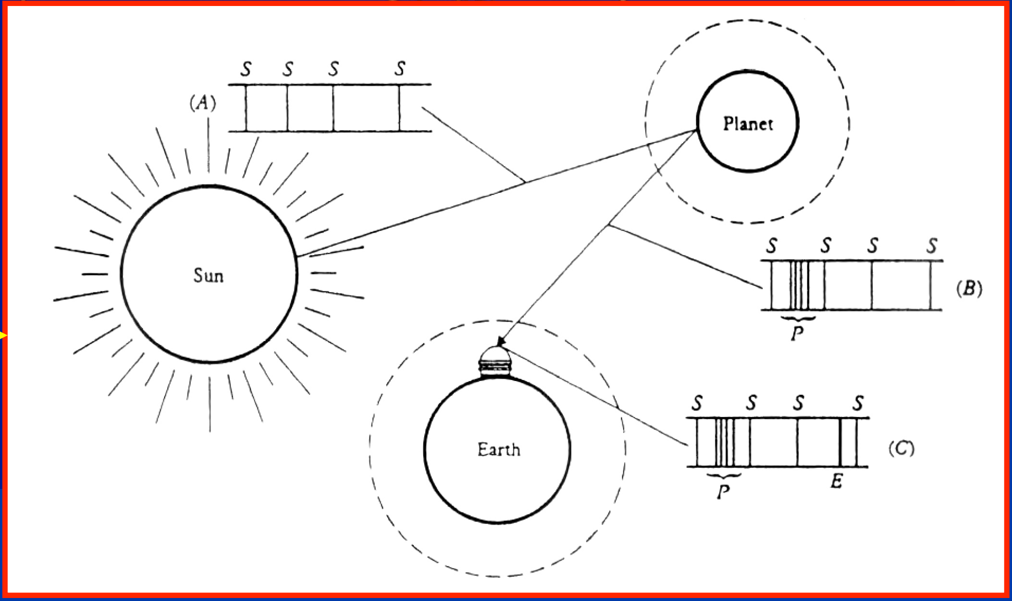


2. Indirectly from atmospheric temperature maps: using the ***Thermal Wind Equation***.



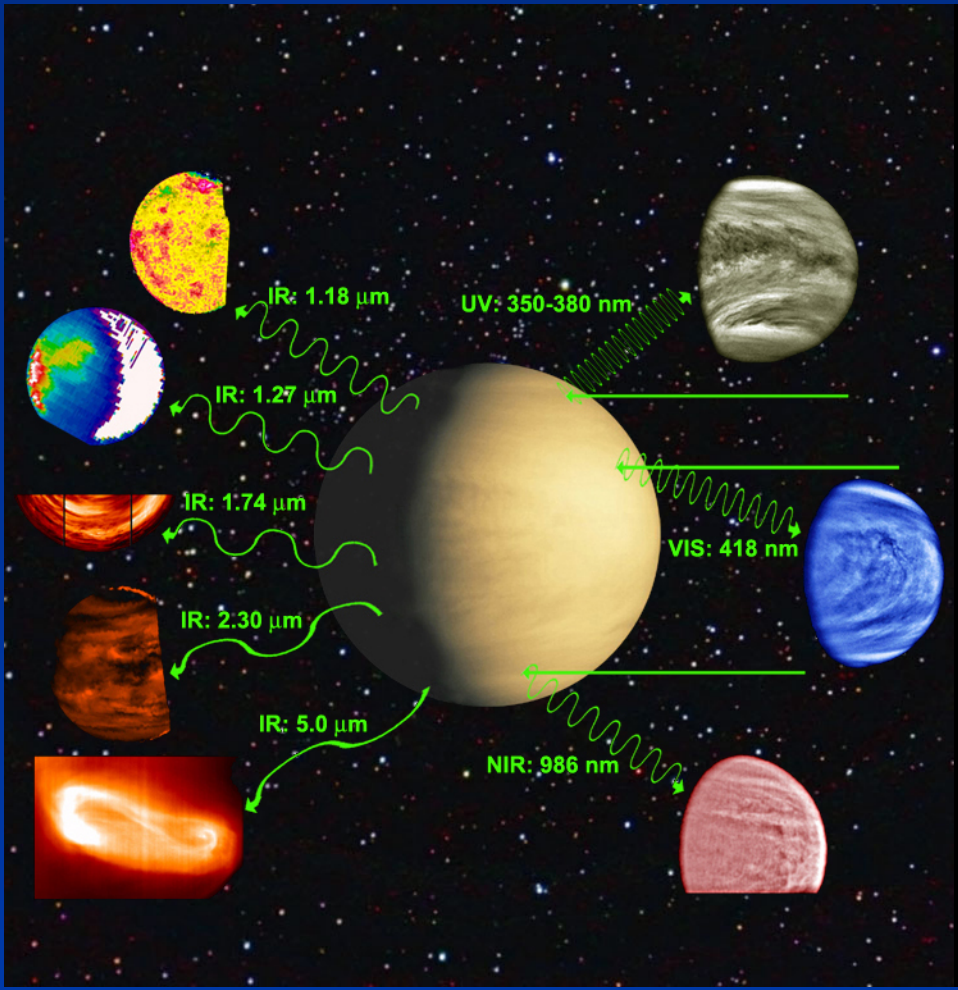


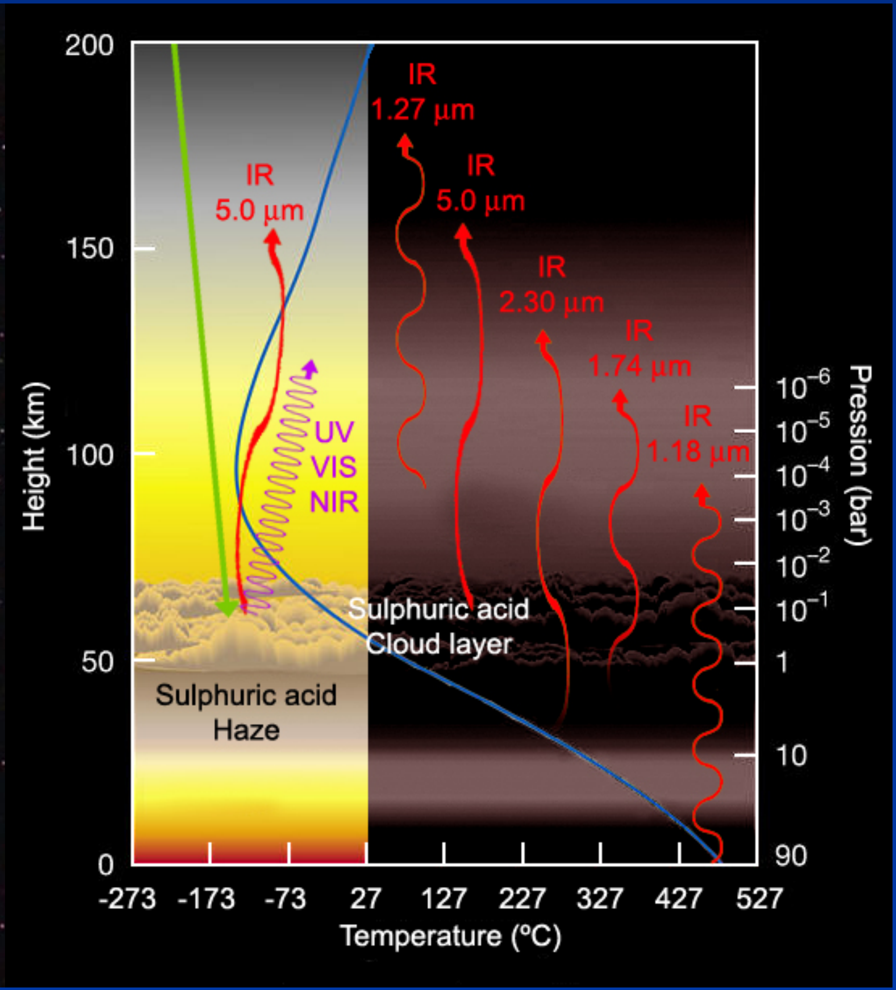
3. Measuring the ***Doppler-shift*** of solar scattered/ absorption lines in atmospheric spectra.



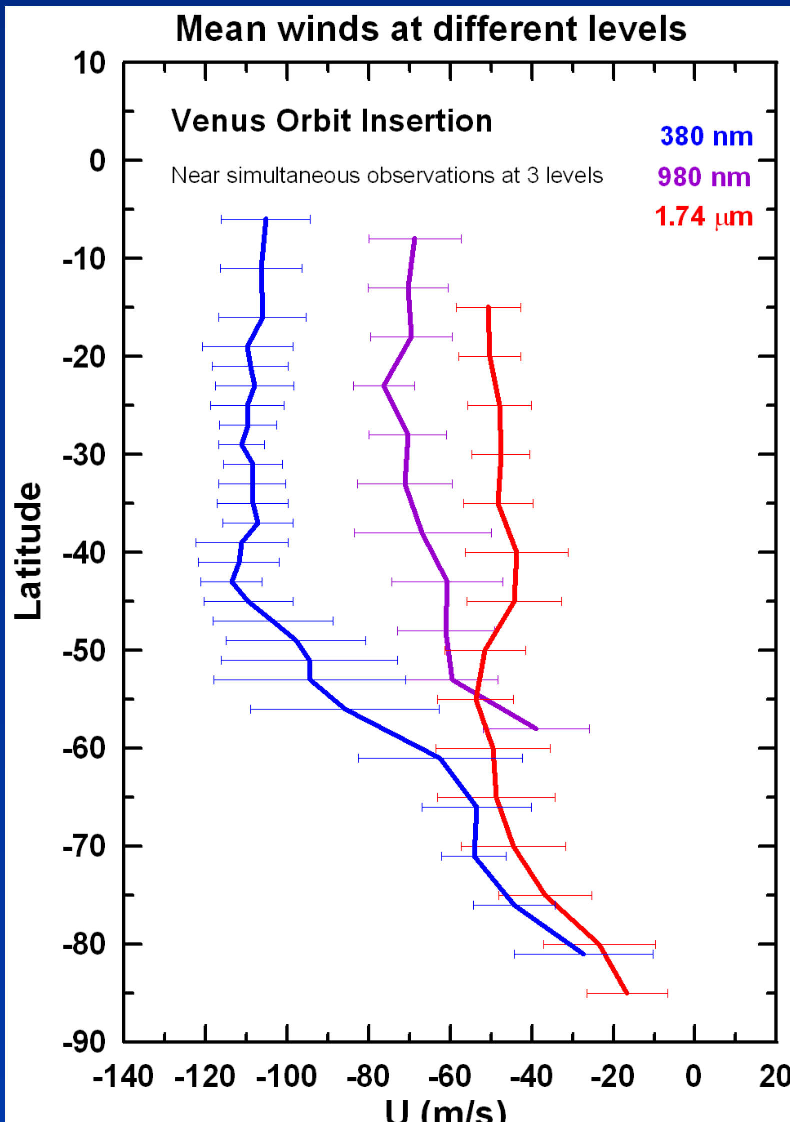
Remote sensing of the planet Venus

Depending on the wavelength with which we observe Venus, we will be able to sense different vertical levels of its atmosphere.

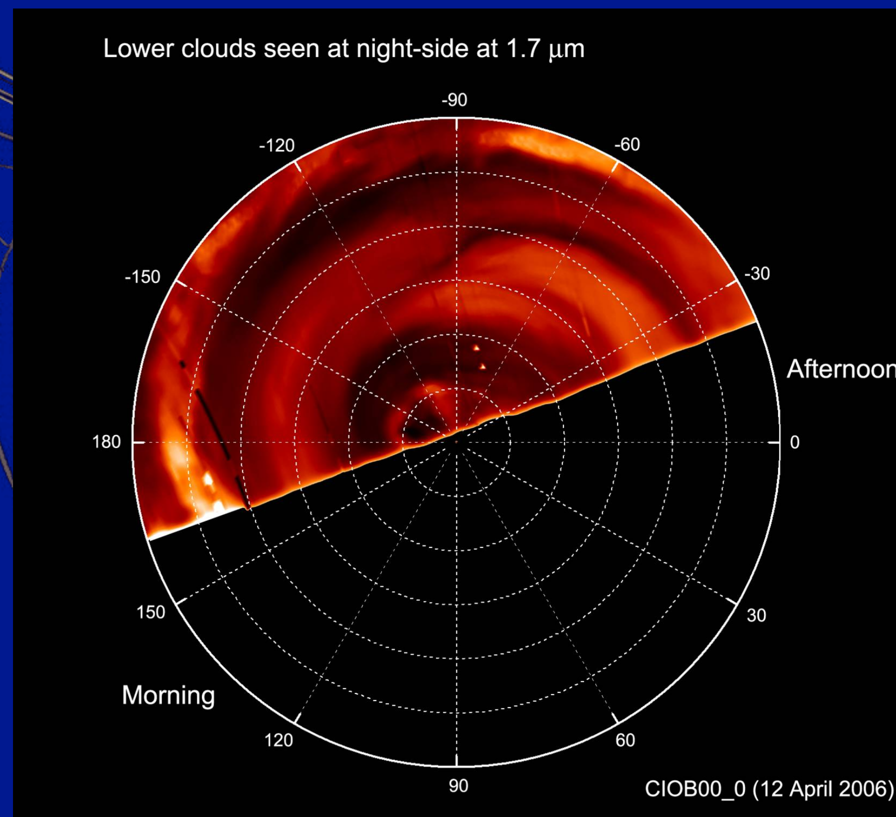




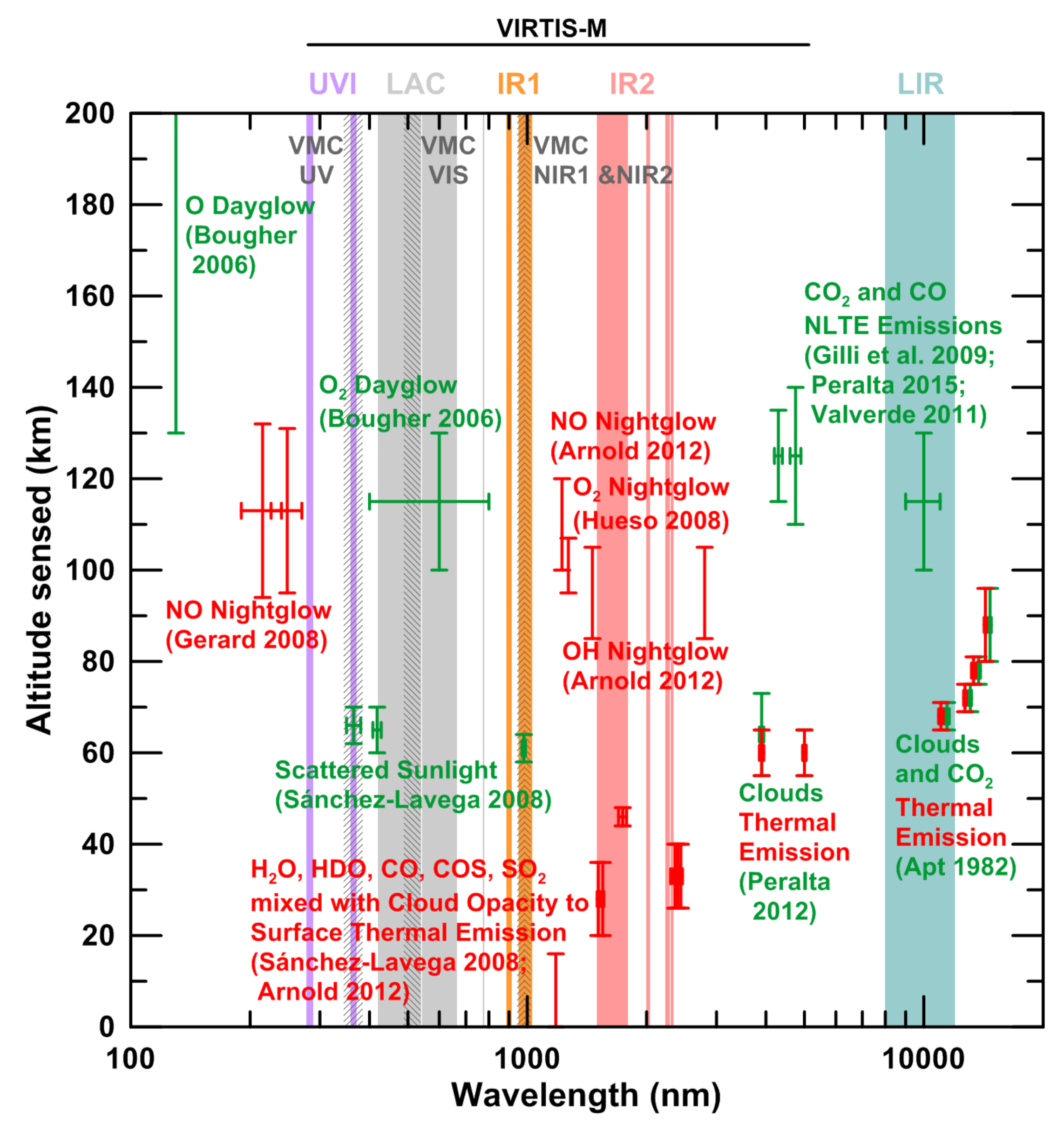
Different wavelengths: 3D view of Venus' winds

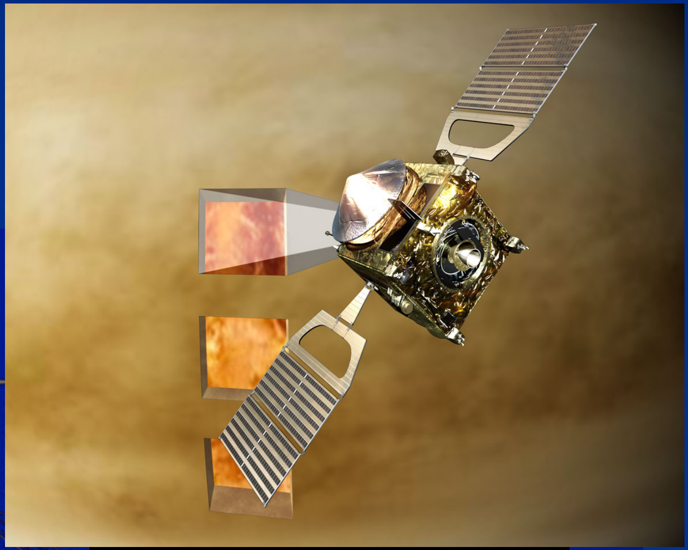


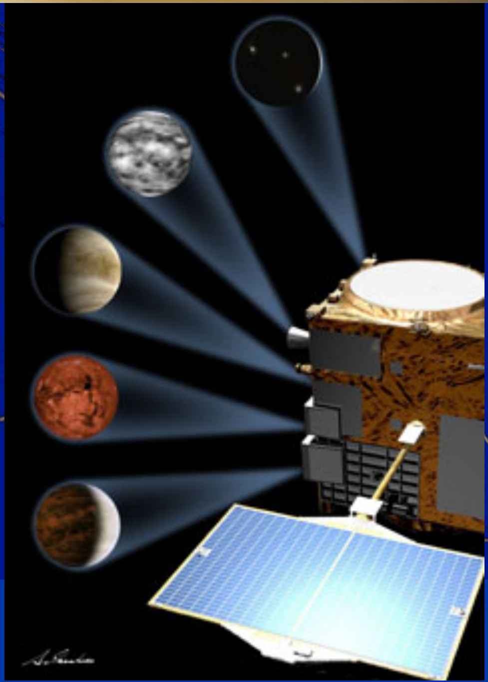
Zonal Wind Profile measured for images taken with a filter of 380nm



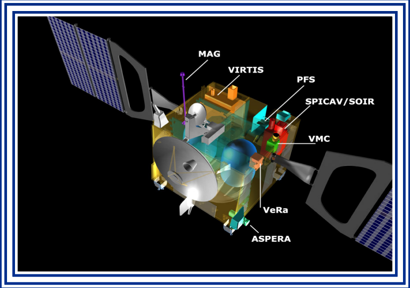
Venus’ levels for nadir images (VEx & Akatsuki)

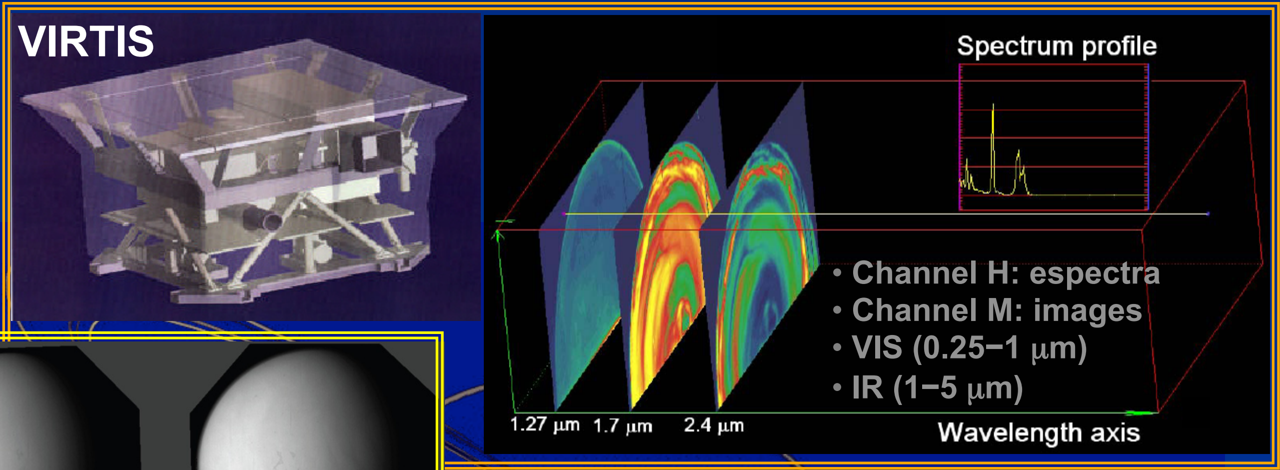


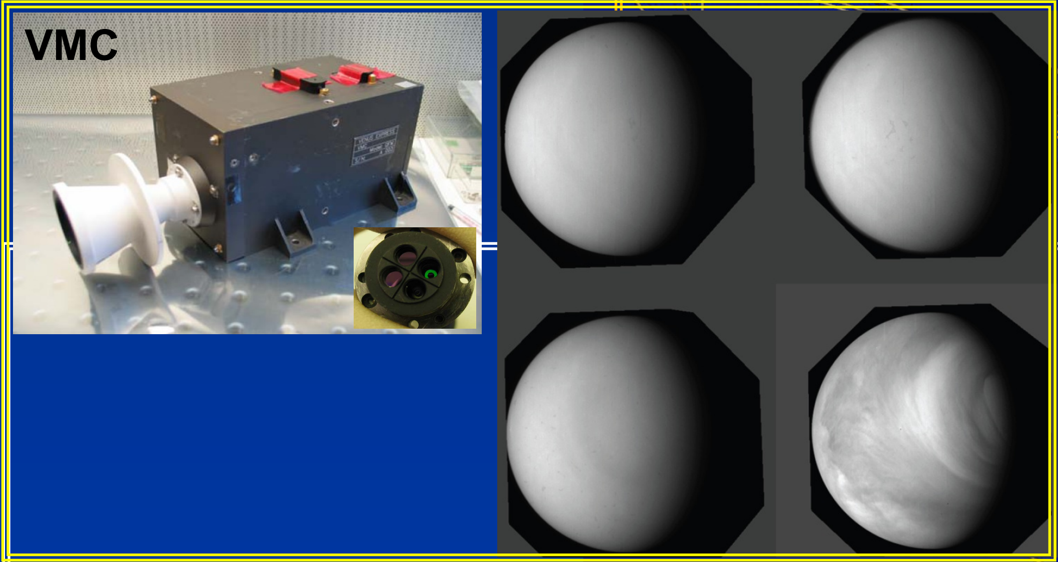


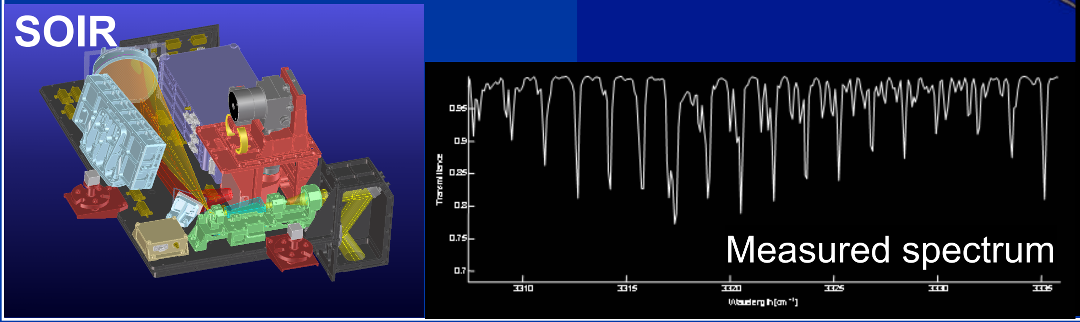


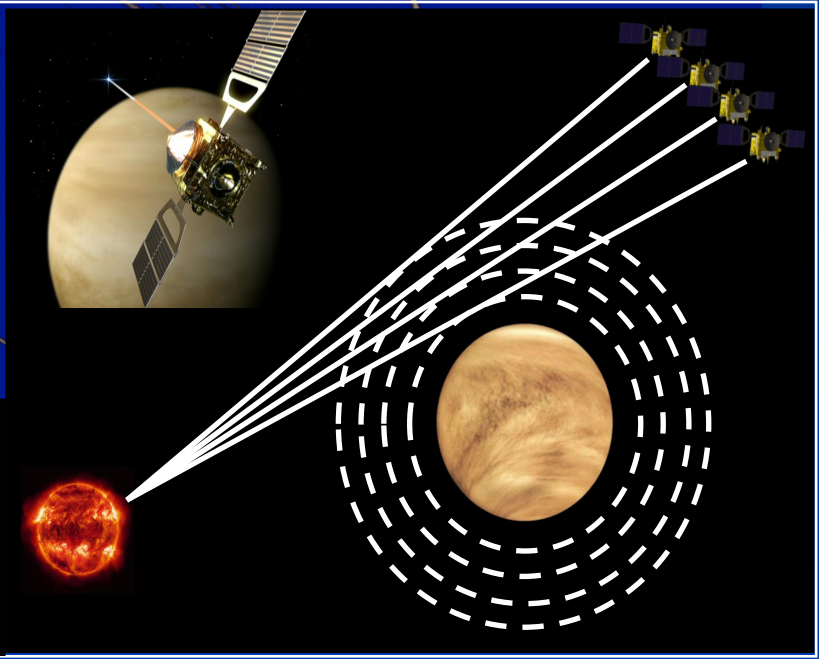
Venus Express: Instruments to measure Winds











Techniques for Tracking Atmospheric features (I)

1. ***TEMPLATE MATCHING*.**
   1. Sum of Absolute Differences (SAD)
   2. Sum of Square Differences (SSD)
   3. Cross-Correlation (CC)

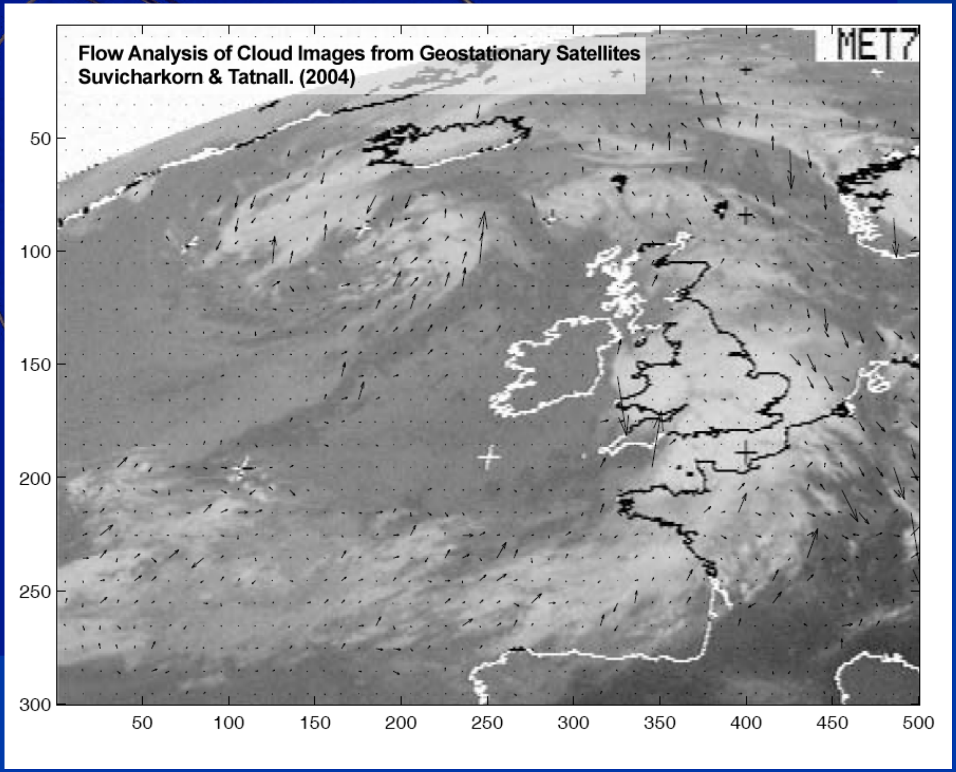
Most used in Solar System Planets, but not for the Earth:

- **Sensitive to noise.**
- **Slow algorithm.**
- **Fails in pairs of images with different bits, spatial resolution, etc …**

2. ***OPTICAL FLOW*. Calculate the motion using the differential change of Intensity at every pixel position for 2 images taken at times t and t+δt:**

   $I(x,y,z,t) = I(x+\delta x, y+\delta y, z+\delta z, t+\delta t)$.

   The most known are:
   1. Phase-Correlation.
   2. Lucas-Kanade method.
   3. Horn Schunk method.
   4. …



Techniques for Tracking Atmospheric features (II)

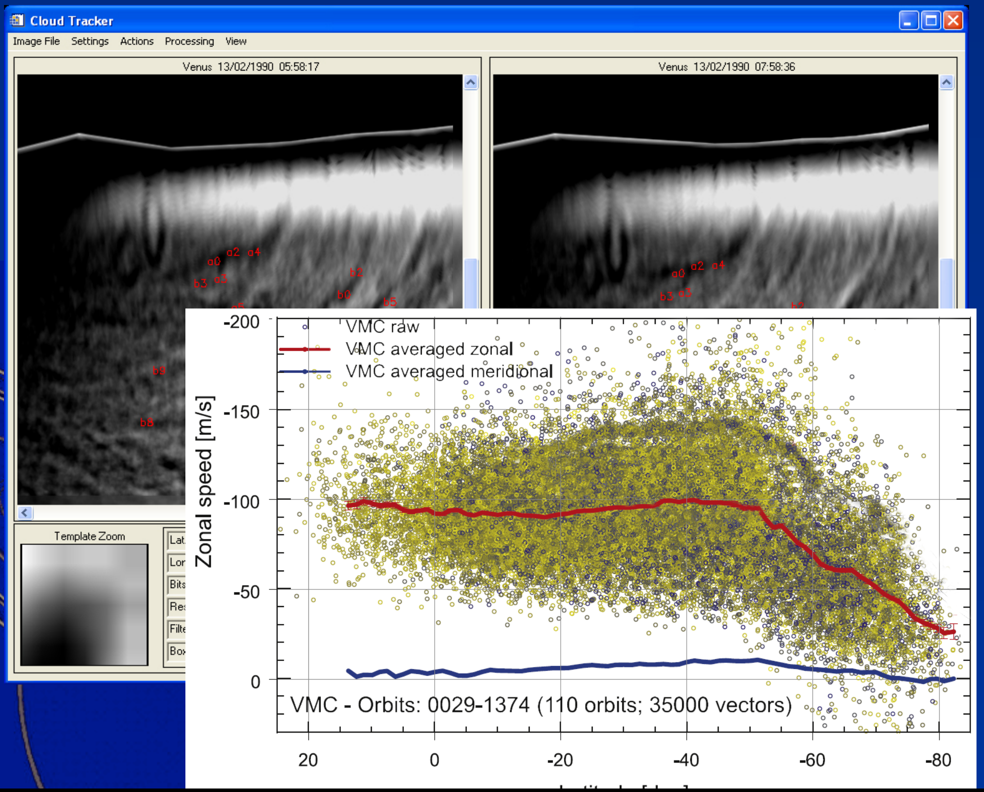
1. ***Manual Tracking*.**
    1. Trustable when experience adquired.
    2. Avoid outliers as tracers.
    3. Very slow. Demands learning stage.

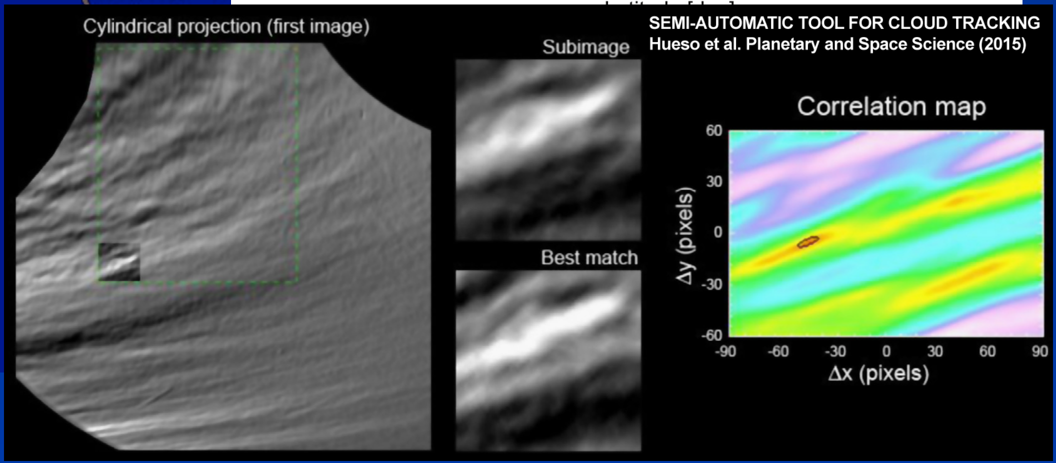
2. ***Automatic Tracking*.**
    1. Blind: includes outliers and bad measurements.
    2. Hundreds times more measurements.
    3. Fastest method.

3. ***Semi-Automatic Tracking*.**
    1. Human operator accepts/rejects each automatic measurement.
    2. High number of measurements in a short time.

$$u = (R+H)\cdot\cos\phi\cdot\frac{\Delta\lambda}{\Delta t}$$

$$v = (R+H)\cdot\frac{\Delta\phi}{\Delta t}$$

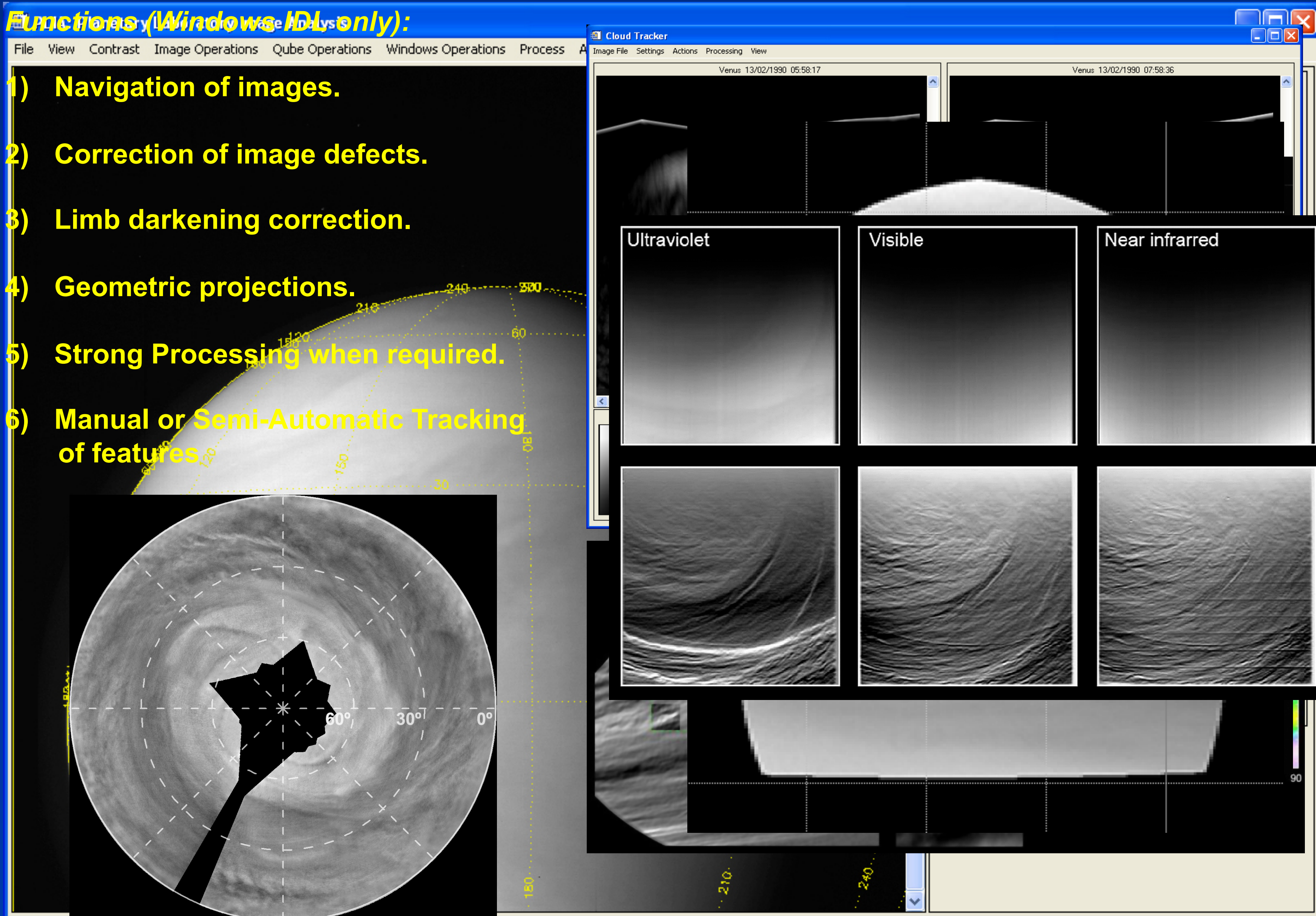




Planetary Laboratory for Image Analysis (PLIA)

Functions (Windows IDL only):

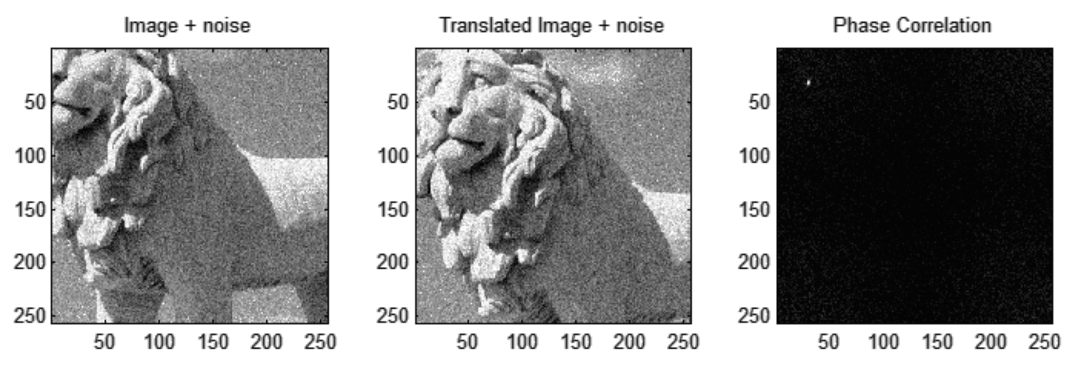
1) **Navigation of images.**
2) **Correction of image defects.**
3) **Limb darkening correction.**
4) **Geometric projections.**
5) **Strong Processing when required.**
6) **Manual or Semi-Automatic Tracking of features**



Take a breath! This is Phase-Correlation

The **Phase Correlation** is a "frequency domain" approach to determine the relative translation movement between 2 images.

The traslation is estimated determining the position of the maximum peak present in the inverse Fourier Transform of the **Normalized Cross Correlation (NCS)**.



Demostration:

Provided two images (ia and ib), one the translated version of the other,

$$i_b(x,y) \stackrel{\text{def}}{=} i_a(x-\Delta x, y-\Delta y)$$

The Fourier Transform will be,

$$\mathbf{I}_b(u,v) = \mathbf{I}_a(u,v) e^{-2\pi i\left(\frac{u\Delta x}{M}+\frac{v\Delta y}{N}\right)}$$

Then we calculate the Normalized Cross Correlation (NCS) to factor out the phase difference.

$$NCS = \frac{\mathbf{I}_a\mathbf{I}_b^*}{|\mathbf{I}_a\mathbf{I}_b^*|} = \frac{\mathbf{I}_a\mathbf{I}_a^* e^{2\pi i\left(\frac{u\Delta x}{M}+\frac{v\Delta y}{N}\right)}}{|\mathbf{I}_a\mathbf{I}_a^* e^{2\pi i\left(\frac{u\Delta x}{M}+\frac{v\Delta y}{N}\right)}|} = $$

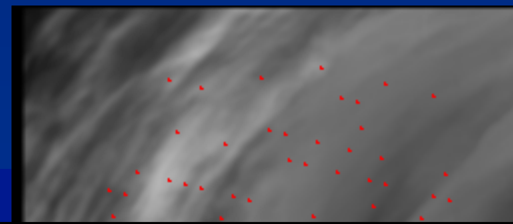
$$= \frac{\mathbf{I}_a\mathbf{I}_a^* e^{2\pi i\left(\frac{u\Delta x}{M}+\frac{v\Delta y}{N}\right)}}{|\mathbf{I}_a\mathbf{I}_a^*|} = e^{2\pi i\left(\frac{u\Delta x}{M}+\frac{v\Delta y}{N}\right)}$$

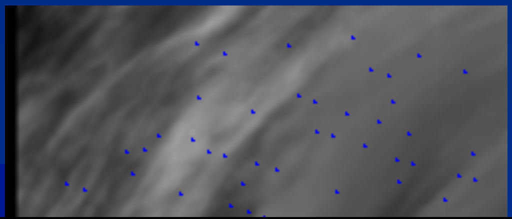
And this results in a single peak at (Δx,Δy) after an inverse Fourier Transform,

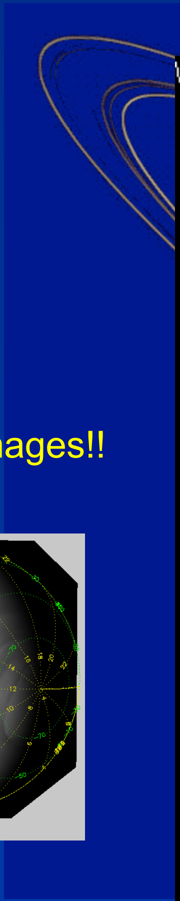
$$PC = \mathcal{F}^{-1}\{NCS\} = \delta(x-\Delta x, y-\Delta y)$$

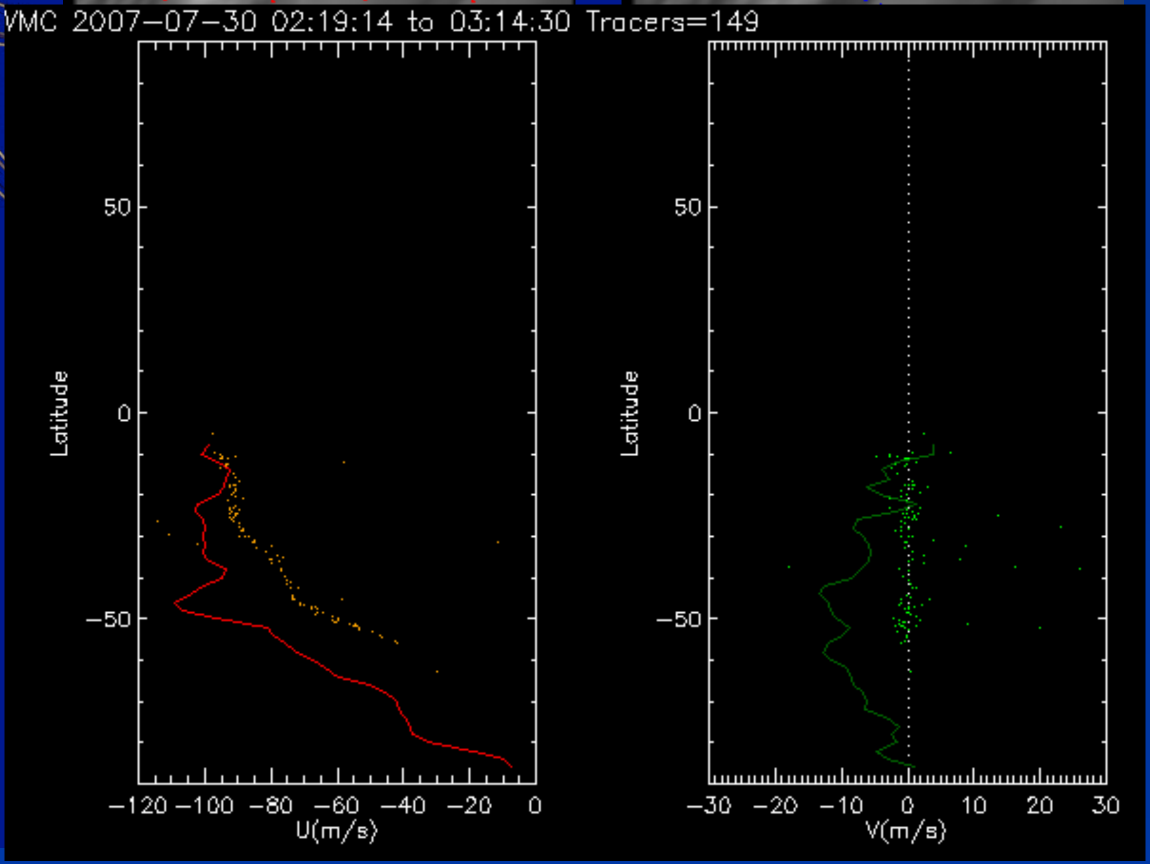
Take a breath! This is Phase-Correlation

Preliminary Cloud Tracking tests in infrared VIRTIS-M images with **Phase Correlation** are PROMISING!!

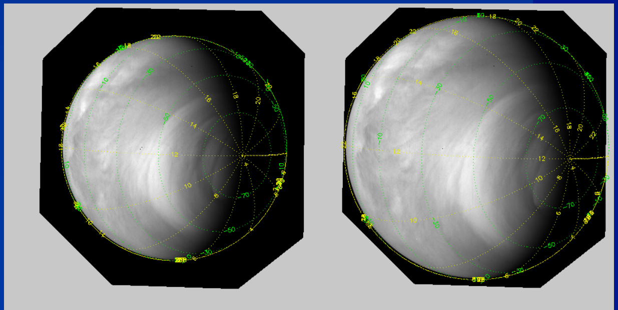








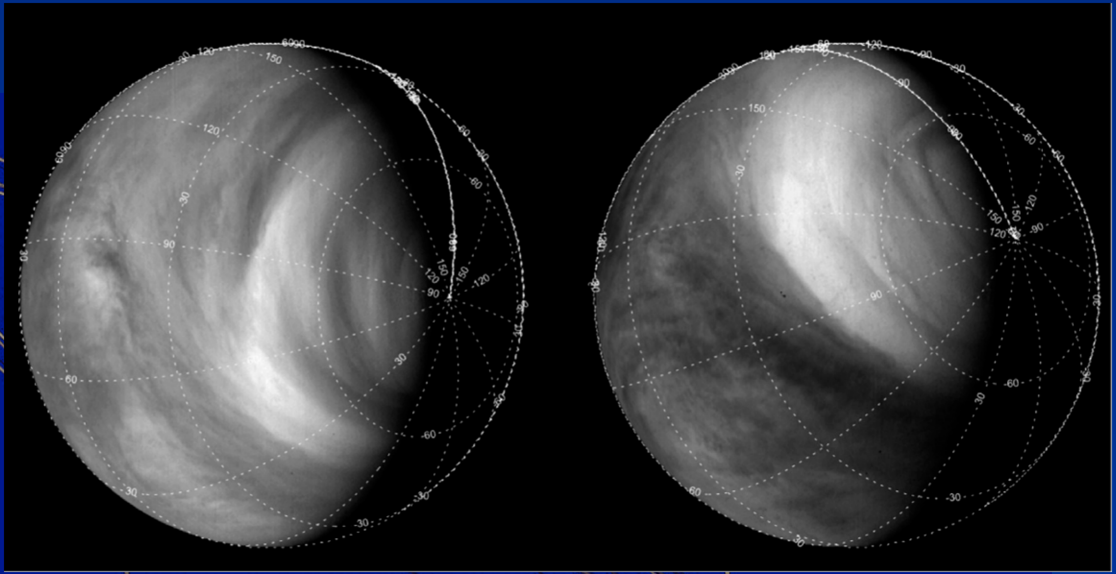
And also with ultraviolet VMC images!!

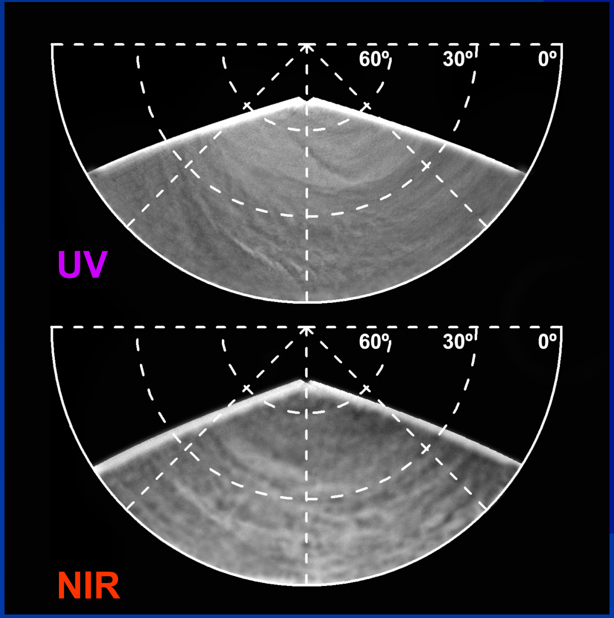


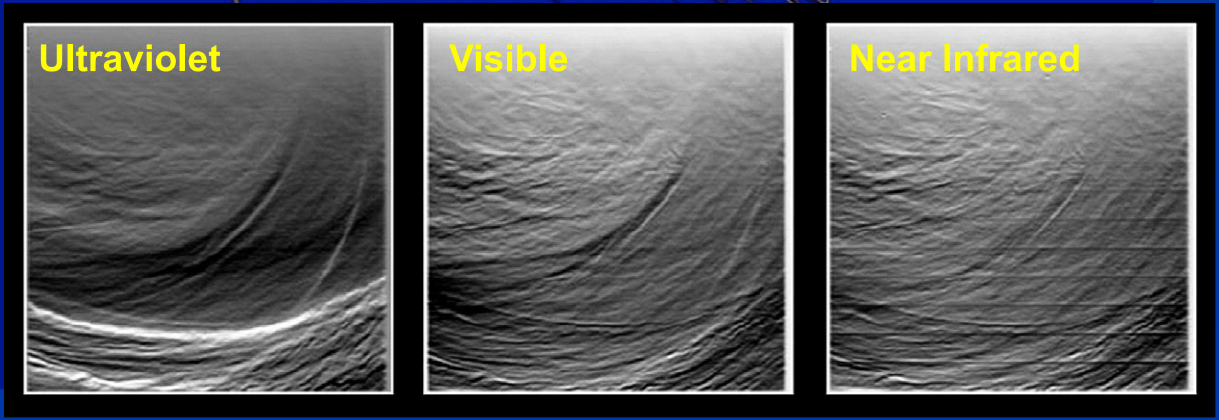
Scattered Sunlight: cloud features

The upper cloud layer of Venus can be sensed with three wavelengths, as shown by Hueso (2015):

1. **UV** (360−400 nm) sensing 65−70 km.
   High contrast features at the cloud top.
   VMC better in contrast and coverage.
   VIRTIS-M better spatial resolution.
2. **VIS** (570−680 nm) sensing 58−64 km.
   Low contrast features different to tops.
   Slight better contrasted than in NIR.
3. **NIR** (900−955 nm) sensing 58−64 km.
   Low contrast features different to tops.



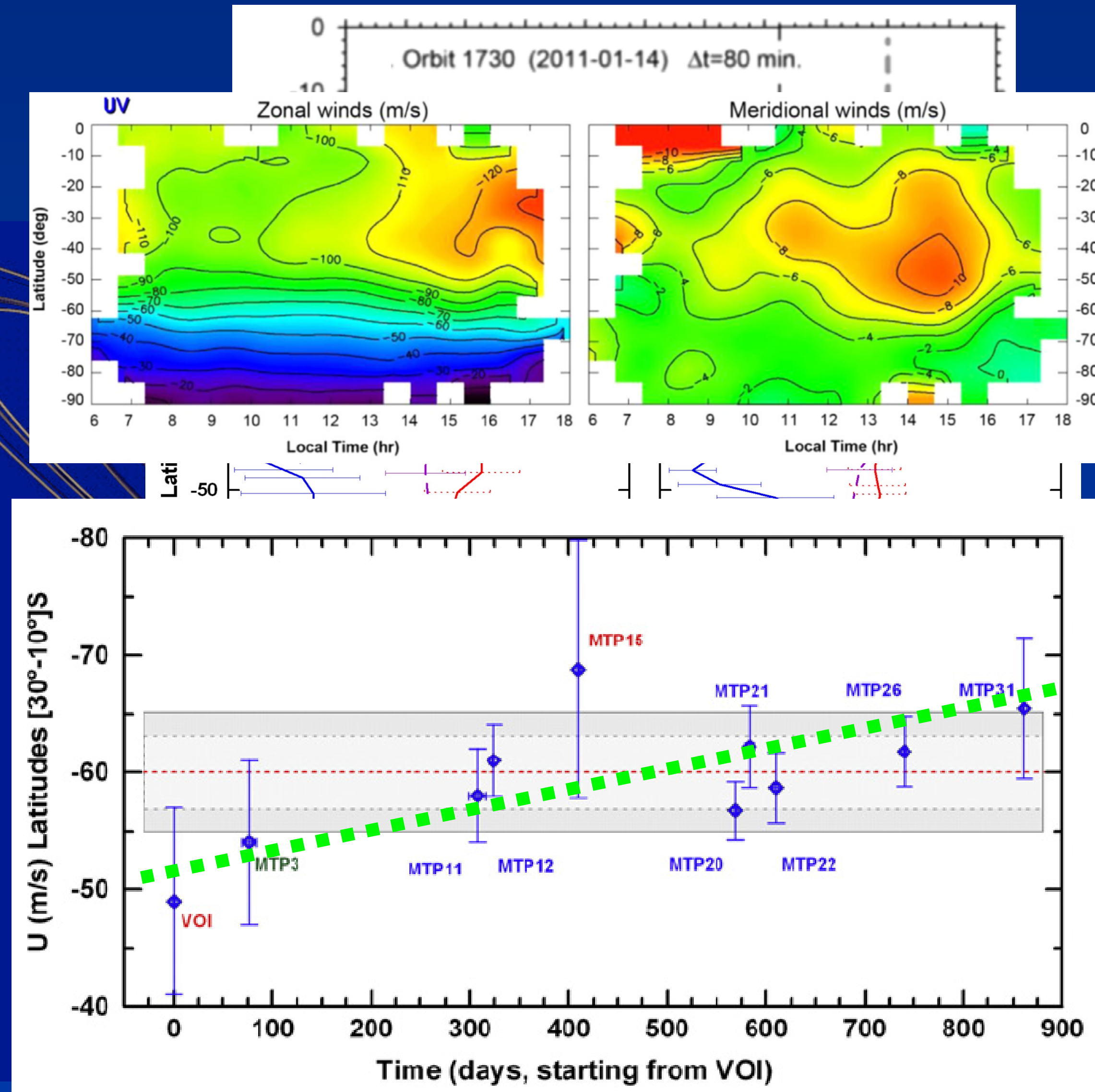




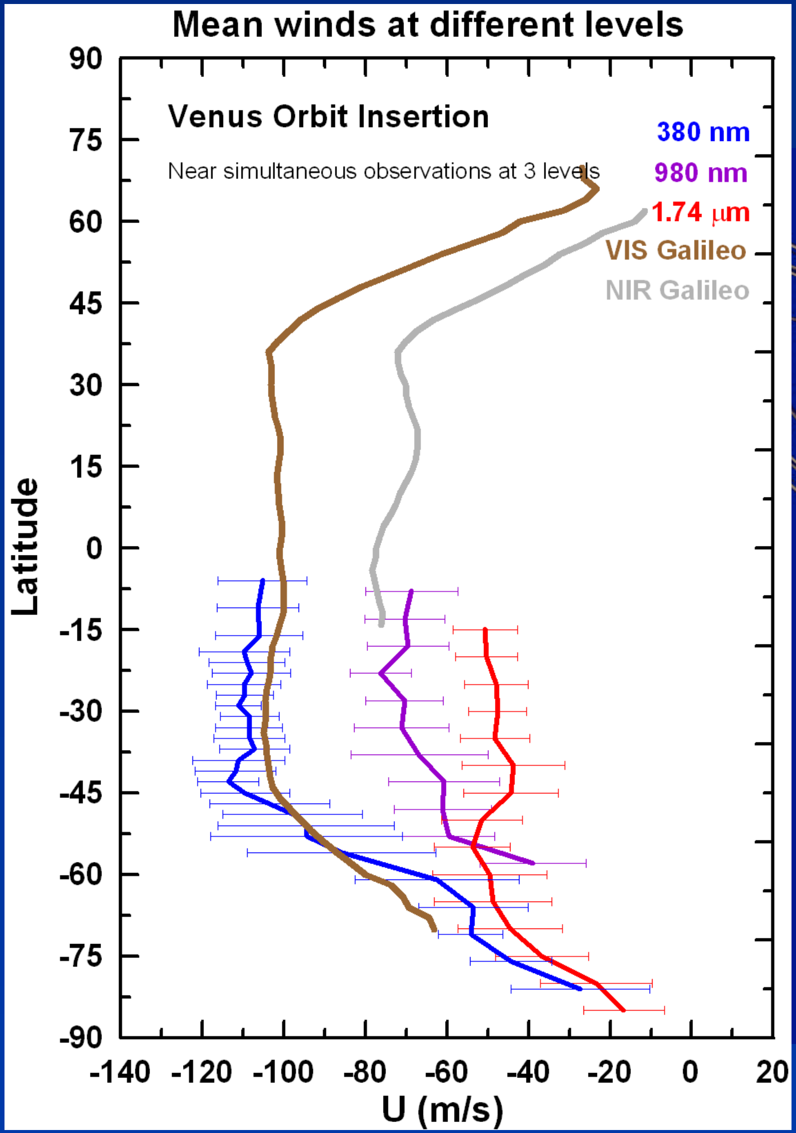
Scattered Sunlight: wind results from VIRTIS-M

Some interesting results about winds from scattered sunlight images (Hueso et al. 2015):

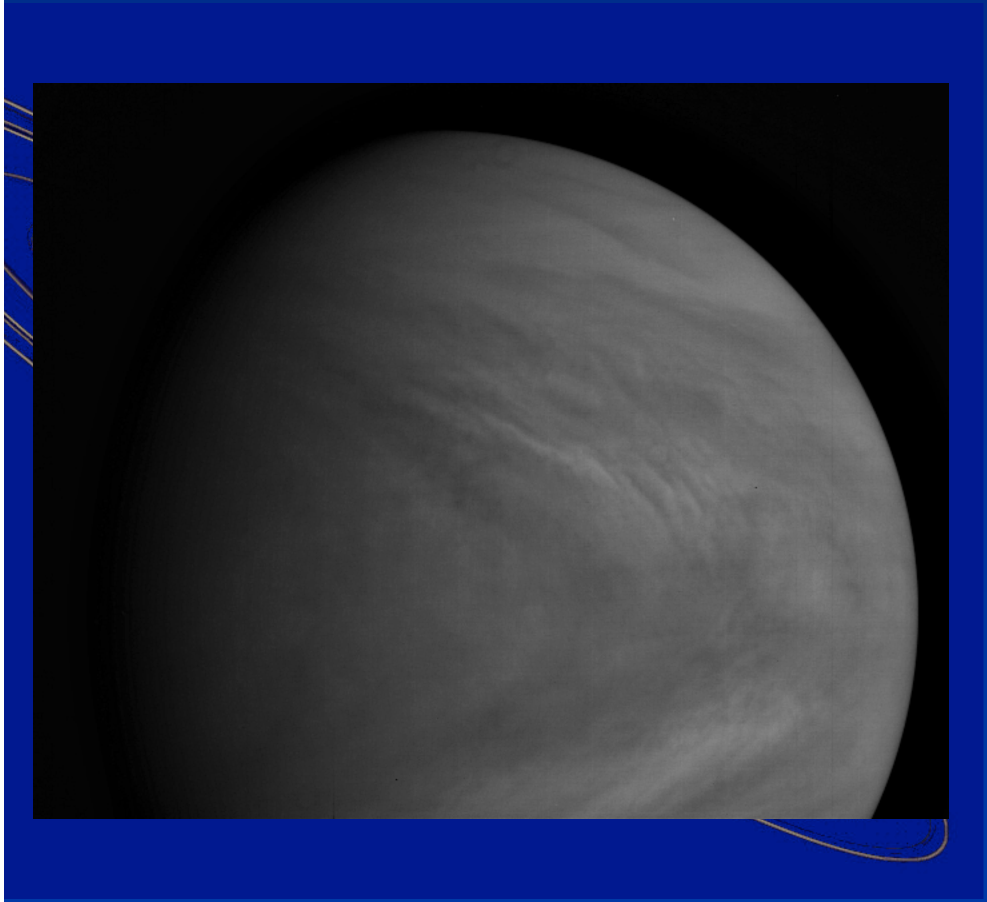
- Winds at the cloud tops (**UV**) is stronger, while **VIS** and **NIR** images provide similar results.
- Right below the cloud tops, zonal winds can suffer strong variations in short times (days).
- Zonal winds at the cloud tops have a clear dependence with the local time.
- Confirming previous results from VMC (Khatuntsev, 2013; Kouyama, 2013), a long-time variation of the zonal winds is also found at the cloud tops with VIRTIS-M.



Scattered Sunlight: VEx and Galileo compared

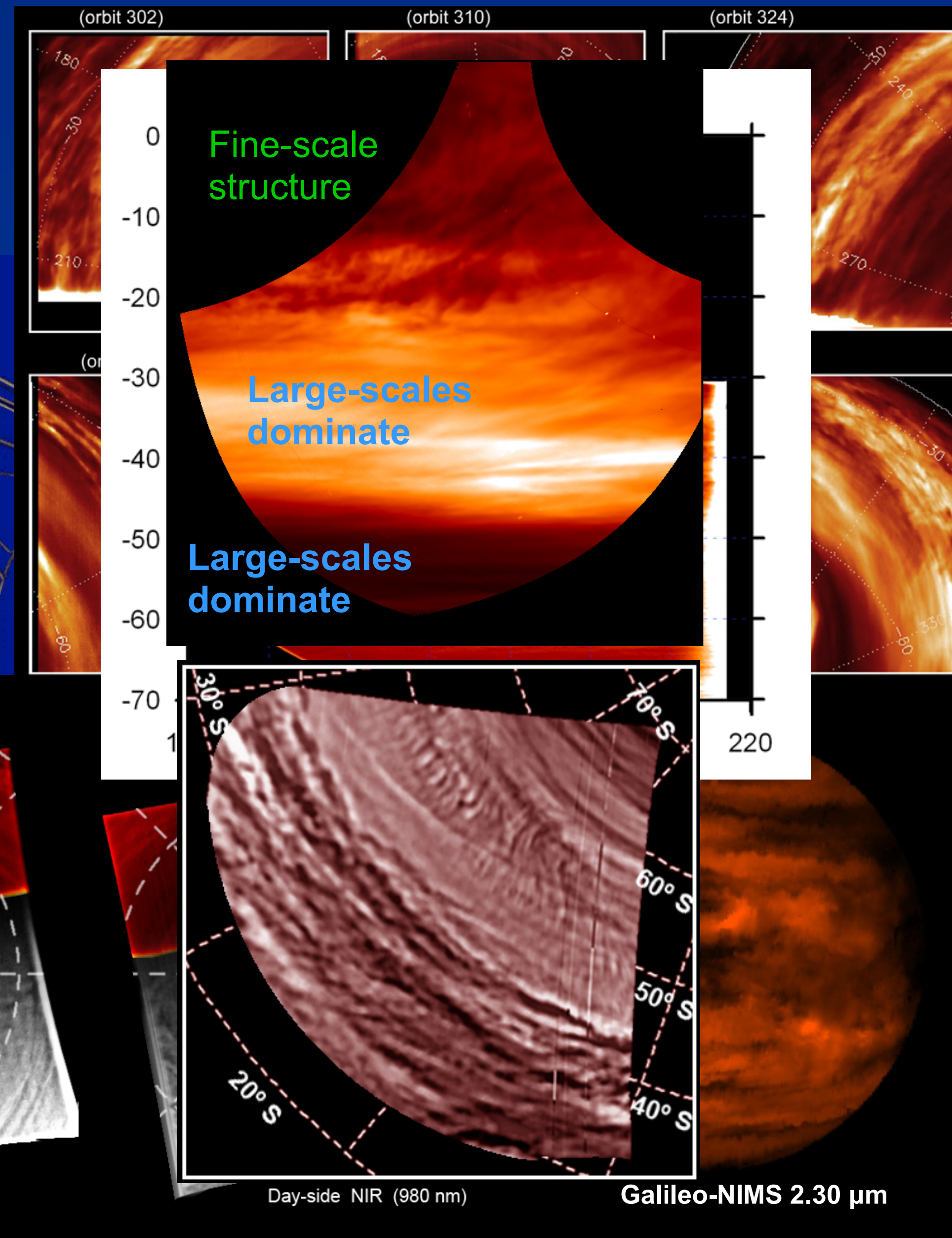


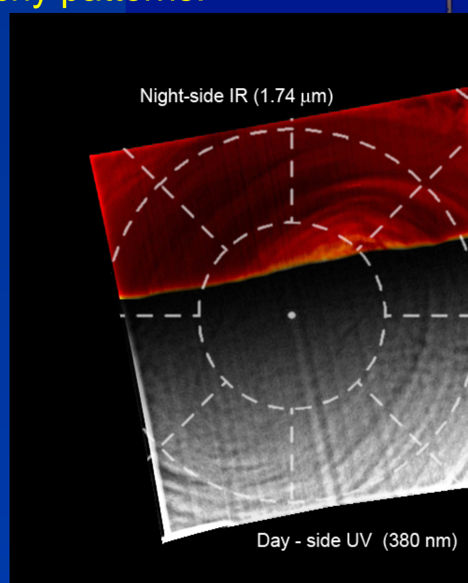
Zonal Wind Profile measured for images taken with a filter of 380 nm.



Cloud Opacity to Surface Radiation: cloud features

- The lower clouds can be sensed in the nightside of Venus using the Infrared wavelengths 1.74 and 2.30 µm.
- The vertical level seen ranges 44−48 km.
- Features caused by the different cloud opacity to the thermal radiation from the surface. **These patterns are the easiest to track**.
- Cloud features have different scales at different latitudes. For example, latitudes lower than 40º frequently exhibit patchy patterns.

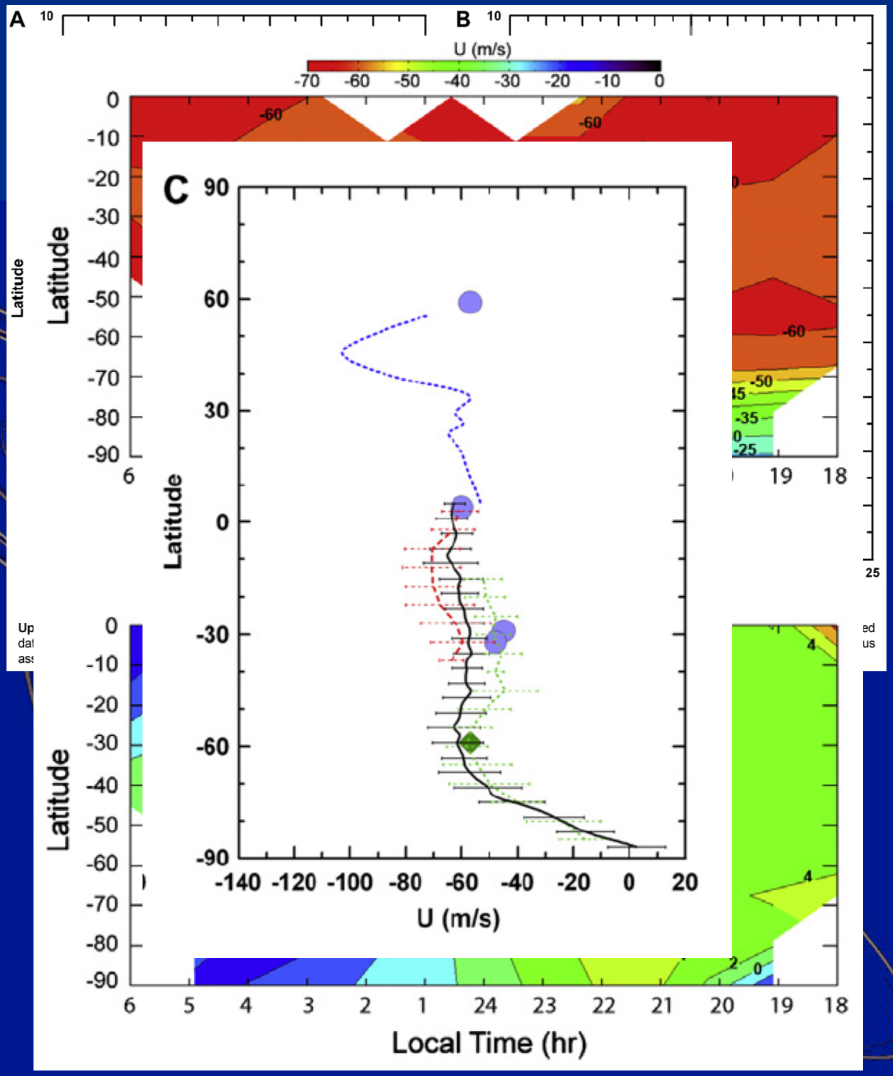




Cloud Opacity to Surface Radiation: wind results

Some interesting results about winds from images of nightside lower clouds (Hueso et al. 2012):

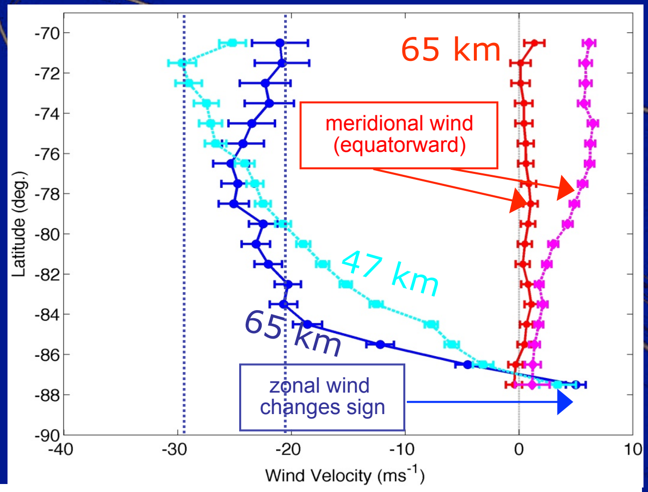
- Winds at the lower cloud (**1.74 & 2.30 µm**) have magnitudes similar to those measured with scattered sunlight (**VIS** and **NIR** images).
- No clear meridional circulation can be detected.
- Nor zonal or meridional winds seem to depend on the local time.
- Consistency with results from past decades (Pioneer Venus entry probes and Galileo-NIMS): **Long-Time Stability?**

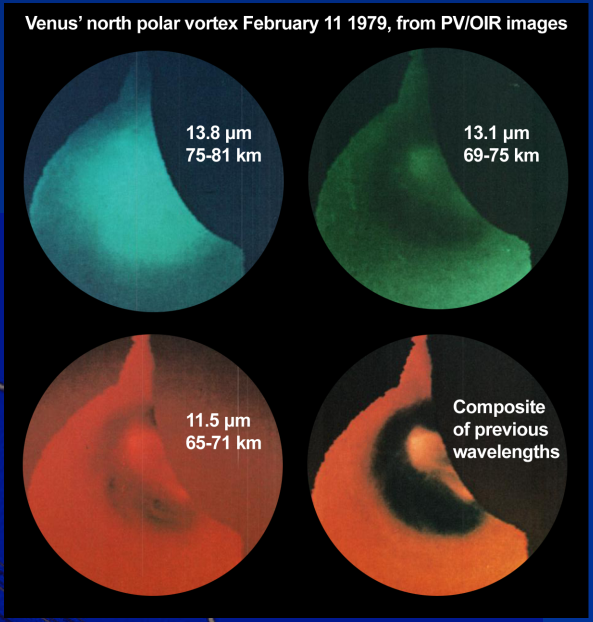


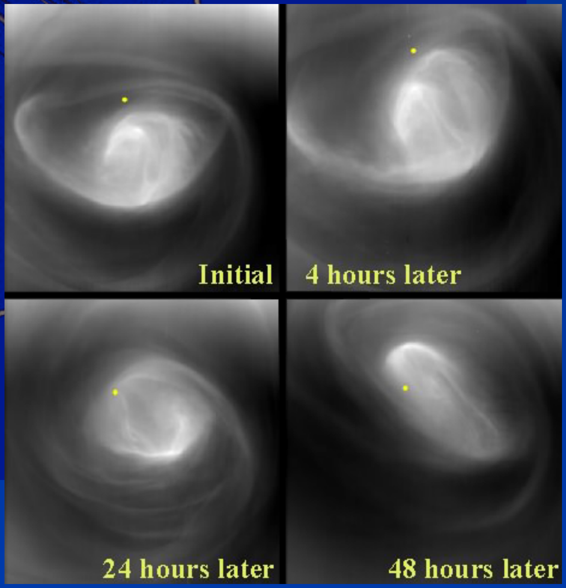
Clouds' Thermal Emission: features and winds

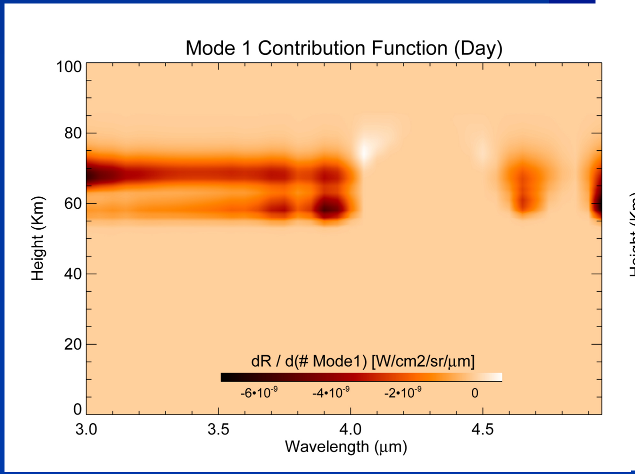
- The cloud tops can be sensed in both day and nightside of Venus using specific IR wavelengths: 3.9, 4.6, 5.0 or 11.5 μm.
- A range of altitudes above the cloud tops can be also imaged with the CO_2 thermal emission (13.0−14.8 μm).
- Tracking features at lower latitudes is challenging with VIRTIS-M.

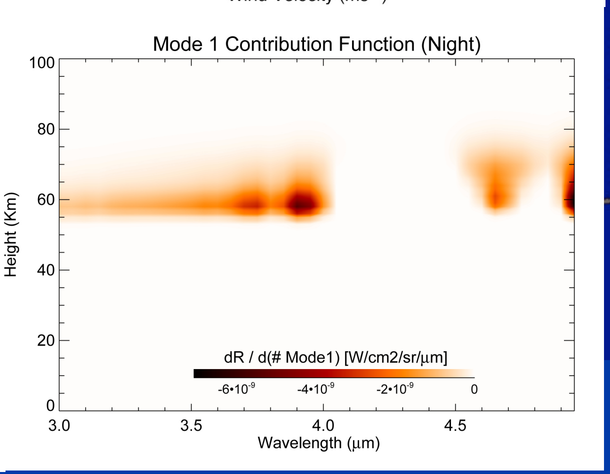

Galileo-NIMS 4.56 μm





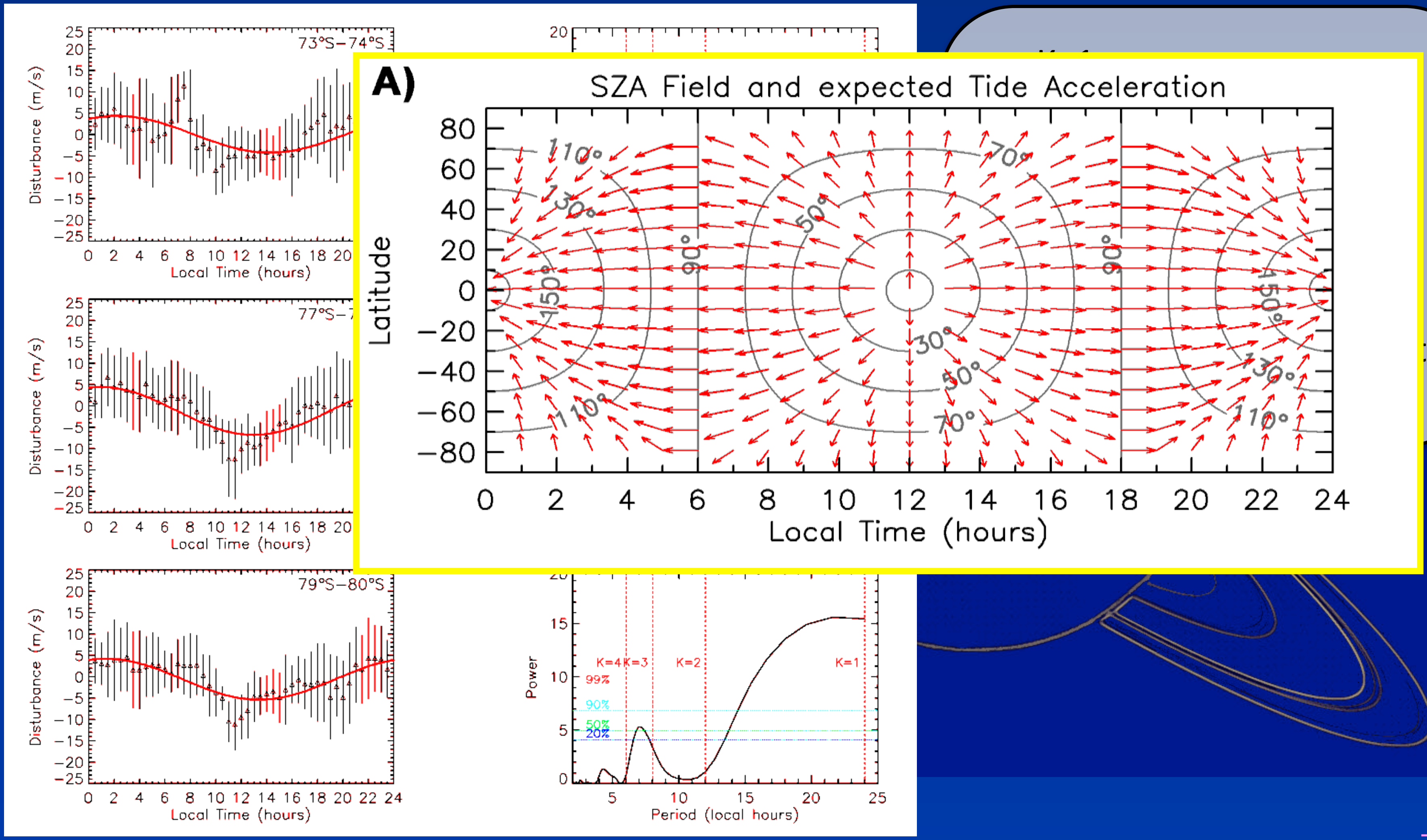






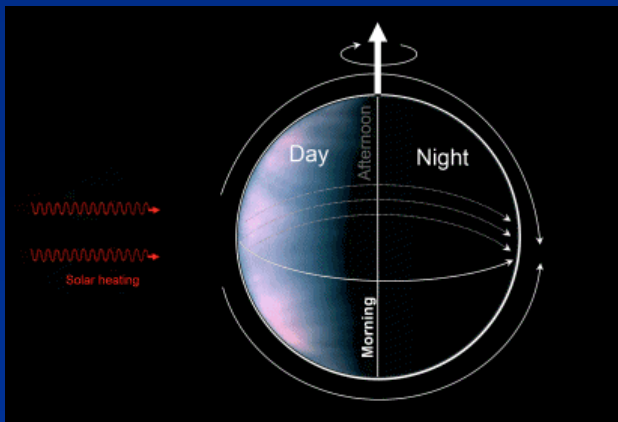
Clouds' Thermal Emission: solar tides on winds

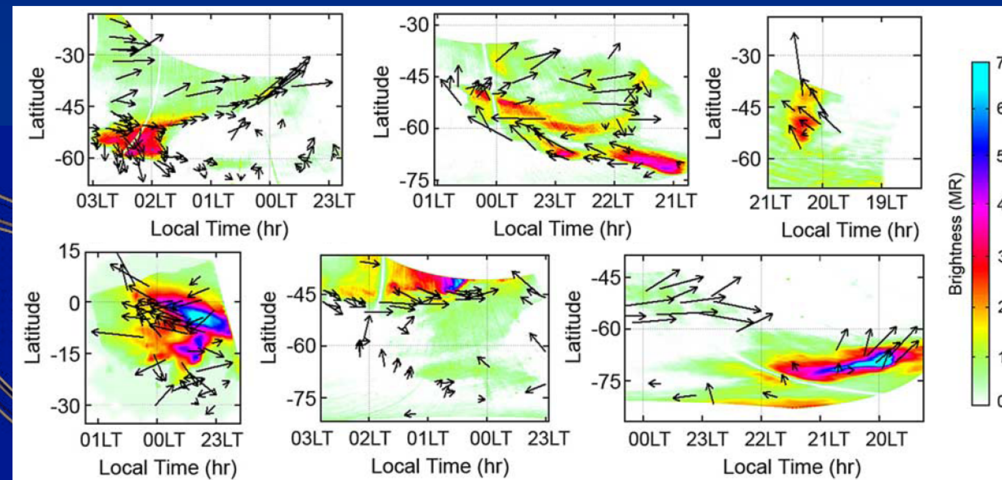
Solar-fixed waves in winds: **Diurnal Tide**



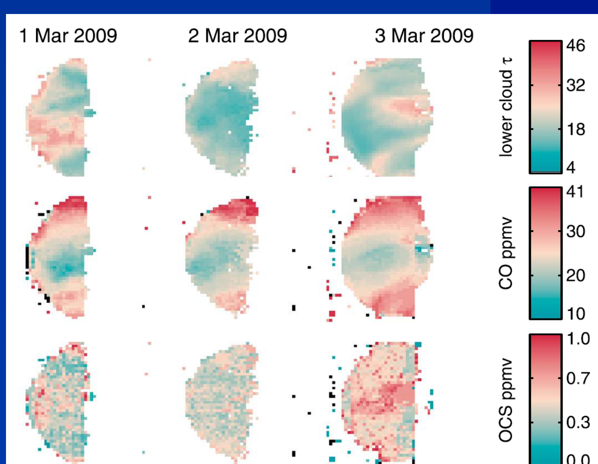
Other atmospheric features to track in IR images

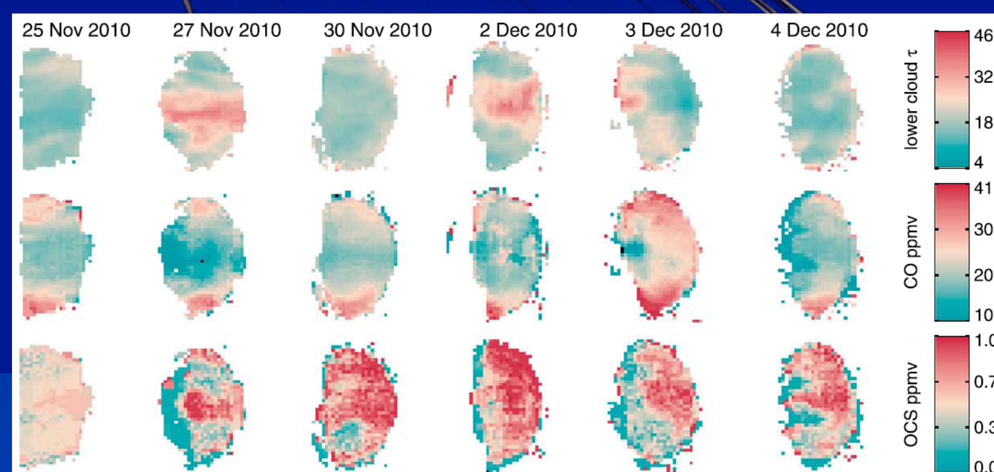
- Several UV-to-IR wavelengths can be used to sense Day/Nightglow from different species of Venus' Upper atmsphere. **Feature tracking is complex.**



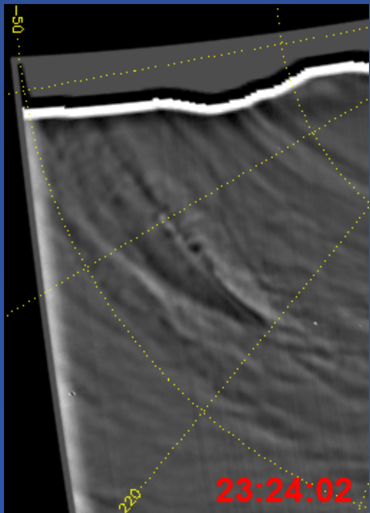


- Arney et al. (2014) used a RT model separated cloud opacity from concentrations of different species in the lower atmosphere of Venus (H_2O, HCl, CO, OCS and SO_2). **Feature tracking must be tried.**



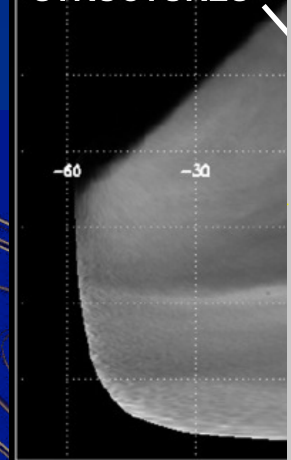


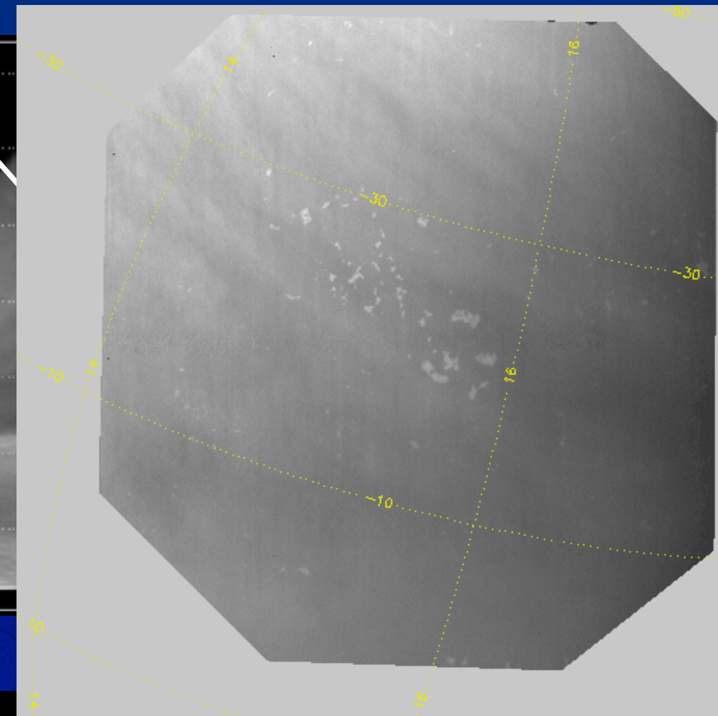
Beware of tracking some atmospheric features…



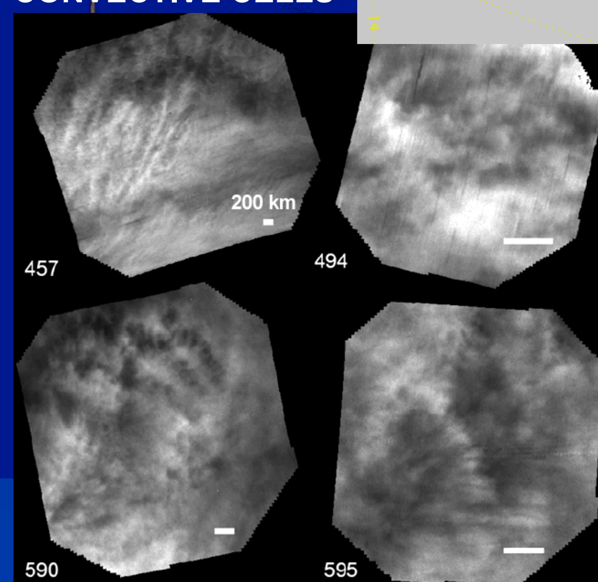
MESOSCALE WAVES

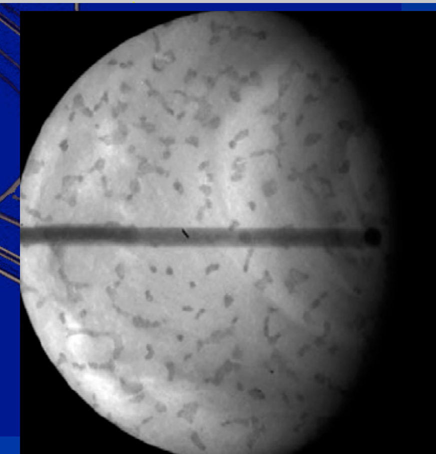
FEATURELESS ELONGATED STRUCTURES

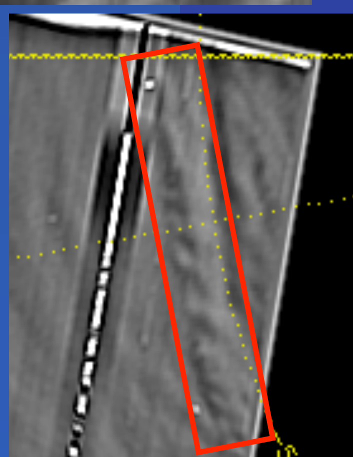




CONVECTIVE CELLS

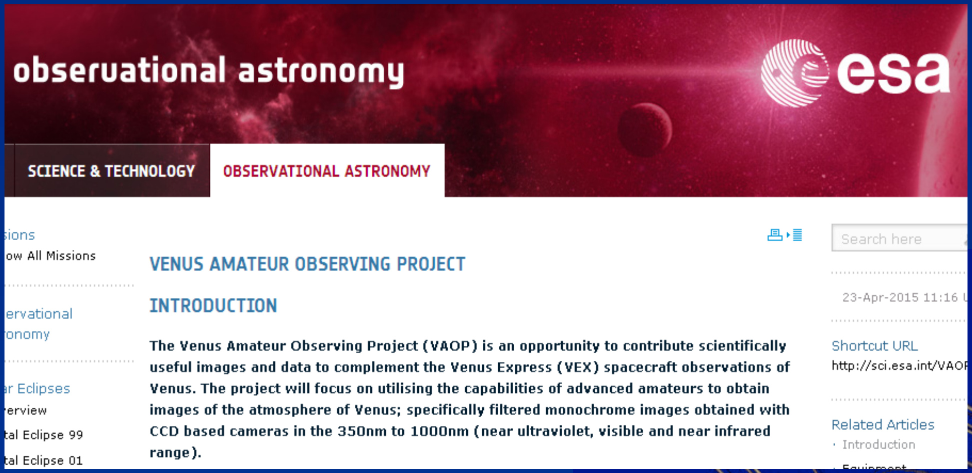


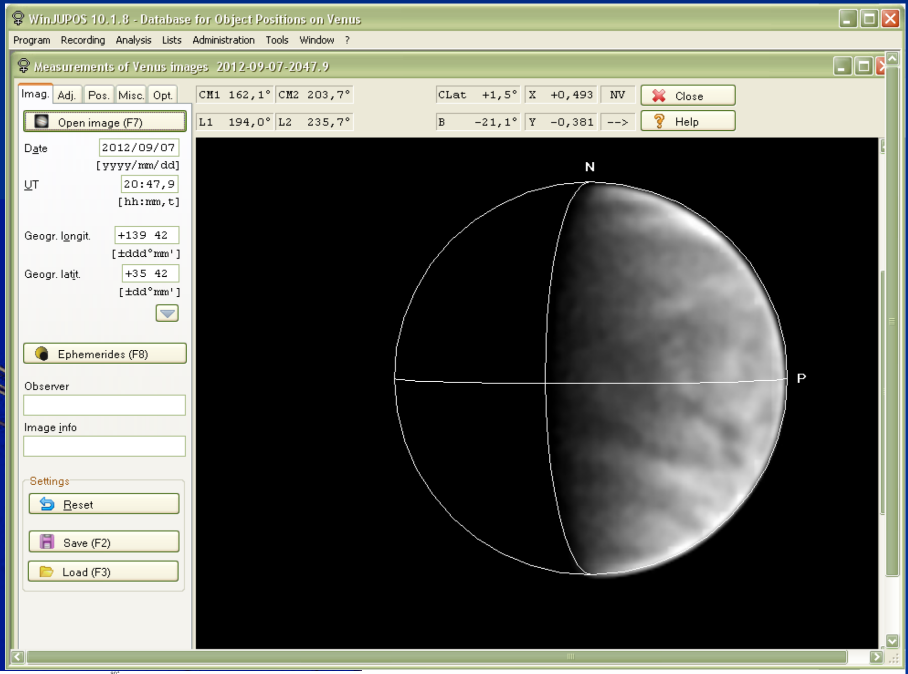


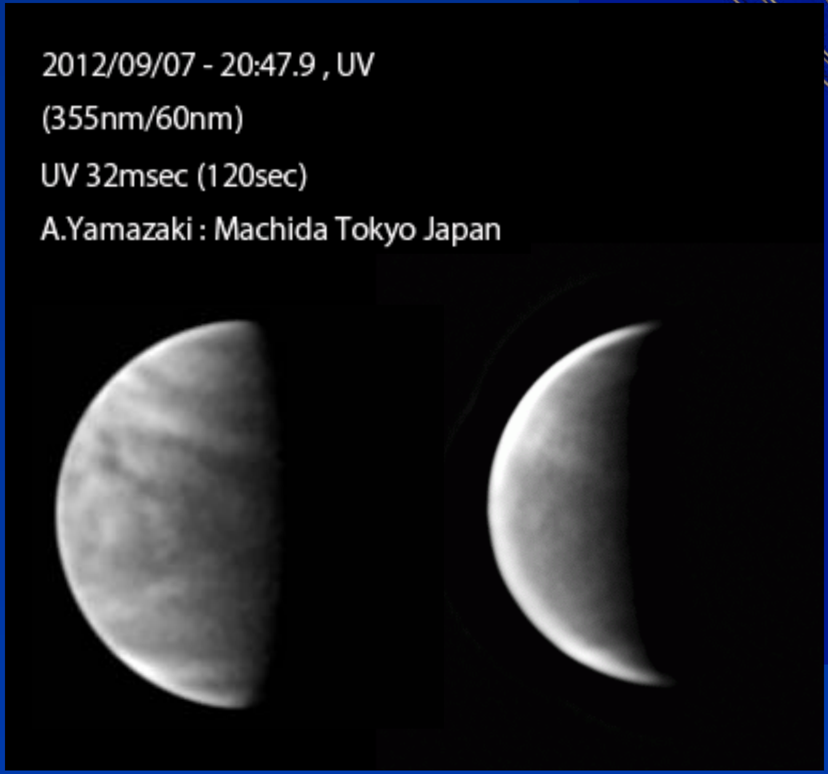


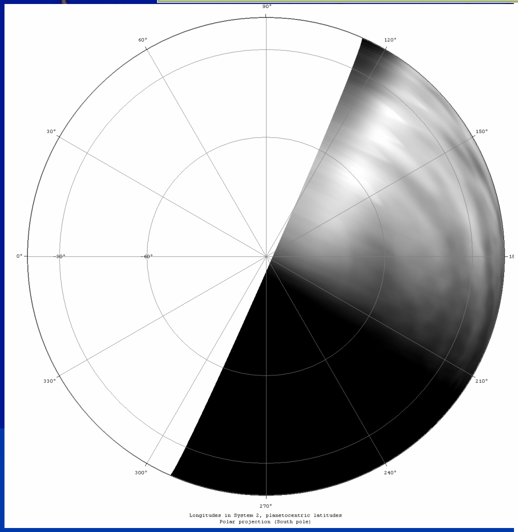
KELVIN-HELMHOLTZ INSTABILITIES

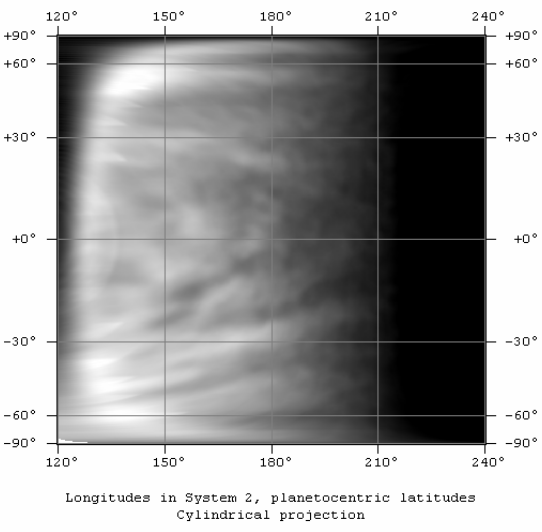
Ground-based observations: mandatory comparison



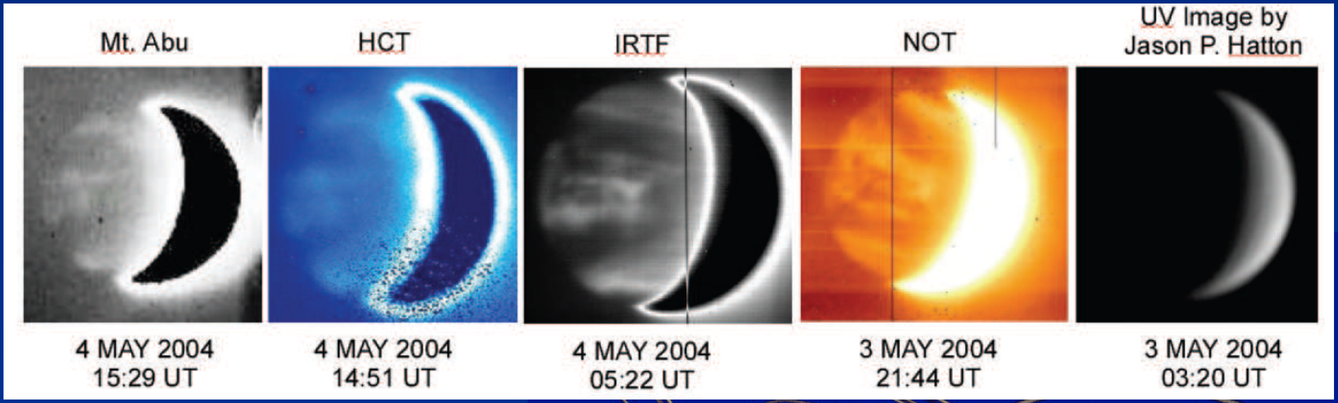






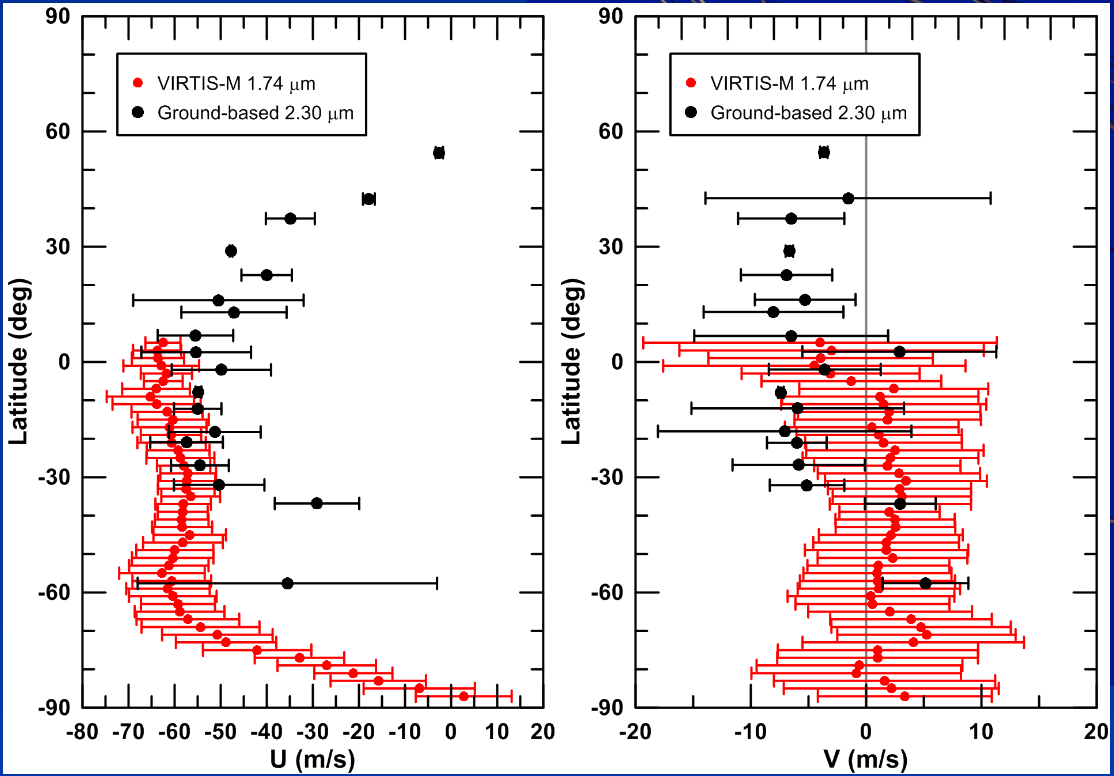


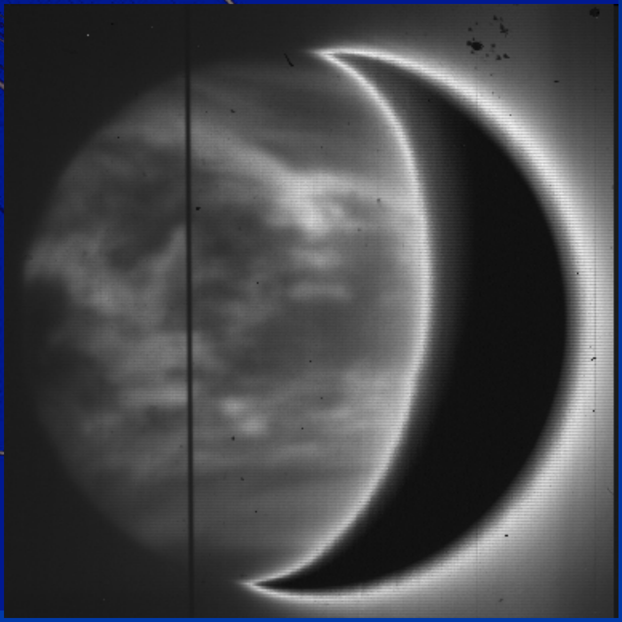
Ground-based observations: cloud tracking results



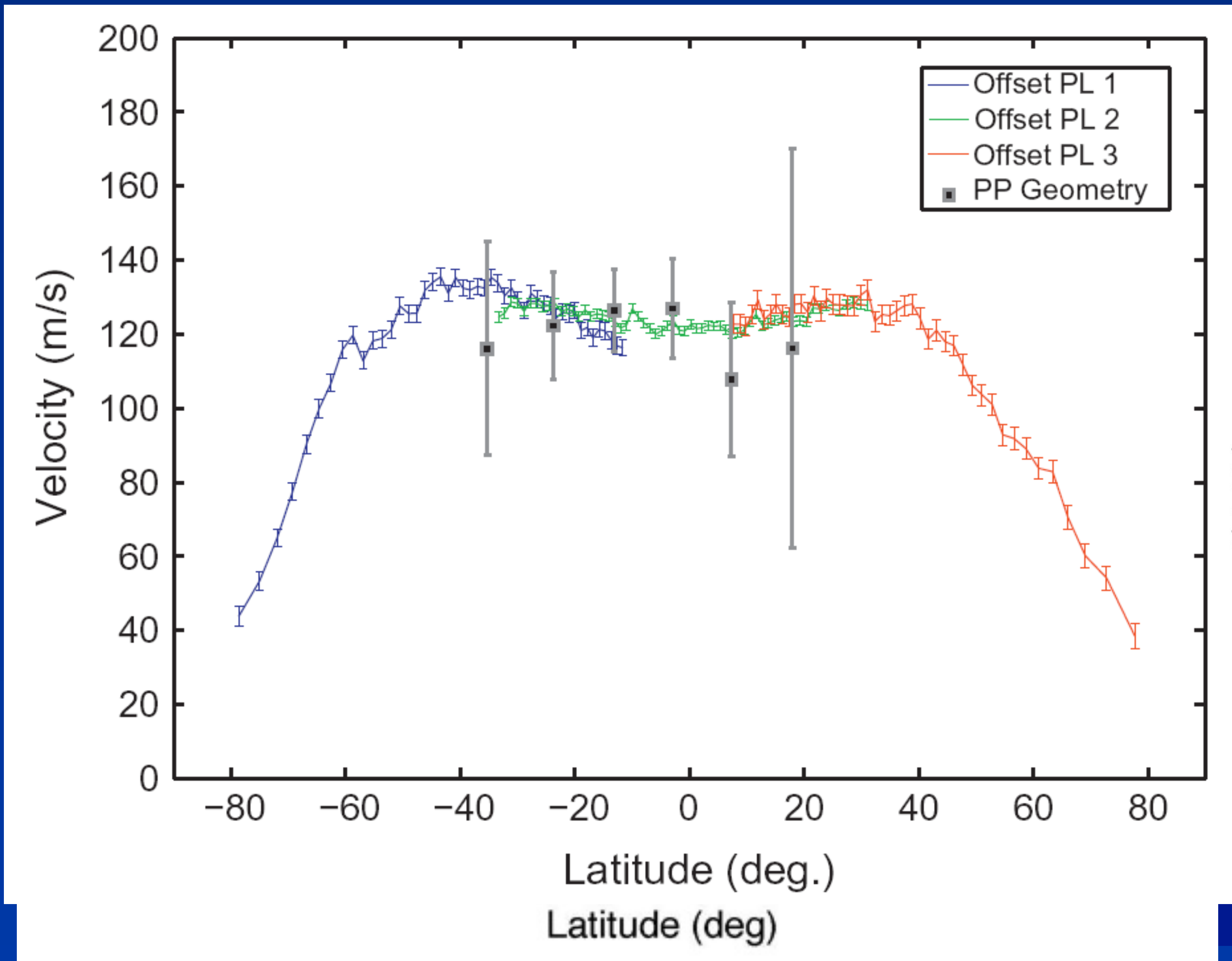
COMPARISON:

- 2.30 μm images (Limaye 2006)
- 1.74 μm images (Hueso 2012)



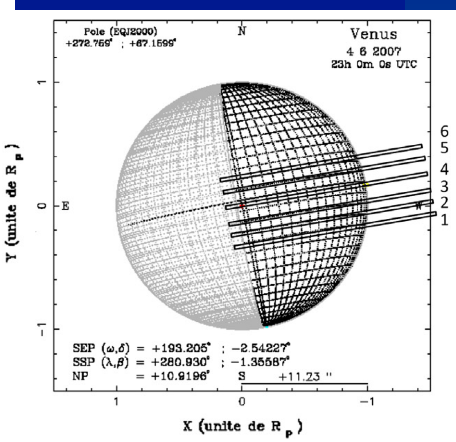


Ground-based observations: Doppler results

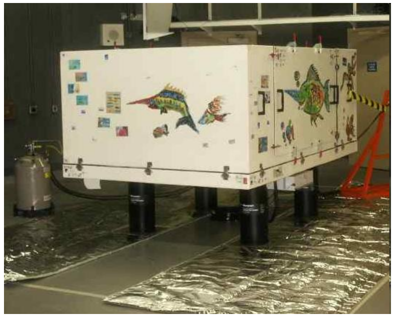


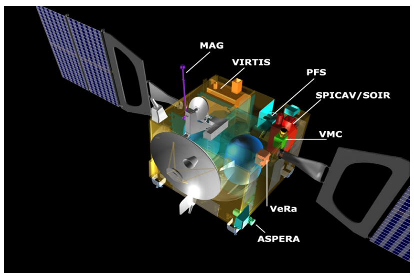
COMPARISON:

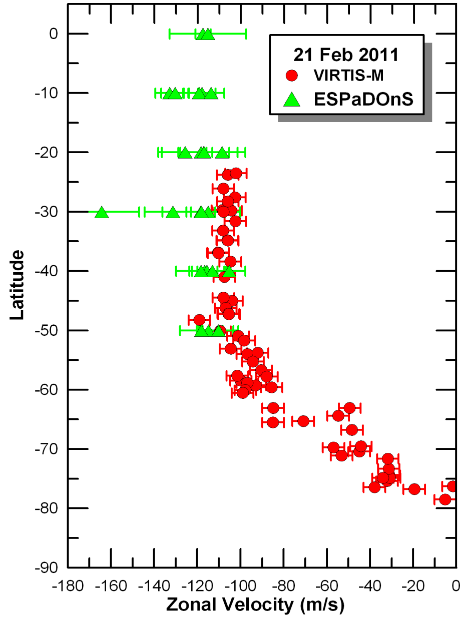
- 480 nm images (Peralta 2007)
- UV/VIS spectra (Machado 2012)

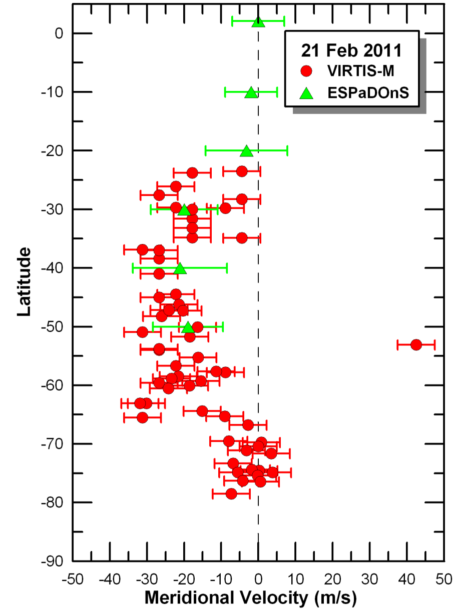


Ground-based observations: Doppler results



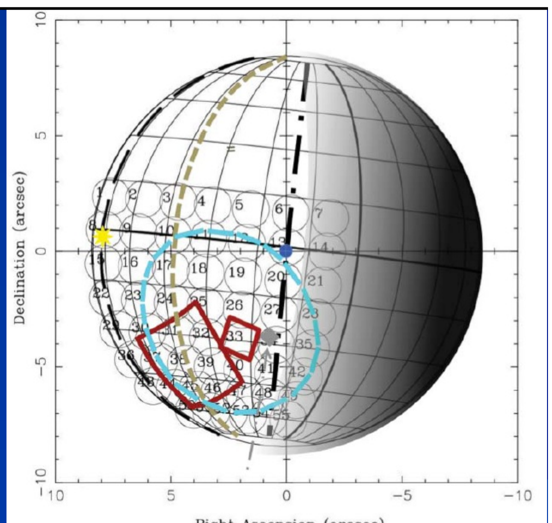


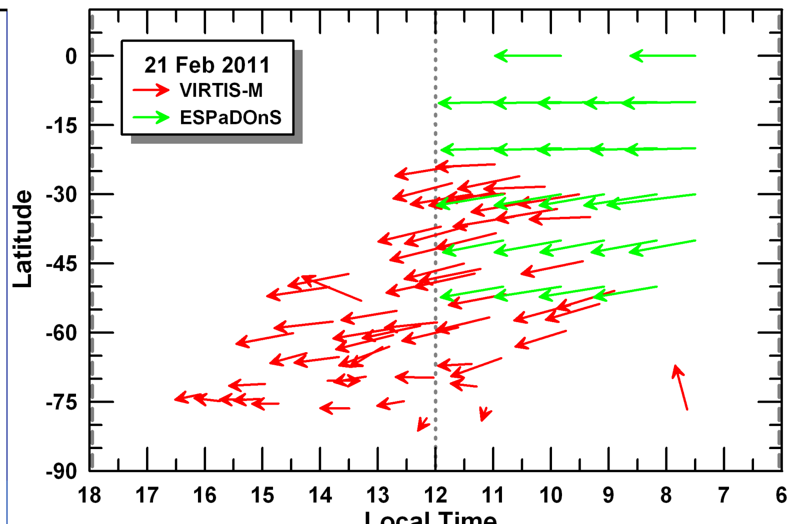


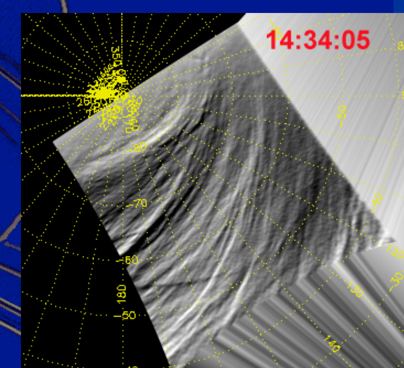


COMPARISON:

- 380 nm images (Machado 2014)
- UV/VIS spectra (Machado 2014)







Finally… a brilliant future full of challenges!!

eurovenus
STUDYING EARTH'S TWIN

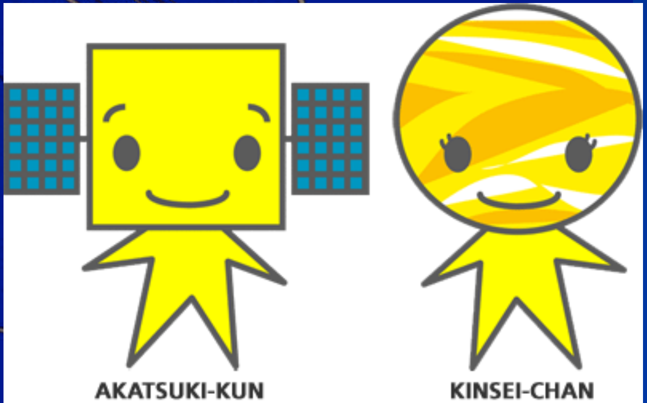
ESTRATEGIES:

1. Stablish collaborations with ground-based observers in order to build a worldwide net of coordinated observations with Akatsuki.
2. Set feasibility of all possible wavelengths (UV-VIS-IR) allowing to track atmospheric features.
3. Improve the technique for automatic feature tracking ➔ the more good measurements, the more “gold” we’ll find.

SOME SCIENTIFIC OBJECTIVES (VEx and Akatsuki):

- First characterization of lower atmosphere circulation.

1. Full characterization of atmospheric waves, with special focus on the Y-feature.
2. Find, Characterize and Simulate possible Shear Instabilities.
3. First-time inference of the turbulent component and obtain the Venus’ Power Spectrum of Kinetic Energy.
4. Build a definitive database of winds.
5. Revise Thermal Wind equation for Venus…



DOMO ARIGATO GOZAIMASE!