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Improved automatic estimation of winds at the cloud top of Venus using superposition of cross-correlation surfaces

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ABSTRACT

Accurate wind observation is a key to study atmospheric dynamics. A new automated cloud tracking method for the dayside of Venus is proposed and evaluated by using the ultraviolet images obtained by the Venus Monitoring Camera onboard the Venus Express orbiter. It uses multiple images obtained successively over a few hours. Cross-correlations are computed from the pair combinations of the images and are superposed to identify cloud advection. It is shown that the superposition improves the accuracy of velocity estimation and significantly reduces false pattern matches that cause large errors. Two methods to evaluate the accuracy of each of the obtained cloud motion vectors are proposed. One relies on the confidence bounds of cross-correlation with consideration of anisotropic cloud morphology. The other relies on the comparison of two independent estimations obtained by separating the successive images into two groups. The two evaluations can be combined to screen the results. It is shown that the accuracy of the screened vectors are very high to the equatorward of 30 degree, while it is relatively low at higher latitudes. Analysis of them supports the previously reported existence of day-to-day large-scale variability at the cloud deck of Venus, and it further suggests smaller-scale features. The product of this study is expected to advance the dynamics of venusian atmosphere.

1. Introduction

The atmosphere of the Venus is known for having interesting dynamical features such as the super-rotation several tens of times faster than the planetary rotation. Although many theoretical and numerical studies have been conducted, observations to examine them have been quite limited.

The Venus is covered with thick clouds that are present at 45–70 km above its surface. Therefore, cloud tracking has been used extensively to estimate horizontal winds, which was first conducted by ground based observations (Boyer and Guérin, 1969) and was succeeded by observations with spacecrafts such as Mariner 10 (Limaye and Suomi, 1981), Pioneer Venus (e.g., Limaye et al., 1982; Rossow et al., 1990), Galileo (e.g., Belton et al., 1991; Kouyama et al., 2012), and Venus Express (e.g., Moissl et al., 2009; Ogohara et al., 2012; Kouyama et al., 2013a; Khatuntsev et al., 2013). Most of these studies use image of ultraviolet (UV) reflected at the daytime cloud top. Some (also) use near infrared images, which enables one to estimate winds at lower altitudes (e.g., Peralta et al., 2007).

However, the gap between these studies and the theoretical/numerical studies is still large. This is partly because the vertical and horizontal coverage of cloud tracking is limited, but it is also because their spatial resolution and accuracy is limited or uncertain (note that, since large-scale horizontal wind disturbances are expected to have a "red" spectral feature from a dynamical point of view[1], the spatial resolutions is limited by accuracy, in effect). In previous studies, cloud motion vectors (CMVs) are estimated either by visually tracking clouds over successive images (manual tracking) or by computing cross-correlations among two images (digital tracking). Manual tracking generally performs better, but it requires great efforts, and obtained CMVs tend to be sparse. In digital tracking, the cross-correlation among sub-images from two images is computed. To find cloud motion, the region to take a sub-image from one of the two images is slid to maximize the correlation. It is, however, well known that the correlation is

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[1] It is also the case for the Earth's atmosphere above the boundary layer (e.g., Nastrom and Gage, 1985). In addition, since latent heat release is not important in venusian atmosphere, small-scale energy input is likely more limited than in the Earth's atmosphere.

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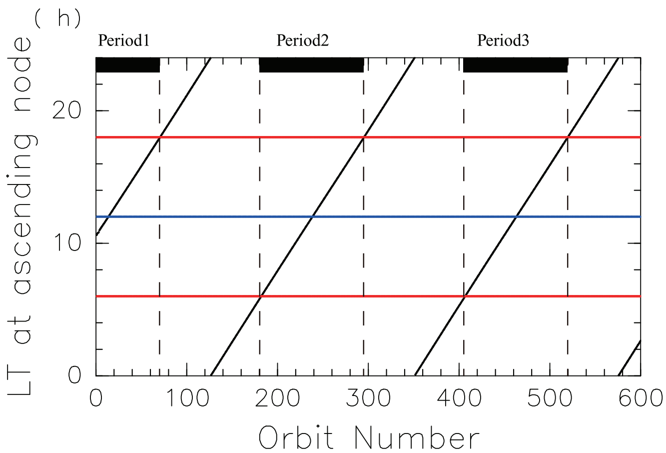

Fig. 1. The LTAN of the VEX up to the orbit 600 (11, December, 2007). The red lines show 6 a.m. and 18 p.m., blue line shows the noon. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

sometimes maximized by a false match among distant portions of cloud deck, which causes large errors. In recent studies (Kouyama et al., 2012; 2013a; Ogohara et al., 2012), the false match is corrected by comparing neighboring CMVs and, if the difference exceeds a threshold, selecting secondary (or tertiary, etc.) correlation peaks. The treatment significantly reduces the error, but it appears that the results are still not free from significant errors.

Many of the studies use standard deviations (for example, computed first for each latitude and time, and then averaged over time) to indicate the uncertainties of error in CMVs. However, not only measurement error but also actual variability contributes the standard deviations, so it is not very meaningful when the error is much greater than the variability. If cloud tracking is to be improved to resolve spatial features of cloud-top wind fields, a more elaborate measure of uncertainty is needed.

An obvious uncertainty of CMVs is associated with the pixel discretization of the brightness measurement. An error in destination finding by one pixel causes a difference corresponding to the pixel size. This limitation is relaxed to some extent by conducting sub-pixel CMV determination (e.g., Kouyama et al., 2012). On the other hand, there are sources of uncertainty that make it difficult to track clouds even at the original image resolution, such as pointing inaccuracy, noise, and (time-evolving) cloud morphology (see, e.g., Moissl et al., 2009 for more discussion). Especially, fuzzy low-contrast features typically found in mid and high latitudes are the serious source of uncertainty. Since the brightness morphology has high spatial variability, it would be desirable not only to estimate the overall accuracy but also to evaluate it individually for each CMV.

For the Pioneer Venus and Galileo, imaging observation was conducted with time intervals about 2–4 h (Rossow et al., 1990). The television camera onboard the Mariner 10 and the Venus Monitoring Camera (VMC) onboard the Venus Express (VEX) provide images much more frequently. As mentioned earlier, one of the deficiency of digital cloud tracking is the false match. The deficiency might be alleviated if features are tracked across multiple images with a short time interval. Also, use of multiple images might improve the accuracy of CMVs; superposition is a basic technique of signal processing to improve signal-to-noise (*S*/*N*) ratio.

In the past studies that conducted digital cloud tracking for Venus, each CMV was derived from two images. Limaye and Suomi (1981) compared CMVs obtained from two image pairs taken from three successive images in order to assess the quality of CMVs. Also, one can average CMVs to reduce random errors. In contrast, we propose a digital cloud tracking method that synthetically uses successive multiple images to derive a CMV. Cross-correlation surfaces obtained from multiple pairs of images are superposed. It is shown in this study that an adequate superposition eliminates the false match and increases the accuracy. A method similar to ours has been proposed in the field of particle image velocimetry studies (Sciacchitano et al., 2012). This study provides a theoretical rationale on how such a method improves feature tracking.

We also propose two methods to evaluate the precision and error of each CMV. One of them provides a relative measure of precision provided that the peak finding is correct, and it is applicable to the conventional digital tracking using a pair of images. The other method is a more direct measure of errors, but it is available only when a sufficient number of images are used for one estimation. The two methods can be used together to screen CMVs.

The rest of this paper is organized as follows. Section 2 gives a brief description of the datasets. Section 3 introduces our cloud tracking method and shows the result for an orbit of the VEX. Section 4 describes the error estimation methods and their statistics. Section 5 shows CMVs for multiple orbits and compares them with previous studies. Conclusions are drawn in Section 6.

2. Dataset

We use the version 2.0 UV data of the VMC onboard the VEX. Features of the VEX spacecraft are described by Markiewicz et al. (2007). VEX was put into an elliptical polar orbit with a period of 24 h in April 2006. Its orbiter has a pericenter near the north pole and an apocenter near the south pole (Markiewicz et al., 2007).

The VMC has four channels at 365, 513, 950, and 1010 nm (Markiewicz et al., 2007). Each of the channels provides 16-bit images of 512 × 512 pixels. The wavelength of the UV channel, 365 nm, is the same as that of the Pioneer Venus Orbiter Cloud Photopolarimeter. The spatial resolution of the VMC images is 50 km/pixel at the sub-spacecraft point (SSP) when the spacecraft is at the apocenter. The observation is conducted when the spacecraft is in the ascending nodes; that is, when it is traveling from south to north.

We use the data having the resolution at SSP between 40 km and 21 km, which corresponds to the SSP latitude between 66°S and 47°S. The time it takes for the spacecraft to travel between these latitudes is approximately 4 h. The low latitude limit of 47°S is introduced so that the images used cover the full disk. The high latitude limit of 66°S is determined in terms of the travel time and latitudinal coverage.

Fig. 1 shows the Local Time of the sub-spacecraft longitudes of Ascending Nodes (LTAN) where the spacecraft crosses the equator from the south.We define three periods according to LTAN: the periods 1 (days 29–72), 2 (days 210–298), and 3 (days 436–500). These periods are defined to have LTAN between 6 and 18 h. The longitudinal coverage of UV images is maximized when the LTAN is at around the local noon.

The detector of the camera was damaged by viewing the Sun during the cruise to Venus. As a result, the UV images suffer fixed pattern noise (Titov et al., 2012). In this study, we did not use images with the exposure time greater than 20 ms, since they are often overexpose the bright portions of images.

3. Cloud tracking method

This section explores the problem of the conventional cloud tracking and introduces our cloud tracking method. It is demonstrated how it works and how it improves the digital tracking.