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AKATSUKI returns to Venus

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Abstract

AKATSUKI is the Japanese Venus Climate Orbiter that was designed to investigate the climate system of Venus. The orbiter was launched on May 21, 2010, and it reached Venus on December 7, 2010. Thrust was applied by the orbital maneuver engine in an attempt to put AKATSUKI into a westward equatorial orbit around Venus with a 30-h orbital period. However, this operation failed because of a malfunction in the propulsion system. After this failure, the spacecraft orbited the Sun for 5 years. On December 7, 2015, AKATSUKI once again approached Venus and the Venus orbit insertion was successful, whereby a westward equatorial orbit with apoapsis of ~440,000 km and orbital period of 14 days was initiated. Now that AKATSUKI's long journey to Venus has ended, it will provide scientific data on the Venusian climate system for two or more years. For the purpose of both decreasing the apoapsis altitude and avoiding a long eclipse during the orbit, a trim maneuver was performed at the first periapsis. The apoapsis altitude is now ~360,000 km with a periapsis altitude of 1000–8000 km, and the period is 10 days and 12 h. In this paper, we describe the details of the Venus orbit insertion-revenge 1 (VOI-R1) and the new orbit, the expected scientific information to be obtained at this orbit, and the Venus images captured by the onboard 1-μm infrared camera, ultraviolet imager, and long-wave infrared camera 2 h after the successful initiation of the VOI-R1.

Keywords: Venus, Atmosphere, Meteorology, Exploration, AKATSUKI

Introduction

Venus is our nearest neighboring planet with a size very similar to that of the Earth. It has been explored by the USSR, the USA, and Europe since the 1970s. The USSR VENERA series probes (Moroz 1981) landed on the surface of Venus and revealed that the temperature at the surface is 740 K and the pressure is 92 bars, which is quite different from our terrestrial environment (Colin 1983). The atmosphere consists mainly of CO_2. A striking finding is that the atmosphere rotates westward around the planet with a period of 4 d at an altitude of 50–60 km, while the planet itself rotates westward more slowly with a period of 243 days; this is called superrotation (Schubert 1983). The USA's Pioneer Venus orbiter studied Venus over 12 years by remote sensing techniques (Lellouch et al. 1997; Taylor et al. 1997). Moreover, the Venusian atmosphere was studied during the Venus Express mission of the European Space Agency (Svedhem et al. 2007), which had an operational period ranging from 2006 to 2014. This mission was a modified version of the

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Mars Express mission (Chicarro et al. 2004) that was dedicated to investigations of the Martian atmosphere solely by the use of spectroscopic techniques. Venus Express also employed several spectroscopic instruments.

AKATSUKI was also designed to study the Venusian atmosphere, but in contrast to the Venus Express strategy, five cameras with narrowband filters will image Venus at different wavelengths to track the distributions of clouds and minor gaseous constituents at different heights (Fig. 1). In other words, we aim to study the Venusian atmospheric dynamics in three dimensions, while Venus Express collected mainly spectroscopic observations of the atmosphere. These two spacecraft are capable of revealing complementary aspects of the Venusian atmosphere. On Venus Express, the Venus monitoring camera (VMC) (Markiewicz et al. 2007) with four narrowband filters from ultraviolet (UV) to near infrared (IR) made similar observations, but as Venus Express was in a polar orbit, it could not track the cloud patterns appearing on Venus. AKATSUKI is on a westward equatorial orbit and is capable of taking successive images in the low- and midlatitudes of Venus, which is advantageous for studies of the atmosphere.

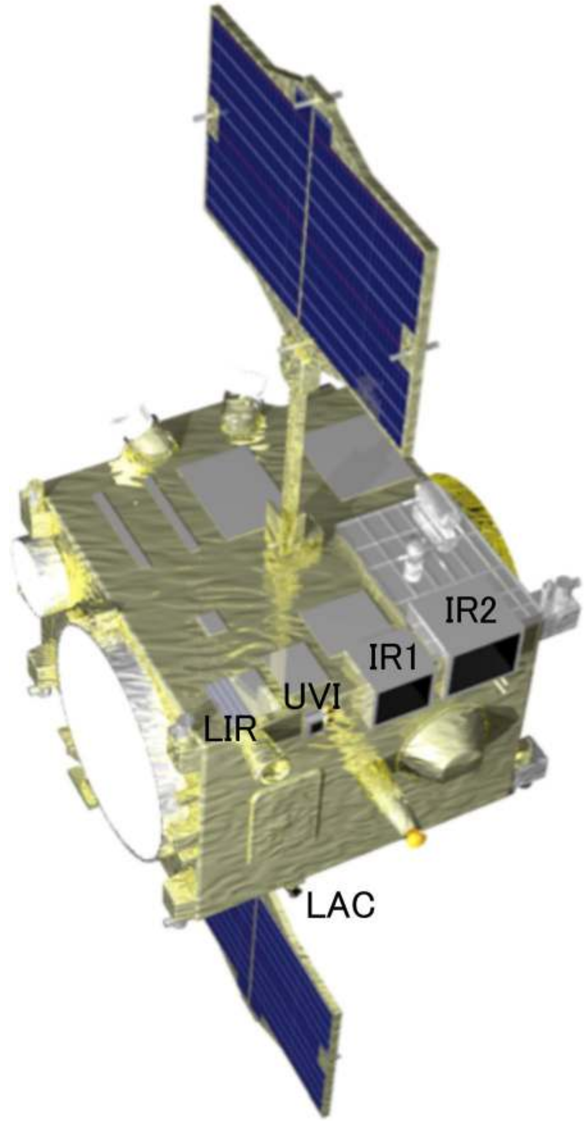

Fig. 1 View of AKATSUKI. The five photometric sensors employed as mission instruments included a 1-μm infrared camera (IR1), 2-μm infrared camera (IR2), ultraviolet imager (UVI), long-wave infrared camera (LIR), and lightning and airglow camera (LAC)

AKATSUKI has started collecting observations, and the first images of Venus taken by the onboard 1-μm infrared camera (IR1), ultraviolet imager (UVI), and long-wave infrared camera (LIR) are presented in "First images of Venus by the cameras" section. The scientific background for this research and data processing procedures are described in detail by Nakamura et al. (2011, 2014).

Methods

The development of the Japanese Venus Climate Orbiter AKATSUKI was first proposed to the Institute of Space and Astronautical Science (ISAS) in 2001, and this initiative was strongly supported by the international Venus science community as an interplanetary mission (Nakamura et al. 2007, 2011). The main goal of AKATSUKI is to shed light on the mechanism driving the fast atmospheric circulation of Venus. The systematic imaging sequencing capability of AKATSUKI is advantageous for detecting meteorological phenomena on various temporal and spatial scales. AKATSUKI has following five photometric sensors as mission instruments for imaging (Fig. 1): IR1, a 2-μm infrared camera (IR2), UVI, LIR, and a lightning and airglow camera (LAC). Except for the LIR, these photometers have changeable filters in the optics to allow for imaging at different wavelengths. AKATSUKI's long, elliptical orbit around Venus is suitable for obtaining cloud-tracked wind vectors continuously in the low- and midlatitudes. With these instruments, we expect to be able to characterize the meridional circulation, midlatitude jets, and their various wave activities.

IR1 is designed to monitor the dayside of Venus at 0.90 μm and the nightside at 0.90, 0.97 and 1.01 μm, which are located in atmospheric windows (Iwagami et al. 2011). The measurements at 0.90 and 1.01 μm will yield information about the surface material (Baines et al. 2000; Hashimoto and Sugita 2003; Hashimoto et al. 2008). IR2 utilizes atmospheric windows at wavelengths of 1.73, 2.26 and 2.32 μm (Satoh et al. 2015). With these wavelengths, IR2 is most sensitive to thermal radiation originating from altitudes of 35–50 km. IR2 also employs two more wavelengths, namely one at 2.02 μm to detect variations of cloud top altitudes as intensity variations of reflected sunlight (Satoh et al. 2015) and an astronomical H-band centered at 1.65 μm. The UVI is designed to measure ultraviolet radiation scattered from the cloud top altitudes in two bands centered at 283 and 365 nm (Nakamura et al. 2011). The LIR detects thermal radiation emitted from the cloud tops over a rather wide wavelength region of 8–12 μm, and this enables mapping of the cloud top temperatures (Taguchi et al. 2007; Fukuhara et al. 2011). Unlike other imagers onboard AKATSUKI, LIR takes images of both the dayside and nightside equally. The corresponding cloud top temperature maps will reflect the cloud height distributions, whose detailed structures are unknown except for in the northern high latitudes at areas observed by Pioneer Venus (Taylor et al. 1980). The map data will also reflect the atmospheric temperature distribution. LAC is a high-speed imaging sensor that measures lightning flashes and airglow emissions on the nightside of Venus (Takahashi et al. 2008). In addition to the photometric observations mentioned above, radio occultation experiments obtain vertical profiles of the temperature, sulfuric acid density, and ionospheric electron density with high resolution (Imamura et al. 2011). For this particular experiment, the spacecraft has been equipped with an ultra-stable oscillator, which is identical to the one on Venus Express; thus, comparisons of the results from the two spacecraft are possible.

Orbit

The Japan Aerospace Exploration Agency (JAXA) successfully launched AKATSUKI at 06:58:22 (JST) on May 21, 2010, with the H-IIA F17 launch vehicle. After the successful cruise from Earth to Venus, which took about half a year, the propulsion system malfunctioned during the Venus orbit insertion (VOI) maneuver on December 7, 2010 (Nakamura et al. 2011; Hirose et al. 2012). The orbital maneuvering engine (OME) was shut down at 158 s during VOI, while 12 min of operation had been planned. Consequently, the spacecraft did not enter Venus's orbit; instead, it entered an orbit around the Sun with a period of 203 days.

The cause of the malfunction was determined to be an obstruction of the fuel-side check valve, which restricted the passage of fuel into the OME, and hence, the ratio of oxidizer to fuel gradually increased. Eventually, the combustion temperature became too high to operate the OME. The obstruction turned out to be a solid salt that was generated in the check valve during the mixing of fuel and oxidizer vapors along with helium gas, which was needed for pressurization. The vapor of the oxidizer reached the fuel-side check valve because it was able to penetrate through the seal material (polymer) of the valves. At the design phase of the spacecraft, four valves were intentionally installed to avoid the migration of vapor and the potential for unexpected explosions in the pressurized gas line. However, the possibility of vapor transmission through the seal material also should have been carefully considered.

The OME was ultimately found to be broken and unusable, but most of the fuel still remained. Thus, a decision was made to use the reaction control system (RCS) for orbital maneuvers in November 2011, which were successfully executed so that AKATSUKI would re-encounter Venus in 2015.

After the orbital maneuvers in November 2011, the orbital period became 199 days and the encounter with Venus was set for November 22, 2015. This specific date was originally chosen to achieve the shortest encounter time given the spacecraft's now limited expected lifetime. However, a detailed trajectory analysis revealed that the orbit around Venus after insertion on November 22, 2015, would be unstable. Therefore, to achieve a more stable orbit, another orbital maneuver was performed in July 2015 to set the spacecraft on a trajectory to meet Venus on December 7, 2015.

Figure 2 shows the trajectory of AKATSUKI in relation to the orbits of Venus and Earth. After December 1, 2015, the spacecraft's orbit was just outside of Venus's orbit and the velocity of the spacecraft relative to the Sun was less than that of Venus, which allowed Venus to catch up to the spacecraft from the back end. On December 7, 2015, the spacecraft approached the planet from outside of Venus's orbit and VOI-Revenge 1 (R1) procedure was implemented by using four 23 Newton class thrusters of the RCS.

Figure 3 shows the observed two-way Doppler residuals at the Usuda Deep Space Center 64-m antenna with no-burn trajectory. VOI-R1 burn (1228 s) was successfully achieved from 23:51:29 on December 6 through 00:11:57 on December 7 (UTC, onboard time). On the ground, the burn was observed at an 8-min 19-s delay (radio wave travel time between Venus and the Earth on December 7, 2015). Each colored line shows the case when the injection was interrupted at a certain percentage of the burn duration (e.g., "015" indicates 15 % of the burn duration). This graph shows that, even if the burn was interrupted, the inclination of the Doppler residuals did not become flat because of the spacecraft's velocity changes caused by Venus. During the burn, the time-series variation of the Doppler residuals provided unique information and was monitored very carefully with the telemetry data sent from the spacecraft.

AKATSUKI is the first Japanese satellite to orbit a planet. After the VOI-R1, the apoapsis altitude was ~440,000 km with an inclination of 3° and orbital period of 13 days and 14 h. Figure 4 shows the VOI-R1 geometry depicted with the Venus center coordinate. For the dual purposes of decreasing the apoapsis altitude and avoiding a long eclipse during the orbit, a trim maneuver was

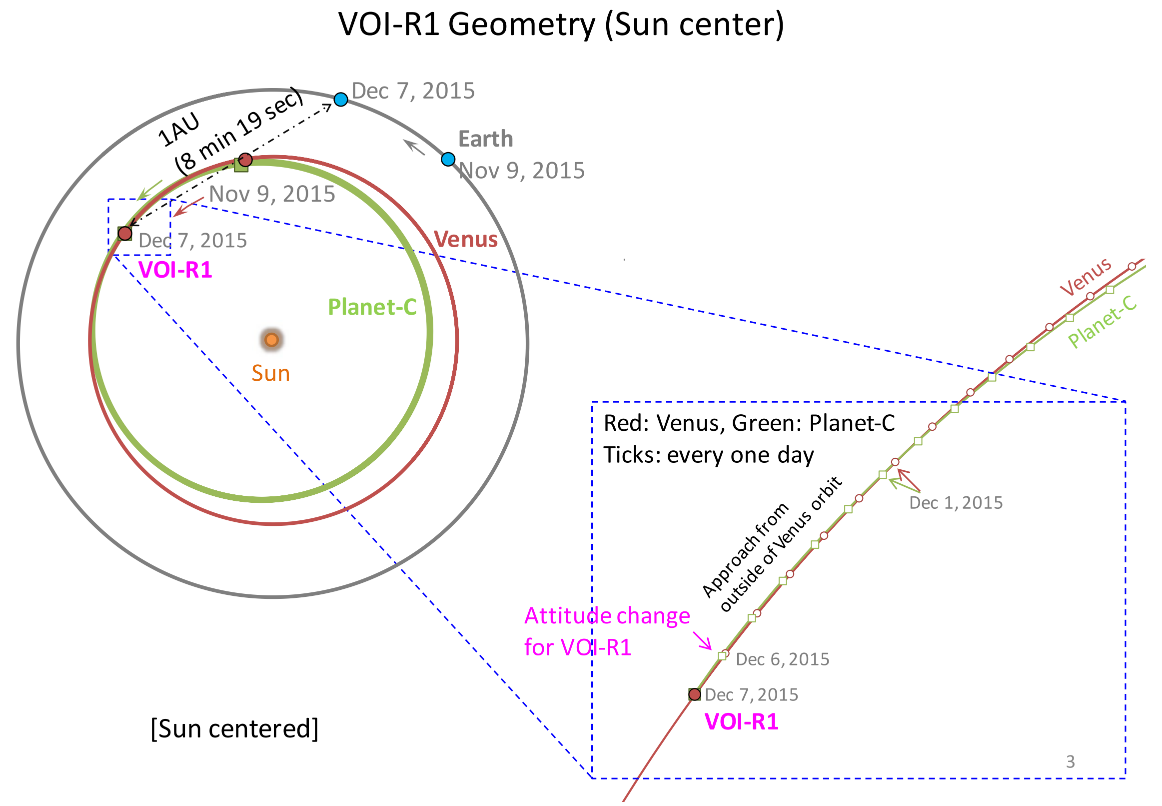

Fig. 2 VOI-R1 geometry with the Sun center coordinate. The orbits of AKATSUKI, Venus, and Earth are shown by *green*, *red*, and *gray lines*, respectively

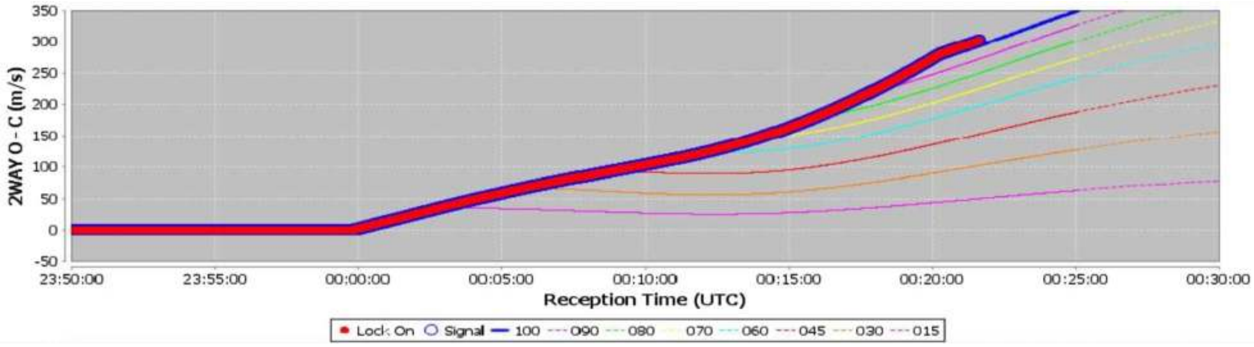

Fig. 3 Two-way Doppler residuals observed by the Usuda Deep Space Center 64-m antenna at VOI-R1 (*thick red line*) with some expected *curves* (*colored thin lines*). *Each thin curve* shows the case when the injection was interrupted at a certain percentage of the burn duration. For example, "015" indicates 15 % of the burn duration

performed at the first periapsis. The apoapsis altitude is now ~360,000 km with a periapsis altitude of 1000–8000 km, and the period is 10 days and 12 h.

New observation plan

To understand the atmospheric dynamics and cloud physics of Venus, onboard science instruments are used to sense multiple height levels of the atmosphere, which enables visualization of the three-dimensional structure and dynamics. Although the new orbit around Venus is much more elongated than the original plan, the science goals and the observation strategy are basically unchanged from the original ones (Nakamura et al. 2011). The spatial resolution to be achieved around the apoapsis was degraded by a factor of 5–6 ("Global imaging" section), which had an influence on the quality of cloud

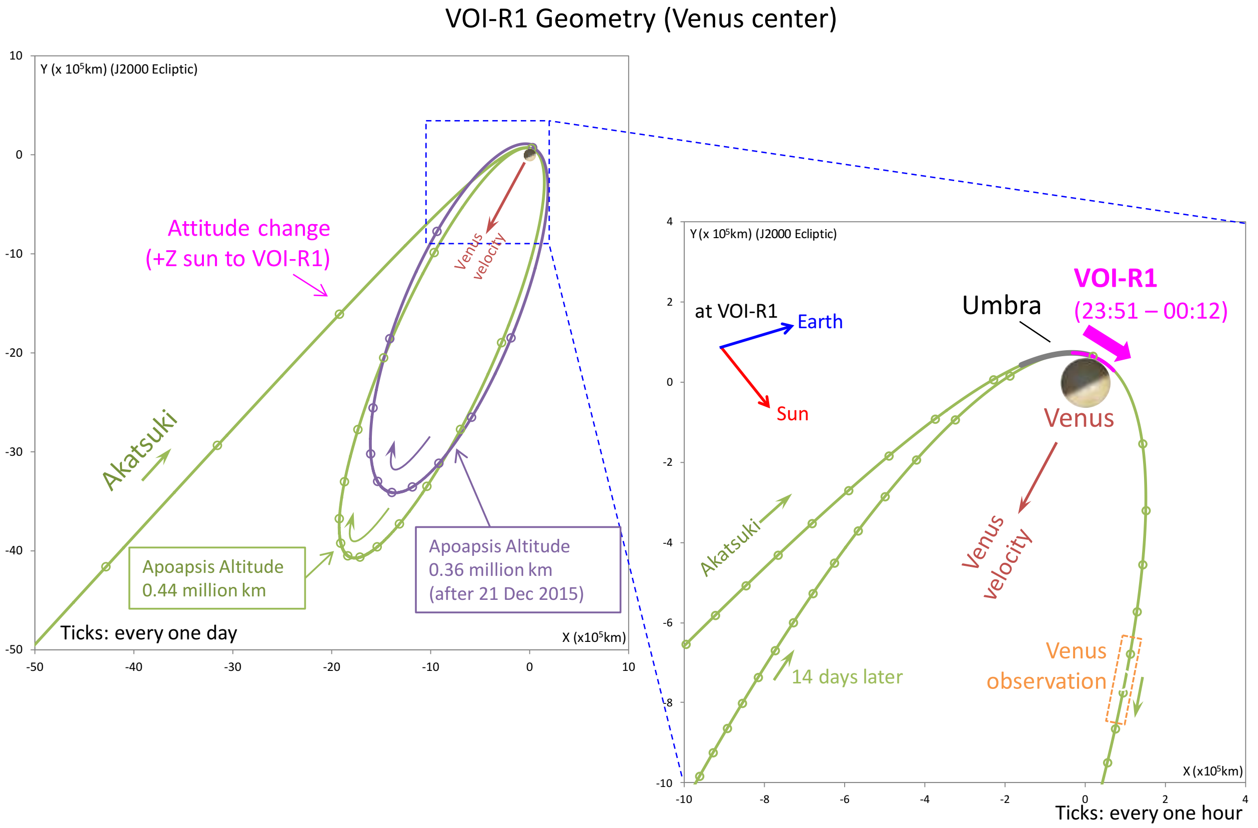

Fig. 4 VOI-R1 geometry with the Venus center coordinate. After VOI-R1, the apoapsis altitude was ~440,000 km and the orbital period was 13 days and 14 h (*green line*). A trim maneuver was performed at the first periapsis, and then, the apoapsis altitude changed to ~360,000 km and the period was 10 days and 12 h (*violet line*)

tracking measurements. However, planetary-scale winds are still expected to be retrievable from such images, and high-resolution images obtained at close distances can be used to complement them. Although the frequencies of LAC operations and radio occultation observations became much lower, the lightening observations by LAC are still very unique, and the scientific value of radio occultation observation can be maximized by coordination with the imaging observations. The observation modes are roughly classified into the groups described below in the following four subsections; these observations are conducted sequentially in each orbital revolution (Fig. 5).

Global imaging

Global imaging observations are conducted by using the IR1, IR2, UVI, and LIR in the portion of the orbit where the typical camera field of view (FOV) of 12° exceeds the apparent Venus disk; this condition is satisfied over 96 % of the time in one orbital revolution except for in the near periapsis region. From this portion of the orbit, cloud images will be obtained every 1–2 h for each observation wavelength. The pixel resolution at the Venusian surface from the apoapsis altitude of ~360,000 km is 74 km for UVI, IR1, and IR2 and 300 km for LIR, while it is 12 km for UVI, IR1, and IR2 and 50 km for LIR from the altitude of 58,000 km where the apparent Venus disk fits into the FOV of 12°. Because the orbital period in the original plan would have allowed observations of the full global disk only during 60 % of each orbit (Nakamura et al. 2011), the new orbit enables more continuous global monitoring. Another merit of the new orbit is that the observation geometry is stable over several days at the expense of the lower spatial resolution on average. By using the obtained global images, development of the atmospheric structure can be monitored, and wind vectors can be derived by tracking small-scale cloud features (Kouyama et al. 2012, 2013; Ogohara et al. 2012a, b; Ikegawa and Horinouchi 2016). This continuous and long-term monitoring of Venus will also provide unprecedented life cycle details of the most prominent cloud structure of Venus, the dark Y-feature, which has been interpreted to be a planetary wave that may explain the zonal wind variability and provide key hints about the nature of the mysterious

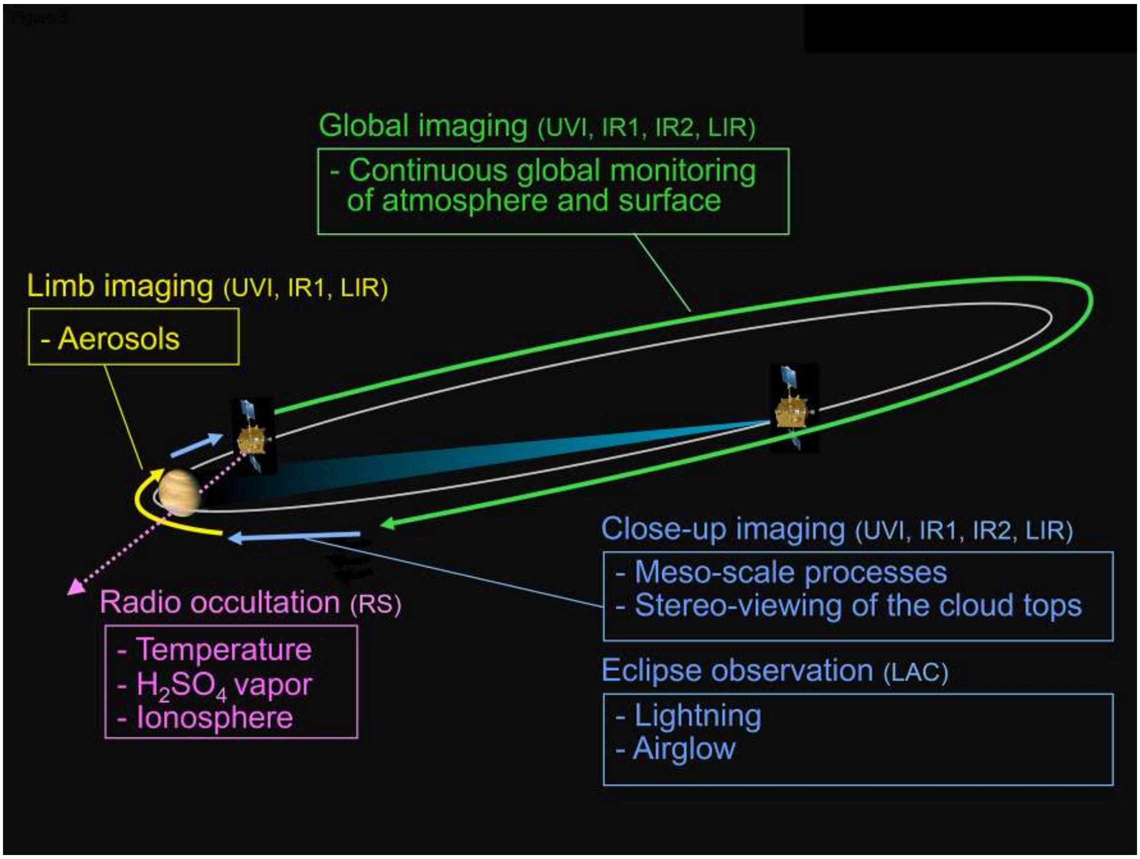

Fig. 5 Schematic view of the observation sequence along the orbit

UV absorber (Peralta et al. 2015). Monitoring of surface features on the nightside by IR1, including searches for active volcanism (Hashimoto and Imamura 2001), is also conducted primarily in this observation mode.

The camera pointing direction for this type of observation is not always nadir, but it can be shifted to the sunlit side for dayside imaging and to the dark side for nightside imaging. The purposes of this angular offset are (1) to include the planetary limb in the image so that the pointing direction can be determined accurately from the limb position, (2) to maximize the area of the atmosphere or the surface observable with each filter, and (3) to avoid stray light when observing the nightside.

Close-up imaging

In this observation mode, a particular point on the cloud layer is continuously monitored by using the UVI, IR1, IR2, and LIR from distances shorter than ~50,000 km for the purpose of observing the temporal development of mesoscale processes and also for stereo-viewing of the cloud tops. The pixel resolution at the Venusian surface is 0.2–1.6 km for UVI, IR1, and IR2 and 0.9–7.0 km for LIR from the periapsis altitude of 1000–8000 km. During this observation sequence, the spacecraft attitude is controlled so that the camera FOV continuously captures roughly the same region of the cloud tops.

Limb imaging

The vertical distribution of aerosols that extend up to ~100 km altitude is observed with the limb-viewing geometry around the dayside periapsis passages by using UVI, IR1 (0.90 μm), and LIR. The layered distribution of aerosols seen in the limb images taken by the Galileo solid-state imager (SSI) (Belton et al. 1991) and Venus Express VMC (Titov et al. 2012) suggests that unknown chemical/dynamical processes are at work in aerosol formation; extensive observations covering wider regions with multiple wavelengths should provide clues to the mechanism. When the periapsis altitude is 1000 km, the minimum distance to the tangential point is 3500 km, and this gives a vertical resolution of 0.7 km for UVI and IR1 and 3 km for LIR.

Eclipse observations

The eclipse (umbra) region along the orbit is allocated to lightning observations by LAC. Eclipses occur mostly near the periapsis with a typical duration of 30 min. LAC is operated in nadir-pointing geometry and waits for lightning flashes to collect data with an event trigger method. LAC can also observe night airglows by continuously recording the brightness along swaths scanned by the attitude maneuver or the orbital motion of the spacecraft.

Radio occultation

Radio occultation experiments (RS) that use an ultra-stable oscillator (USO) are performed when the spacecraft is hidden by Venus as viewed from the tracking station (Imamura et al. 2011). Venus Express radio occultation has revealed vertical temperature profiles at various locations and local times (Tellmann et al. 2009); one merit of the AKATSUKI's observation system is that the location probed by RS can be observed by the cameras a short time before the ingress or short time after the egress because of the equatorial orbit, thus enabling quasi-simultaneous observations. Since the dense Venusian atmosphere causes considerable ray bending exceeding several tens of degrees, spacecraft steering is required to compensate for this effect while the occultation geometry changes from ingress occultation to egress occultation.

First images of Venus by the cameras

AKATSUKI took images of Venus immediately after the VOI-R1 with the following three instruments: IR1, UVI, and LIR. The other two instruments (IR2 and LAC) were not operated at this time because their functions had not been checked before the VOI-R1. The first images of Venus were taken at the positions of ~67,000 km for IR1 and ~72,000 km for UVI and LIR, far from the Venus disk. The solar phase angle at the sub-observer point was ~45° with the evening terminator in view (Fig. 4). Figure 6a–c shows the images taken by IR1, UVI, and LIR, respectively, and Table 1 presents a summary of the observations. No data reduction procedures have been performed for the images except for several onboard processing steps (i.e., median filtering and subtraction of the dark current for IR1 and UVI, desmearing for UVI, and accumulation of 32 images and subtraction of a shutter image for LIR).

The IR1 image shows the 0.90-μm solar radiation scattered by the upper clouds (Iwagami et al. 2011). This channel is centered on the continuum. Although the area near the eastern limb was not visible because of the limited operation of the discrete attitude control (in spite of the quick orbital motion of AKATSUKI), it was confirmed that Venus has a faint appearance over the entire disk in this channel. Belton et al. (1991) showed from the 0.986-μm images obtained by the Galileo SSI that Venus has a contrast of 3 % after the removal of terminator and limb brightness gradients. The contrast sources for the IR1 images, together with those for the IR2 and LIR images, are discussed in Takagi and Iwagami (2011). The continuous IR1 images with such contrast will be used to sound horizontal cloud-tracked velocities near the base of the upper clouds (58–64 km) (e.g., Peralta et al. 2007; Sánchez-Lavega et al. 2008).

The UVI image at a wavelength of 283 nm reflects the spatial distribution of SO_2, which attenuates solar radiation scattered by clouds at cloud level, and that of the upper haze, which enhances scattering. This is the first time a snapshot of Venus has been captured at this wavelength. Relatively bright cell-like structures exist in the low latitudes. Dark and bright streaky structures, which form part of the bow shape, become prominent in the midlatitudes. Bright polar bands are also clearly seen in the high latitudes. Although this channel is outside of the band of the unknown UV absorber, which was measured by previous spacecraft (Pioneer Venus, Galileo, and Venus Express), the morphology at 283 nm was found to be similar to those seen in previous UV images. Together with the other UVI image at a wavelength of 365 nm, the continuous UVI images will be used to derive horizontal

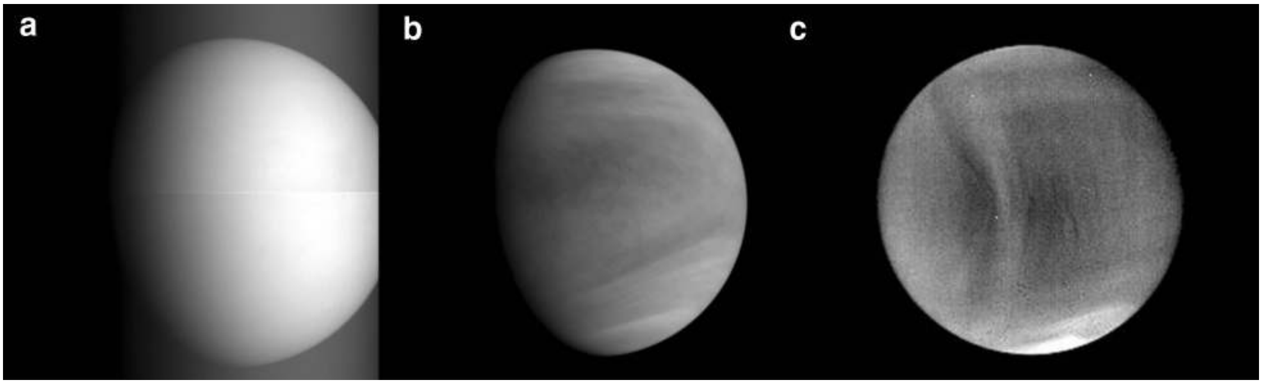

Fig. 6 First memorial images taken by the **a** IR1, **b** UVI, and **c** LIR on "the AKATSUKI satellite" of Venus

Table 1 Summary of the Venus observations taken immediately after the VOI-R1 operation

	IR1	UVI	LIR
Observation date	December 7, 2015	December 7, 2015	December 7, 2015
Observation time (UT)	4:51:56	5:19:53	5:26:02
Wavelength	0.90 μm[a]	283 nm	10 μm
Exposure time (s)	3.0	0.25	34[b]
Distance between AKATSUKI and Venus (km)	6.8×10^4	7.2×10^4	7.3×10^4
Apparent diameter (°)[c]	10.4	9.7	9.6
Spatial resolution (km/pixel)[d]	14.2	15.1	63.9
Sub-observer point			
Latitude (°)	−6.7	−6.6	−6.6
Longitude (°)	96.4	95.1	94.9
Solar phase angle (°)	45.0	46.3	46.6
Subsolar point			
Latitude (°)	−2.6	−2.6	−2.6
Longitude (°)	141.4	141.5	141.5
Solar phase angle (°)	48.9	50.0	50.2

[a] The filter for dayside imaging was used

[b] The composite image was made by superimposing 32 images. Exposure time for an image was 1.1 s

[c] A tangent height assumed to be 70 km from the surface was added to the radius of Venus (6051.8 km)

[d] Spatial resolution was calculated with the pixel scale of 0.012 (°/pixel) for IR1 and UVI and 0.05 (°/pixel) for LIR

cloud-tracked velocities near the cloud top altitudes of 62–70 km (e.g., Kouyama et al. 2012, 2013; Ogohara et al. 2012a, b; Ikegawa and Horinouchi 2016). The spatial resolution of the IR1 and UVI images shown in Fig. 6a, b is ~15 km/pixel, which is three or four times better than that (~50 km/pixel) of the images obtained by the Venus Express VMC near the apocenter (Titov et al. 2012). Comparisons between the time series of the images at the two channels (283 and 365 nm) will also shed light on their relationship with the cloud top structure. The solar phase angle dependence of aerosol scattering and dark-bright contrasts will be used to develop an aerosol model and determine the vertical distribution of UV absorbers, SO_2, and the unknown UV absorber (Lee et al. 2015; Petrova et al. 2015; Satoh et al. 2015). This aerosol model will be taken into account in albedo calculations, and the optical depth of the UV absorbers can be estimated in a similar manner to method used by Molaverdikhani et al. (2012). Ground-based observations will also be useful for evaluating the gaseous SO_2 distribution over the planet; an example can be found in Encrenaz et al. (2013).

The LIR image shows the thermal radiation emitted from the cloud top altitudes with a single band-pass filter of 8–12 μm (Taguchi et al. 2007; Fukuhara et al. 2011). This is a composite image that was made by superimposing 32 raw images to improve the signal-to-noise ratio. A shutter image was subtracted from the Venus image to correct a pixel-to-pixel variation in offset. No correction for thermal radiation from the LIR itself was performed. The spatial resolution of the LIR image is ~60 km/pixel, which is the highest spatial resolution image of Venus ever obtained in the mid-infrared wavelengths. The southern polar region is the brightest (highest in temperature) region, which corresponds to the polar dipole. Even after considering that the sub-observer latitude is at ~7°S, it is apparent that north–south asymmetry in the brightness of the polar regions exists. The streaky structures seen in the UVI image are also visible in the midlatitudes. Of particular interest is the bright bow-like structure extending toward high latitudes near the evening terminator, which was not seen in the previous LIR images captured just after the VOI failure in December 2010 (Taguchi et al. 2012). Such a bow-like structure is also evident in the ground-based mid-infrared images, but it appeared as a dark feature (Sato et al. 2014). Continuous monitoring of the cloud top morphology will provide clues for understanding what mechanism causes such an interesting feature.

Concluding remarks

In 2010, Japan's first trial to put the spacecraft AKATSUKI into orbit around Venus was unsuccessful. Since that time, ISAS has investigated the cause of the malfunction during the first orbit insertion and made a second challenging attempt at Venus orbit insertion in 2015 with the injured spacecraft. The second orbit insertion was executed flawlessly, and AKATSUKI will be able to achieve all science objectives in the new science orbit. All

AKATSUKI instruments are working well, and the first images have already provided new and intriguing observations of Venus. AKATSUKI will continue to send data for two or more years, and planetary exploration by Japan will enter a new era when AKATSUKI continuously delivers data to the world on the changing planet.

Abbreviations

FOV: field of view; IR1: 1-μm infrared camera; IR2: 2-μm infrared camera; ISAS: Institute of Space and Astronautical Science; JAXA: Japan Aerospace Exploration Agency; LAC: lightning and airglow camera; LIR: long-wave infrared camera; OME: orbital maneuver engine; RCS: reaction control system; RS: radio occultation experiments; SSI: solid-state imager; UVI: ultraviolet imager; VMC: Venus monitoring camera; VOI: Venus orbit insertion on December 7, 2010; VOI-R1: Venus orbit insertion-revenge 1.

Authors' contributions

For the AKATSUKI project of ISAS/JAXA, NM was the project manager, IT was the project scientist, and IN was the project engineer. KY, HC, NJ, IT, IK, TT, TH, TS, NS, HT, HA, and KY were core members of the engineering team. AT, ST, SM, UM, YA, IN, WS, TM, FT, TY, YM, IM, OS, UK, HGL, TM, MY, OK, SN, KY, KT, HN, NR, YY, HT, YM, HY-Y, KH, SK, ST, AH, MS, STM, TS, NK, PJ, and LYJ were core members of the science team. Some members of the science team served as principal investigators (PIs) of the scientific instruments; specifically, WS, IN, ST, TM, TY, and IT were PIs for the work involving the UVI, IR1, IR2, LIR, LAC, and RS, respectively. All authors read and approved the final manuscript.

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Competing interests

The authors declare that they have no competing interests.

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