PLANET-C: Venus Climate Orbiter mission of Japan

Takeshi Imamura (1), Masato Nakamura (1), Munetaka Ueno (2), Naomoto Iwagami (3), Takehiko Satoh (4), Shigeto Watanabe (5), Makoto Taguchi (6), Yukihiro Takahashi (7), Makoto Suzuki (8), Takumi Abe (1), George L. Hashimoto (9), Takeshi Sakanoi (7), Shoichi Okano (7), Yasumasa Kasaba (1), Jun Yoshida (7), Manabu Yamada (5), Nobuaki Ishii (1), Takahiro Yamada (1), Koh-ichiro Oyama (1)

(1) Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, 3-1-1, Yoshinodai, Sagamihara, Kanagawa 229-8510, Japan
(2) Department of Earth Science and Astronomy, University of Tokyo, Komaba 3-8-1, Meguro-ku, Tokyo 153-8902, Japan
(3) Department of Earth and Planetary Science, University of Tokyo, 7-3-1, Hongo, Bunkyo-ku, Tokyo, 113-0033, Japan
(4) Faculty of Education, Kumamoto University, 2-40-1 Kurokami, Kumamoto 860-8555, Japan
(5) Division of Earth and Planetary Sciences, Hokkaido University, Kita 10 Nishi 8, Kita-ku, Sapporo, 060-0810, Japan
(6) National Institute of Polar Research, 9-10, Kaga 1-chome, Itabashi-ku, Tokyo 173-8515, Japan
(7) Department of Geophysics, Tohoku University, Aramaki-aoba, Aoba-ku, Sendai, 980-8578, Japan
(8) Earth Observation Research and application Center, Japan Aerospace Exploration Agency, Harumi Island Triton Square, Office Tower X 23F, 1-8-10 Harumi, Chuo-ku, Tokyo 104-6023, Japan
(9) Department of Earth and Planetary Sciences, Kobe University, 1-1 Rokkodai-cho, Nada, Kobe, Hyogo 657-8501, Japan

Corresponding author:

Takeshi Imamura
Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency
3-1-1, Yoshinodai, Sagamihara, Kanagawa 229-8510, Japan
TEL/FAX: +81-42-759-8179/8457
EMAIL: ima@isas.jaxa.jp

Abstract

The Venus Climate Orbiter mission (PLANET-C), one of the future planetary missions of Japan, aims at understanding the atmospheric circulation of Venus. Meteorological information will be obtained by globally mapping clouds and minor constituents successively with 4 cameras at ultraviolet and infrared wavelengths, detecting lightning with a high-speed imager, and observing the vertical structure of the atmosphere with radio science technique. The equatorial elongated orbit with westward revolution fits the observations of the movement and temporal variation of the Venusian atmosphere which rotates westward. The systematic, continuous imaging observations will provide us with an unprecedented large dataset of the Venusian atmospheric dynamics. Additional targets of the mission are the exploration of the ground surface and the observation of zodiacal light. The mission will complement the ESA's Venus Express, which also explores the Venusian environment with different approaches.

1. Introduction

Venus is one of the most attractive targets in the solar system when we seek to understand the formation of the terrestrial environment. Venus is our nearest neighbor, and has a size very similar to the Earth's; however, previous spacecraft missions discovered an extremely dense (~92 bar) and dry CO_2 atmosphere with H_2SO_4-H_2O clouds floating at high altitudes, and exotic volcanic features covering the whole planet. The abundant gaseous CO_2 brings about a high atmospheric temperature (~740 K) near the surface via greenhouse effect. The atmospheric circulation is also much different from the Earth's. The mechanisms which sustain such conditions are unclear and considered to be the keys to understand the origin of the terrestrial environment. In spite of the many previous missions that explored Venus, such as the Venera, Pioneer Venus, Vega and Magellan, most of the fundamental questions raised so far still remain unsolved.

The Venus Climate Orbiter (VCO) of Japan aims to elucidate the mechanism of the mysterious atmospheric circulation of Venus, with secondary targets being the exploration of the ground surface and the zodiacal light observation during the cruise to Venus. The exploration of the Venusian meteorology is given a high priority not only for understanding the climate of Venus but also for the general understanding of planetary fluid dynamics. VCO is the 24th science spacecraft of the Institute of the Space and Astronautical Science (ISAS), Japan Aerospace Exploration Agency (JAXA), and has a code name PLANET-C. The phase B study of VCO has started in April, 2004, and the flight model integration will start in the middle of 2006. The spacecraft will be launched and arrive at Venus in 2010, and will perform 2 Earth years of operation.

VCO will explore Venus using a set of sophisticated cameras dedicated to meteorological study and radio science technique. Such a VCO's approach complements the Venus Express mission of the European Space Agency (ESA), which aims at totally understanding the Venusian environment using spectrometers, a multi-band camera, a plasma analyzer, a magnetometer, and radio science. The orbits of these two spacecrafts are also different from each other. The present paper describes the science goals of VCO, the mission overview, the specifications of the science instruments, and the relationship with Venus Express.

2. Scientific background

The principal mode of the atmospheric circulation of Venus is a zonal retrograde super-rotation of the entire atmosphere (e.g., Schubert, 1983). The wind speed increases with height and reaches ~100 m s^{-1} near the cloud top (~65 km altitude), although the solid planet rotates very slowly with a period of 243 Earth days corresponding to an equatorial rotation speed of 1.6 m s^{-1}. Since eddy viscosity should transport angular momentum downward and pass it to the solid planet, a mechanism which extracts angular momentum from the solid planet and transports it upward is required to maintain the vertical shear. Various mechanisms have been proposed so far; among them are the combination of meridional circulation and large-scale eddies which transport angular momentum equatorward (Giearsch, 1975; Yamamoto and Takahashi, 2003; Iga and Matsuda, 2005), thermal tides which are excited in the cloud layer and propagate vertically (Fels and Lindzen, 1974; Takagi and Matsuda, 2005), and gravity or Kelvin waves which are excited in the lower atmosphere and propagate upward (Del Genio and Rossow, 1990; Yamamoto and Tanaka 1997). The identification of the responsible mechanism requires the detailed information on the atmospheric waves and meridional circulation above and below the cloud layer.

Meridional circulation is an important issue also from the viewpoint of the thermal balance and the chemical cycle of the atmosphere. Vertically-stacked cells have been proposed based on the wind profiles obtained by entry probes (Schubert et al., 1980), while recent numerical models predict the occurrence of one direct cell in each hemisphere (Yamamoto and Takahashi, 2003). Although strong poleward circulation was observed at the dayside cloud top by cloud tracking (e.g., Rossow et al., 1990), the circulation pattern is still highly uncertain due to the lack of nightside data and the insufficient measurement below the cloud top. In the thermosphere, on the other hand, subsolar-to-antisolar circulation is expected to take the place of meridional circulation (Bougher et al., 1997). Gravity waves are believed to play important roles in determining the circulation structure. The investigation of the thermospheric circulation will offer clues to the question why zonal circulation dominates in the lower atmosphere in such a slowly-rotating planet.

The thermal balance and chemical cycle of the Venusian atmosphere is strongly influenced by the H_2SO_4-H_2O cloud layer at 45-65 km altitudes (Esposito et al., 1983). The H_2SO_4 is thought to be produced photochemically near the cloud top via the oxidation of SO_2: the clouds basically have the characteristics of photochemical aerosols. On the other hand, there must be a strong dynamical coupling between clouds and atmospheric motions in the lower part of the cloud layer, where the static stability is weak and rapid condensation and evaporation of cloud droplets will occur in the course of vertical convection (e.g., Imamura and Hashimoto, 2001). Remote sounding of the spatial distribution and the microphysical properties of clouds, combined with other meteorological observations, might provide key information on such dynamical coupling in the cloud layer. The cloud dynamics is further related to the ultraviolet markings at the cloud top, such as large cell-like structures, bow shape, and circum-equatorial belts, whose dynamical origins are mostly unknown (Rossow et al., 1980).

Lightning discharge is closely related to cloud formation and can be an indicator of strong convective activity. The occurrence of lightning in the Venusian atmosphere has been suggested by various observations (Grebowsky et al., 1997); however, the occurrence is still under debate since the standard mechanism of lightning requires H_2O ice particles, which will not be formed in the Venusian atmosphere. Large solid particles of unknown composition suggested by the Pioneer Venus probe (Knollenberg and Hunten, 1980) might play some roles. New observation techniques are required to confirm the occurrence of lightning and reveal the thundercloud distribution.

The composition and abundance of the Venusian atmosphere might be controlled by the chemical coupling with the crust (Fegley et al., 1997; Wood, 1997; Hashimoto and Abe, 2005). The low-emissivity areas at Venusian highlands observed at radio wavelengths will have been produced by some temperature-dependent thermodynamical reactions between atmospheric constituents and surface minerals. One of the possible atmosphere-surface reactions may influence the atmospheric SO_2 abundance, which controls the cloud albedo, thereby changing the surface temperature; via such a feedback the Venusian climate can be stabilized (Hashimoto and Abe, 2000). The nature of the surface minerals and the related reactions are, however, highly controversial. The knowledge on the current status of volcanism is also an important key to understand the sulfur cycle in the current Venusian environment as well as the climate evolution and the internal structure of the planet (Hashimoto and Imamura, 2001).

Observation of the zodiacal light, i.e. the interplanetary dust (IPD) cloud, is an important issue in the cruising phase of the mission. Big problem on the zodiacal dust cloud is its origin, since the lifetime of the IPD particles under the Poynting-Robertson drag is absolutely shorter than the age of the solar system. We have several approaches to study the IPD cloud, and imaging observations are one of the very effective techniques to reveal its origin because the IPD particles keep the morphological structures of their sources. Observations of zodiacal light took the first step by ground-based measurements at visible wavelength, and the early photoelectric observations suffered from calibration uncertainty and poor spatial resolution. The all-sky map of zodiacal light brightness at visible band now reaches the relative accuracy better than 10% and the spatial resolution of 2 arc-degree, and is being improved drastically by the WIZARD project (Ishiguro et al., 2002). Infrared Astronomical Satellite (IRAS) dramatically changed the smooth featureless picture of the zodiacal dust cloud by revealing numerous bands of asteroidal debris, several narrow trails of cometary dust, and a clumpy dust ring. The success of IRAS was largely due to the improvements in relative accuracy and spatial resolution. The ring clumps comprise always the same configuration in the frame rotating at the rate of the Earth's mean motion. The most important thing is that the IRAS observations of zodiacal emission are free from the Earth's scattering atmosphere. COBE/DIRBE also surveyed almost entire sky with a 0.7 arc-degree size beam and with much better calibration (Kelsall et al., 1998). One of the most important results of the DIRBE/COBE mission is a confirmation of the mean motion resonance dust ring, and an isolation of the leading and trailing blobs in the mean motion resonance feature.

3. Mission overview

3.1 Spacecraft design and orbit

VCO aims to unveil the mysteries described above with 5 cameras and radio science. The configuration of the spacecraft is shown in Fig. 1. The spacecraft, which is three-axis stabilized by momentum wheels, directs cameras toward Venus via the attitude control of the main body. The spacecraft surfaces on which solar array paddles are attached always face to the north or the south, and are used for radiative cooling. The solar array paddles have one freedom of rotation about the north-south axis, and their orientations are controlled to face to the sun independent of the orientation of the main body. The slot-array high gain antenna will be oriented toward the Earth by attitude control when communicating with the ground station. The telemetry rate will be higher than 4 kbps at 1.5 AU, 8 kbps at 1.1 AU, 16 kbps at 0.7 AU and 32 kbps at 0.5 AU. The mass of the spacecraft is 480 kg including fuel, and the science payload weighs 34 kg. The spacecraft will be launched in May 2010 and arrive at Venus in December 2010. During the cruise to Venus, VCO will observe the zodiacal light from various viewing points in the solar system without any contaminations of the sky light, and will map out the spatial distribution of the IPD cloud. The mission life at Venus will be 2 Earth years or more; the duration is limited by the degradation of the onboard batteries. The details of the spacecraft design are given in Ishii et al. (2004).

The orbit around Venus is a long elliptical one near the ecliptic plane (172-degrees inclination) with 30-hours orbital period. The direction of orbital motion is westward, which is the direction of atmospheric super-rotation. The apoapsis altitude is chosen to be 79000 km, or 13 Venus radii (Rv), so that the angular velocity of the spacecraft is roughly synchronized with the 60-m s^{-1} super-rotational flow near the cloud base (50 km) for ~20 hours centered at the apoapsis (Fig. 2). The periapsis altitude is 300 km. Global images of the atmosphere and the ground surface will be obtained every 2 hours successively and continuously from such a ‘quasi-synchronized’ orbit. In order to transmit a quantity of image data to the ground station without serious degradation, the Sensor Digital Electronics Unit (DE) will be used for onboard calibration and data compression.

The systematic imaging sequence of VCO is advantageous for detecting meteorological phenomena with various temporal and spatial scales. The quasi-synchronized orbit is suitable for obtaining cloud-tracked wind vectors, especially the small deviation of local wind vectors from the background super-rotation. With such wind vectors the characterizations of the meridional circulation, mid-latitude jets and various wave activities are anticipated. Close-up images of meso-scale features and limb images will also be obtained near the periapsis. The shadow region along the orbit is utilized for observing faint light such as lightning and airglow. Radio occultation experiment will also be performed when the spacecraft is hidden by Venus as viewed from the ground station.

3.2 Sounding regions

The onboard scientific instruments altogether sense different levels of the atmosphere (Fig. 3). Night airglows at visible wavelengths in the lower thermosphere will be studied by the Lightning and Airglow Camera (LAC). LAC will also detect yet-to-confirm lightning in the clouds. The cloud top level is covered by the Ultraviolet Imager (UVI), which maps SO_2 and unknown absorbers at wavelengths 283 and 365 nm on the illuminated (day) side. The meso- to global-scale structures in the cloud top height will be determined by the Longwave Infrared Camera (LIR) at 10 μm wavelength both on the dayside and the un-illuminated (night) side. UVI and LIR will yield wind vectors via the tracking of small-scale features. Variations in the cloud top height will be studied also by the 2-μm Camera (IR2) with its 2.02-μm filter (a CO_2 absorption band) applied to the dayside.

The main target of IR2 is the motions of the middle and lower atmosphere. Such observations will be done at 1.73, 2.26 and 2.32 μm wavelengths, which are known to be relatively absorption free (so-called atmospheric windows), enabling us to see the deep atmosphere through the clouds on the nightside (Taylor et al., 1997). The distribution of CO will be studied by differentiating 2.26 and 2.32 μm images to understand the production, circulation and dissociation processes of this molecule.

Finally, the deepest level (almost reaching the surface) will be investigated by the 1-μm Camera (IR1) at 1.01 μm wavelength. In addition to the studies of physical properties of the lower atmosphere, suspected volcanic activities will be searched for and the surface emissivity distribution will be mapped with IR1. IR1 will also observe lower clouds on the dayside.

In addition to the imaging-camera suite above, Radio Science (RS) technique will be used to observe the vertical profiles of atmospheric temperature, sub-cloud H_2SO_4 vapor, and ionospheric plasma. The combination of these different types of observations will provide a new view of the three-dimensional structure and dynamics of the Venusian atmosphere.

4. Science instruments and targets

The basic designs of 5 cameras are shown in Fig. 4, while the basic specifications are summarized in Table 1.

4.1 1-μm Camera (IR1)

IR1 is designed to image both the dayside and nightside of Venus at 1.01 μm wavelength, which is located in one of the atmospheric windows (Taylor et al., 1997). The 1.01 μm window allows radiation to penetrate the whole atmosphere. On the dayside IR1 visualizes the distribution of clouds illuminated by sunlight. Although the dayside disk at this wavelength appears almost flat, small-scale features with contrasts of ~3% are thought to originate in the middle and lower cloud region (Belton et al., 1991); tracking of such cloud features provides the wind field in this region over the hemisphere. We expect to determine the wind vectors with accuracy of the order of a few m s^{-1}. On the nightside, IR1 measures the thermal radiation mostly from the surface and a little from the atmosphere. Such measurements will yield information about the lowermost atmosphere and the surface properties (Hashimoto and Sugita, 2003), and also is expected to find out possible active volcanoes utilizing the fact that hot lava emits much more radiation than surrounding areas in this wavelength region (Hashimoto and Imamura, 2001).

As an imaging instrument, IR1 has many features in common with IR2. These cameras share electronics for 16 bit A/D conversion since the detector arrays in these cameras are electronically nearly identical. Each of both cameras consists of a large baffle which eliminates stray light from the sun, F/4 optics with a focal length of 84.2 mm and a 1040 x 1040 pixels detector array (1024 x 1024 area is used) with a pixel pitch of 17 μm. The optics and the detector array altogether yield an effective field of view of 12 degrees, giving the pixel resolution of ~16 km from the apoapsis (13 Rv) and ~6 km from the distance of 5 Rv.

IR1 utilizes a 1.01 μm band-pass filter with a bandwidth of 0.04 μm and a ND (neutral density) filter, the latter is used to observe the dayside disk. The detector array is a Si-CSD(charge sweeping device)/CCD which is cooled down to 260 K to achieve a signal-to-noise ratio of ~300 on the dayside and ~100 on the nightside. The total weight excluding the electronics is 2.3 kg and the electronics weighs 3.7 kg. The power consumption is 9.4 W.

4.2 2-μm Camera (IR2)

The atmospheric windows IR2 utilizes are at 1.73, 2.26, and 2.32 μm: the first two are nearly absorption free, while the last one contains a CO absorption band. At these wavelengths, IR2 is most sensitive to infrared radiation originating from altitudes 35-50 km. To track cloud motions, a series of 2.26- μm images are exclusively used. As the inhomogeneity of the Venusian cloud layer is thought to occur predominantly at altitudes 50-55 km (Belton et al., 1991), the IR2 observations should yield wind maps in this region. As CO is photochemically produced above the cloud and subsequently transported to the deeper atmosphere (such sinks are not yet precisely located), distribution of CO should give us additional information about the circulation of the atmosphere. We will extract the CO distribution at 35-50 km altitudes by differentiating images taken at 2.26 and 2.32 μm (Collard et al., 1993). To study cloud microphysics, cloud opacities at 2.26 and 1.73 μm, together with IR1 1.01- μm images, will be analyzed with the aid of radiative transfer calculation. Such analysis gives us information on the spatial and temporal variations in the cloud particle size and density (Carlson et al., 1993).

IR2 employs two additional wavelengths, 2.02 μm (a prominent CO_2 absorption band) and an astronomical H-band centered at 1.65 μm. At 2.02 μm, we expect to detect variations of cloud-top altitude as intensity variations of reflected sunlight. The sensitivity to the cloud height may not be compared to what LIR would achieve but the horizontal resolution is superb. The H-band aims at observing the zodiacal light. Each of these 5 wavelengths can be selected by rotating a 6-position filter wheel which has a blank position as well for protection and acquisition of dark frames.

The PtSi sensor IR2 utilizes is not ultra sensitive in 2-μm region but has a number of advantages: it is very stable, uniform, and durable against energetic radiation of over 30 kRad. To suppress the thermal electrons in the detector, it is cooled down to 65 K by a single-stage stirling cooler driven at 50 W. The cooler consists of a compressor, a cold head with a cold tip, and a driver electronics unit. Although the cold tip of the cooler is attached to the detector mount, heat is removed via conduction from the lens and lens housing also, making these components cooled to approximately 170 K. Combined with a cold filter fixed in front of the detector housing, we expect to achieve the signal-to-noise ratio over 100 when imaging the Venusian nightside.

In order to fabricate observations of the zodiacal light, the camera optics is designed to suppress the instrumental background as well as the stray light. The large baffle of the camera is very useful for the interplanetary dust (IPD) observations, because it enables us very wide coverage in the solar elongation angle from 180 arc-degree (anti-solar direction) to 30 arc-degree. The device is specially designed for the camera to realize precise measurements of the instrumental zero level. Stability of the zero level is essentially important for the IPD observations, because the target is extending beyond the instantaneous field of view of the camera. The architecture of the device is based on the similar technology of 512 x 512 PtSi IR CSD which was applied for astronomical observations (Ueno, 1996). Insensitive (or dark) pixels, which monitors the instrumental zero level steadily and places 8 lines in each edge of the 1024 x 1024 sensitive pixels, were employed for the device (corresponding to 1040 x 1040 pixels in total). Balanced type FDAs (floating diffusion amplifier) are also important to maintain the precise zero level of the signal and to suppress the interfering noise in the spacecraft. Expected sensitivity of IR2 in low noise mode will reach 1.5 x 10^{-6} W m^{-2} sr^{-1} of surface brightness, or 13 magnitude of point source at H band with a single exposure of 2 minutes integration. The typical surface brightness of zodiacal light at 1AU from the sun (~4 x 10^{-7} W m^{-2} sr^{-1}) is within the detection limit after 2 x 2 pixels on-chip binning. The wide field of view with fine spatial resolution is a big advantage in removing the star light component, which contributes in the sky brightness at H band (Hauser et al., 1998). The wide coverage in solar elongation angle is also very important to observe rather inner part of the zodiacal light, which is key information to count the contribution of the isotropic component of the IPD cloud. The isotropic component is hard to estimate precisely by the former missions, because it is very difficult to distinguish the zodiacal light from the smooth background of the integrated extragalactic light. Recent observations by the star-tracker camera onboard the Clementine spacecraft shows rather abundant dust particle in isotropic component (Hahn et al., 2002). The determination of the amount of the isotropic component is very important for studying its origin and also has a big impact on the cosmological studies. Pointing toward the inner direction of the solar system is very effective for these studies, because the isotropic component gains its brightness at the inner part, while the light by extra-galactic origin is constant along the heliocentric distance. The cruising trajectory itself is also very unique because VCO will trek into the IPD cloud clumps at the beginning, and will change her heliocentric distance from 1.1 AU to 0.7AU. The camera has enough chance to trace the resonance structure produced by the Earth and Venus, since the cloud structure of the mean motion resonance is co-rotating around the sun together with the earth. The camera will thus give us a very unique opportunity to observe the IPD cloud, and will paint the complete three-dimensional distribution of the IPD cloud. The expected results on IPD observations with IR2 are radial dependence of the zodiacal light, accurate trace of resonance structures by Venus and the Earth, determination of the symmetrical plane of the IPD cloud, inner distribution and scale height, and precise measurements of the uniform component of IPD cloud.

We have developed a sophisticated lens support mechanism to satisfy the conflicting requirements.

(1) The lens elements need to be *loosely* supported at room temperature to allow contraction of lens housing when it is cooled to the operating temperature once in the space.

(2) The lens elements need to be *tightly* supported at room temperature so they could survive high level of vibration at the moment of spacecraft launch.

To achieve the desired performance, the lens support employs springs of optimized strength in both radial and lateral directions. Alignment errors of optical elements after a shaking/cooling cycle have been measured with a test model and we have found the mechanism very promising.

The entire system of IR2 is mounted on a cold plate for higher efficiency of cooling. The cold plate is bolted onto the northern or southern surface of the spacecraft with the camera pointing perpendicular to the north-south axis. The camera is located inside the spacecraft while the compressor and the cold head of the cooler are mounted on the other side of the cold plate, in other words, exposed to the space to effectively dispose heat. The weight of IR2 including the lens shade and the cold plate is slightly over 9 kg, the heaviest of 5 cameras onboard VCO.

4.3 Ultraviolet Imager (UVI)

UVI is designed to measure ultraviolet radiation scattered from cloud tops at ~65 km altitude in two bands centered at 283 nm and 365 nm wavelengths with the bandwidth of 15 nm. The Venusian atmosphere shows broad absorption of solar radiation between 200 and 500 nm; SO_2 at the cloud top explains the absorption in the range between 200 nm and 320 nm, while the absorption above 320 nm should be due to another absorber that is not identified yet (Esposito et al., 1997). Identification of the absorber is important not only for atmospheric chemistry but also for the energy balance and dynamics of the atmosphere, because the species influence the albedo and the heating profile of the atmosphere. UVI will make clear the spatial distributions of these ultraviolet absorbers and their relationships with the cloud structure and the wind field. The tracking of cloud motions yields the wind vectors at the cloud top (Rossow et al., 1990). Furthermore, the vertical distributions of cloud particles and the haze layer above the main cloud will be studied with limb observations.

With the field of view of 12 degrees, the full disk of Venus can be captured in one image at distances >8.5 Rv. UVI uses a UV-coated backthinned frame transfer Si-CCD with 1024 x 1024 pixels and the pixel size of 13 μm. The spatial resolution is ~16 km at apoapsis and ~6 km from the distance of 5 Rv. The fullwell of the CCD is 10^5 e^- per pixel, and the singal-to-noize ratio is 120. The output is digitized with 12 bit A/D conversion. The total mass including the optics, CCD detector assembly and electronics is ~3.4 kg, and the power consumption is 9.4 W.

4.4 Longwave Infrared Camera (LIR)

LIR detects thermal emission from the cloud top in a rather wide wavelength region 8-12 μm to map the cloud-top temperature. Unlike other imagers onboard VCO, LIR is able to take images of both dayside and nightside with equal quality and accuracy. The cloud-top temperature map will reflect the cloud height distribution, whose detailed structure is unknown except in the high latitude observed by the Pioneer Venus (Taylor et al., 1980), as well as the atmospheric temperature distribution. The images will visualize the cloud height anomalies which originate from convection cells and various waves within the cloud layer. Furthermore, the tracking of blocky features in successive images will yield wind vectors including those on the nightside, which have been inaccessible in the previous missions. The cloud-top temperature is typically as low as 230 K; LIR has the capability to resolve temperature difference of 0.3 K for such a cold target, corresponding to a few hundred-meter difference in the cloud height. The accuracy of absolute temperature measurement is 3 K.

LIR consists of a sensor unit and an external power supply unit. The sensor unit includes optics, a mechanical shutter, an image sensor and its drive circuit, and attached with a baffle that keeps direct sunlight away from the optical aperture. The F-number of the Germanium lens module is 1.4 and the field-of-view is 12 degrees. The mechanical shutter driven by a stepping motor works not only as a light shutter but also as a calibration source. The image sensor is an uncooled micro-bolometer array with 320 x 240 pixels (240 x 240 area is used) and the pixel size of 37 μm. Since the sensor can work under room temperature, huge and heavy cryogenic apparatus which is usually necessary for infrared devices is unnecessary. This makes the instrument very light and small. The temperature of the bolometer is stabilized to 313 K by a Peltier cooler. The frame rate is 60 Hz, and several tens of images obtained within a few seconds will be accumulated in DE (described below) to increase the signal-to-noise ratio. The spatial resolution is 0.05 degree, which corresponds to ~70 km on the Venus surface when viewed from the apoapsis and ~26 km from the distance of 5 Rv. LIR weighs 3.7 kg and the power consumption is 29 W.

4.5 Lightning and Airglow Camera (LAC)

LAC is a high-speed imaging sensor which measures lightning flashes and airglow emissions on the nightside disk of Venus when VCO is located within the umbra (shadow region) of Venus. One of the major goals of LAC is to settle controversy on the occurrence of lightning in the Venusian atmosphere. Lightning observations will give us information on the charging mechanism, charge separation mechanism, physics of sulfuric acid clouds, mesoscale meteorology and its impacts on atmospheric chemical processes. If lightning discharge occurs in the upwelling cloud regions like as the Earth and Jupiter, we can monitor vertical convections inside the cloud layer via lightning detection. The 777.4 nm [OI] band associated with the excitation of atomic oxygen is expected to be a strong emission from the laboratory discharge experiment in a simulated Venusian atmosphere (Borucki et al., 1996). Possible lightning flashes were detected on the nightside disk of Venus at this wavelength by a ground-based telescope (Hansell et al., 1995).

We will also obtain information on the global circulation in the lower thermosphere by continuous observations of large-scale structures in the O_2 Herzberg II (552.5 nm) night airglow, whose production is the consequence of the recombination of atomic oxygen in downwelling. The Herzberg II bands of molecular oxygen are the strongest emissions among the visible Venusian airglows, and their integrated intensity in the 551-552 nm region, which includes rotational lines in the 0-10 band, is 270 R (Rayleigh) (Slanger et al., 2001). LAC also enables us to observe wave-like structures produced by gravity waves which might play important roles in the dynamical coupling between the lower and the upper atmosphere. Furthermore, LAC will measure the 557.7 nm [OI] and 630.0 nm [OI] emissions. Both of these atomic oxygen emissions were not detected by Venera 9 and 10 (Krasnopolsky, 1983); however, Slanger et al. (2001) discovered the 557.7 nm emission whose intensity is 150 R ± 20% using a ground-based telescope, while 630.0 nm emission was not detected. The origin of such variability in the 557.7 nm emission is also one of themes of LAC.

LAC is designed to detect lightning flashes with an intensity of 1/100 of standard lightning on the Earth when viewed from 1000 km altitude and to measure 100-R night airglow with a signal-to-noise ratio more than 10. LAC has a field-of-view of 16 degrees, and as the detector it uses a multi-anode avalanche photo-diode (APD) that has 8 x 8 matrix of 2-mm square pixels. We will measure lightning flashes at 777.4 nm [OI] with 4 x 8 pixels and airglow emissions at 552.5 nm [O_2 Herzberg II], 557.7 nm [OI] and 630.0 nm [OI] with 1 x 8 pixels, respectively, using rectangular interference filters with bandwidth of 8 nm. Airglow-free background images are also acquired at 545.0 nm with 1 x 8 pixels with the same kind of filter. A complex of these interference filters is placed on the detector. Individual lightning flash events are sampled at 50-kHz by pre-triggering, while airglow images are recorded continuously at intervals of 20 seconds, scanning the nightside disk of Venus by attitude maneuver or orbital motion of the spacecraft. The field-of-view of one pixel corresponds to about 35 km on the Venusian surface at 1000 km altitude and 850 km at 3 Rv altitude. The total weight of LAC is about 1.5 kg.

4.6 Sensor Digital Electronics Unit (DE)

DE is a science payload to interface and control four cameras; IR1, IR2, UVI, and LIR. For the nominal observation sequence which is repeated every 2 hours, the main satellite system controller (Data Handling Unit) triggers DE unit. DE, then, sequentially triggers detailed observation sequence of each camera, filter wheel and gain settings, exposure, and data transfer. DE is also responsible for (i) acquiring raw data from cameras, (ii) arithmetic data processing and data compression, and (iii) science and telemetry data formatting and packetting. The weight and the power consumption of DE are 4.6 kg and 20 W, respectively, including 512 Mbytes data recorder unit installed in a same box.

The arithmetic data processing includes (a) dark signal subtraction, (b) pixel gain collection, and (c) background region (off Venus) suppression to zero. Due to the limited data downlink capacity, i.e. the 6-7 hours of tracking per day and the telemetry rate of 4-32 kbps, data volume must be reduced by the combination of following approaches; (a) partial cancellation of imaging opportunities depending on the bandpass filters and/or cameras, (b) increase of the observation interval to 4 hours or more, (c) data slicing, (d) pixel binning, and (e) data compression. Since the derivation of wind vectors from successive cloud images at different layers requires high fidelity data acquisition, VCO will use the JPEG2000 (Boliek et al., 2000) lossless data compression technique based upon discrete wavelet transform as far as possible. However, in the epochs of low telemetry rate (4 kbps at < 2.2 AU), lossy compression will also be adopted. The data compression efficiency is strongly dependent on the high frequency component of images; since VCO will acquire the finest Venusian images ever observed from spacecraft or the ground, the data compression efficiency is difficult to estimate at this moment.

4.7 Radio Science (RS)

RS, in its atmospheric occultation mode, provides vertical profiles of atmospheric temperature, sub-cloud H_2SO_4 vapor density and ionospheric electron density. In the experiment, the spacecraft sequentially passes behind the atmosphere and the planetary disk as seen from the tracking station on the Earth, and then reemerges in the reverse sequence. The Venus atmosphere causes ray bending of the radio wave, thereby causing the time-dependent Doppler frequency shift due to the orbital motion of the spacecraft. The frequency variation observed at the tracking station is processed off-line assuming the spherical symmetry of the atmosphere to yield the vertical profile of the refractive index of the atmosphere, which is further converted to the neutral density profile below ~90 km and the electron density profile above (Fjeldbo et al., 1971). The neutral density profile yields the profiles of atmospheric pressure and temperature on the assumption of hydrodynamic equilibrium. The vertical resolution is diffraction-limited to the diameter of the first Fresnel zone, which is typically 1 km. The temporal variation of the signal power will also be analyzed to retrieve the vertical profile of H_2SO_4 vapor, which absorbs the radio wave (Jenkins et al., 1994). When the spacecraft moves into superior conjunctions with the sun, the structure of solar corona will also be studied.

RS will be conducted in one-way mode using X-band (8.4 GHz) downlink stabilized by an onboard ultra-stable oscillator (USO) with the frequency stability on the order of 10^{-13}. The downlink signal will be recorded by an open-loop receiver at the Usuda Deep Space Center of Japan (Imamura et al., 2005). During the occultation the spacecraft must perform attitude maneuvers to compensate for the ray bending, which is as large as ~20 degrees. Due to the 8-degrees tilt of the spacecraft orbit relative to the Venus' ecliptic plane and the 3.4-degrees difference of the ecliptic planes between Venus and the Earth, broad latitude regions will be sounded with emphasis on the low latitude.

The temperature profiles contain information on the static stability, energy balance, and various wave activities in the atmosphere. The H_2SO_4 vapor profiles are indispensable for the study of cloud physics. It should also be noted that the temperature field is related to the zonal wind field through cyclostrophic balance; the meridional distribution of zonal wind can be obtained from the temperature distribution by integrating the thermal wind equation with an appropriate lower boundary condition (Newman et al., 1984). Furthermore, the residual-mean meridional circulation (Andrews et al., 1987) can be diagnosed from the temperature and zonal wind distributions with the aid of radiative transfer calculation.

5. Relationship with Venus Express

The sciences of VCO are strongly related to those of Venus Express, a Venus orbiter of ESA, which was launched in November 2005 and will arrive at Venus in April 2006 (see articles in this issue). Venus Express' science objectives are to study the atmosphere, the plasma environment, and the surface of Venus. The onboard science instruments are: Planetary Fourier Spectrometer (PFS); Spectroscopy for Investigation of Characteristics of the Atmosphere of Venus (SPICAV); Visible and Infrared Thermal Imaging Spectrometer (VIRTIS); Venus Monitoring Camera (VMC); Analyzer of Space Plasmas and Energetic Atoms (ASPERA-4); Magnetometer (MAG); and USO for Venus Radio Science (VeRa). The spacecraft will be injected into a 24-hour polar orbit with the apoapsis altitude of 66000 km (11 Rv) and the periapsis altitude of 250-350 km. The periapsis latitude is 78 N, enabling close-up observation in the northern high latitude and global imaging over the southern hemisphere. The nominal mission will last till October 2007 and the extended mission is planed till December 2008. Regarding atmospheric and surface observations, the striking difference between VCO and Venus Express is that the former focuses on continuous global imaging from equatorial orbit, while the latter puts emphasis on spectroscopy from polar orbit, although VMC on Venus Express will take global images of the southern hemisphere and VIRTIS has a capability to map the planetary disk in mosaic mode. Such different approaches of the two missions are complementary with each other in many aspects of the Venus science.

The information on the vertical distributions of clouds and minor constituents is indispensable for the accurate interpretation of the image data taken by VCO; however, VCO hardly obtains such information, although the multiple-band imaging observations will resolve several different altitude levels. The vertical profiles provided by the Venus Express spectroscopy (PFS, SPICAV, VIRTIS) should offer the basis for the investigation by VCO.

Due to the orbital constraints, VCO cameras take global images of both hemispheres with emphasis on the low to mid-latitude, while VMC and VIRTIS on Venus Express get global views of the southern hemisphere especially in the high latitude region. The former is suitable for detecting planetary-scale symmetric or asymmetric wave modes such as the horizontal Y feature (Del Genio and Rossow, 1990) and characterizing the hemispheric difference. The latter will reveal more about the polar vortex and the so-called polar dipole whose origin is unclear (Taylor et al., 1980).

The way of surface sounding utilizing the near-infrared windows is also slightly different between VCO and Venus Express. IR1 on VCO maps the surface globally and continuously, together with the overlying clouds, exclusively at 1.01 μm wavelength. Such observations allow us to discriminate surface features from cloud features rather easily since clouds move and change their shapes from time to time. Venus Express, having more wavelength bands for surface sounding, yields spectroscopic data on the surface material. Latitudinal coverage is also different between VCO and Venus Express, in the same way as the atmospheric observation.

The fact that the operational period of VCO (2010-2012) does not overlap with that of Venus Express (2006-2008) is disadvantageous to the sciences above to some extent. However, the combination of the successive two missions will allow us to detect long-term variations of atmospheric state with timescales of several years or more. The presence of such variations was suggested by the change in the wind field obtained by the Pioneer Venus cloud tracking (Rossow et al., 1990) and also by the variation of SO_2 abundance above the cloud (Esposito et al., 1997). The observations common to the two missions are the global UV feature and the cloud-tracked winds in the southern hemisphere, the lower cloud distribution, and the temperature and H_2SO_4 profiles obtained by radio science. Long-term monitoring is advantageous also for the detection of active volcanism.

6. Concluding remarks

The Japan Aerospace Exploration Agency is planning the Venus Climate Orbiter/PLANET-C mission aiming at understanding the atmospheric circulation of Venus, with additional targets being the exploration of the ground surface and the zodiacal light observation. This paper describes the science objectives and instrument specifications as well as the characteristics of the spacecraft design. The instruments, the spacecraft design and the orbit of VCO are optimized for imaging observations of meteorological phenomena. The onboard instruments are cameras to map clouds and minor constituents with large-format array detectors (IR1, IR2, UVI, LIR), a high-speed imager (LAC), and USO for radio science. In the nominal sequence, all cameras except LAC will be operated every 2 hours to get global views of the Venusian atmosphere, and LAC will be operated in the shadow region of Venus. Such systematic, continuous imaging observations will provide us with an unprecedented large dataset of Venusian meteorology.

The science plan of VCO is complementary with that of the ESA’s Venus Express. The striking difference between VCO and Venus Express is that the former focuses on global imaging from equatorial orbit, while the latter puts emphasis on spectroscopy from polar orbit, although Venus Express also has imaging capabilities. The cooperation in the data analysis between the VCO team and the Venus Express team should also be fruitful; analyzing both VCO and Venus Express data sets with a common algorithm, and analyzing each data set with different algorithms developed independently by the two teams, would be helpful to ensure the reliability of the results.

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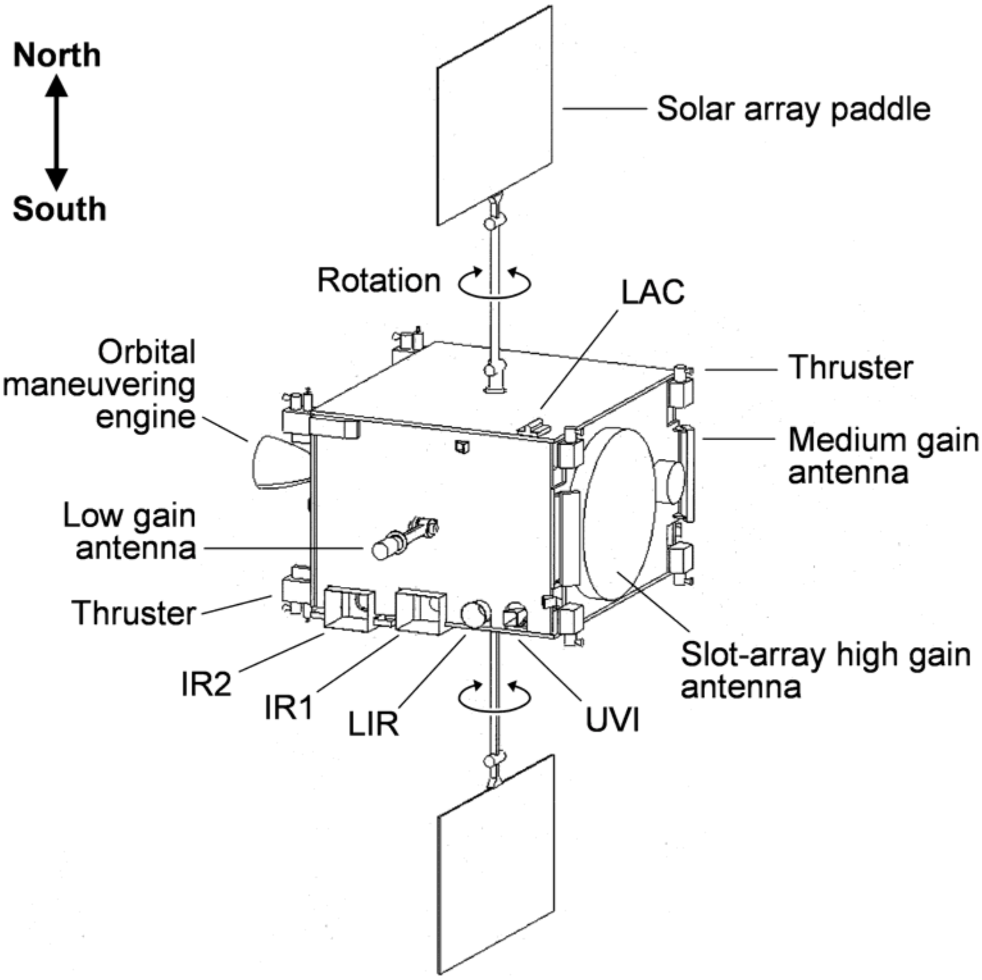

Fig. 1 Configuration of Venus Climate Orbiter/PLANET-C

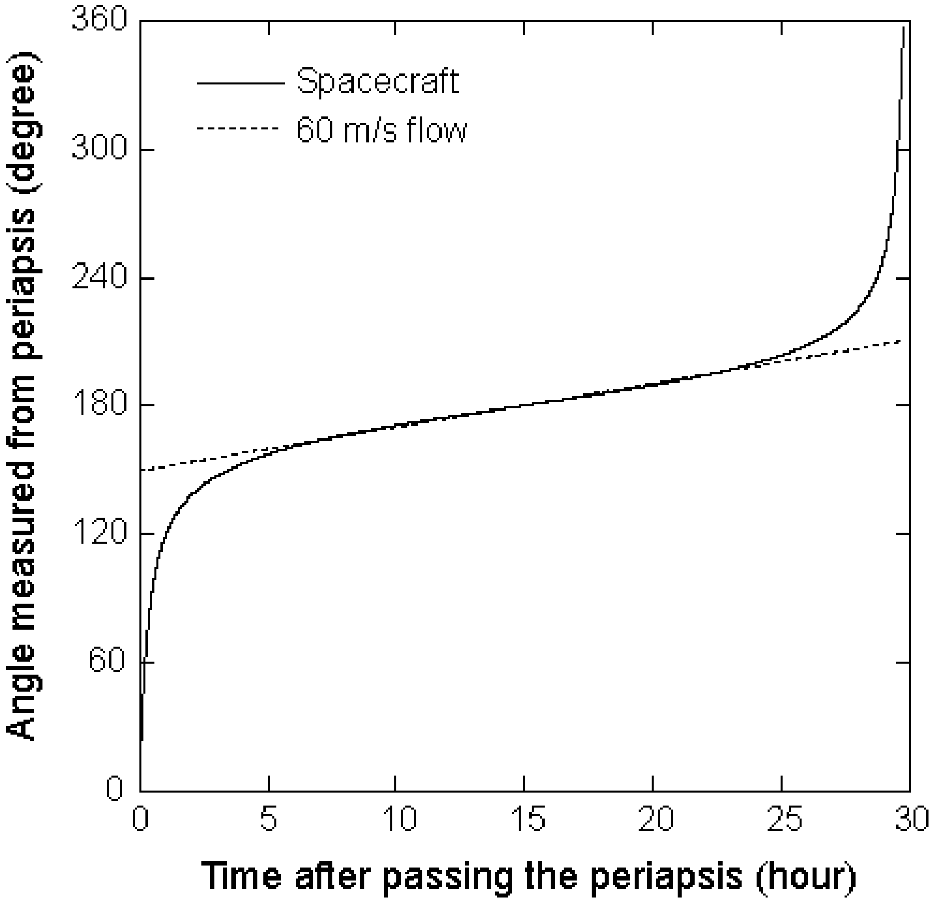

Fig. 2 Angular motion of the spacecraft relative to the center of Venus (solid), plotted with a curve for the constant westward flow of 60 m s^{-1} (dotted).

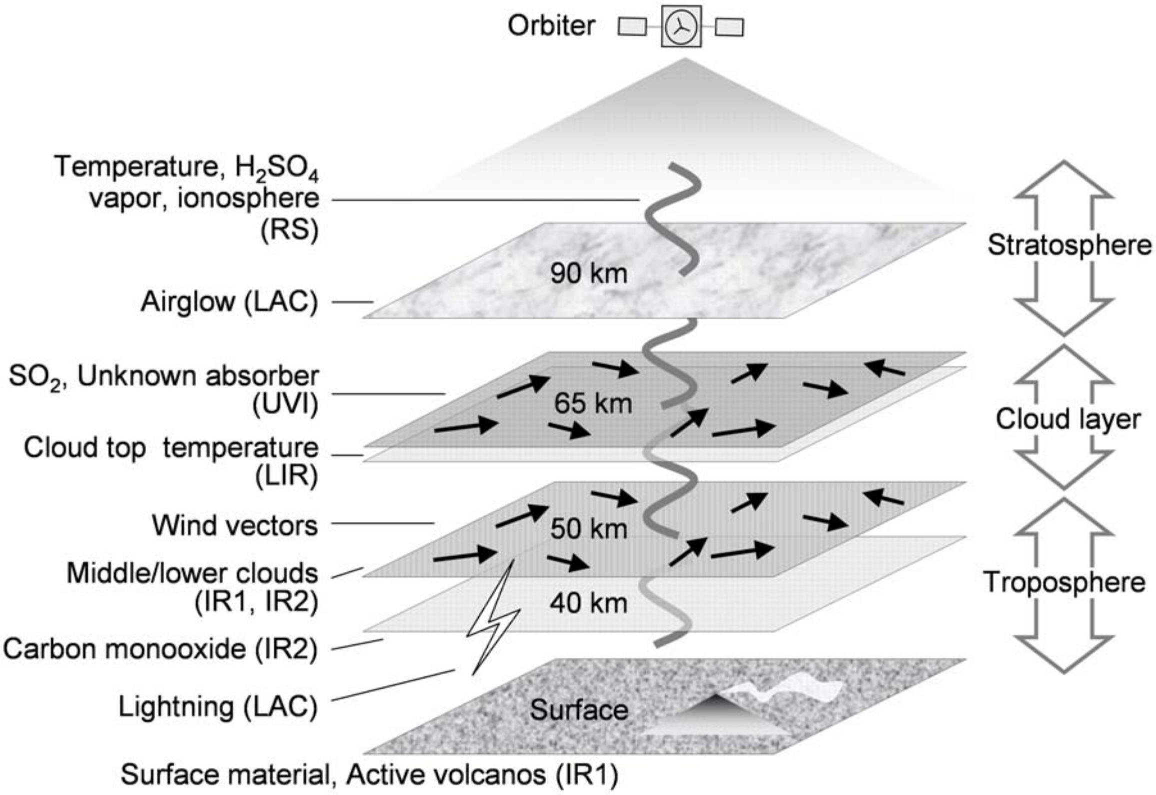

Fig. 3 Schematic of the three-dimensional observation by Venus Climate Orbiter/PLANET-C

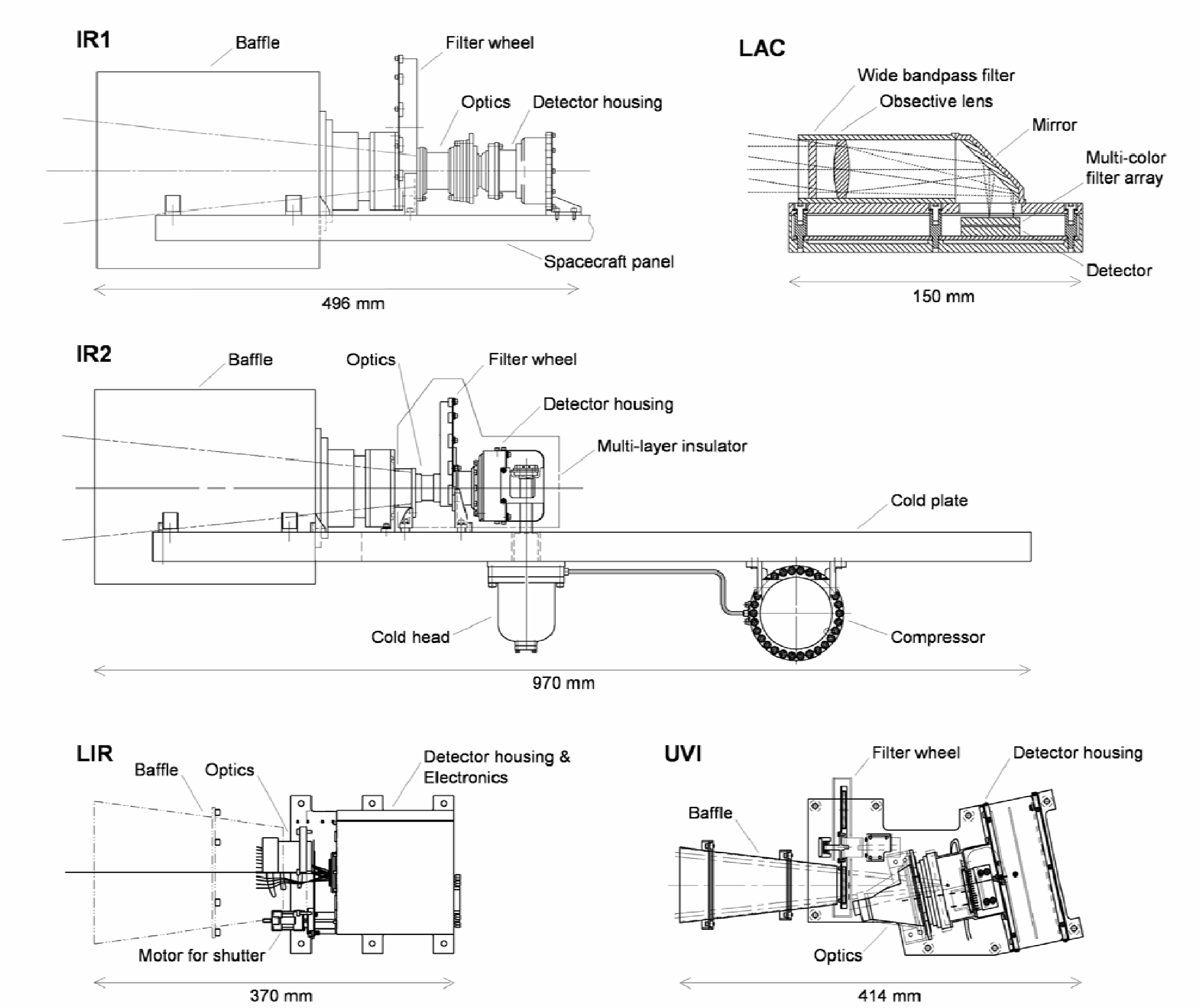

Fig. 4 Designs of the cameras onboard Venus Climate Orbiter/PLANET-C. Scales are common to IR1, IR2, UVI and LIR, while the scale for LAC is twice those of others.

Table 1 Basic specifications of the cameras onboard Venus Climate Orbiter/PLANET-C

Cameras	Field of view	Detector	Filters	Targets
IR1	12 degrees	Si-CSD/CCD 1024 x 1024 pixels	1.01 μm (night)	Surface, clouds
			1.01 μm (day)	Clouds
IR2	12 degrees	PtSi-CSD/CCD 1024 x 1024 pixels	1.73 μm (night)	Clouds, particle size
			2.26 μm (night)	
			2.32 μm (night)	CO below clouds
			2.02 μm (day)	Cloud-top height
			1.65 μm (cruise)	Zodiacal light
UVI	12 degrees	Si-CCD 1024 x 1024 pixels	283 nm (day)	SO_2 at cloud top
			365 nm (day)	Unknown absorber
LIR	12 degrees	Uncooled bolometer 240 x 240 pixels	8-12 μm (day/night)	Cloud-top temperature
LAC	16 degrees	8 x 8 multi-anode APD (50-kHz sampling in lightning search mode)	777.4 nm (night)	OI lightning
			552.5 nm (night)	O_2 Herzberg II ariglow
			557.7 nm (night)	OI airglow
			630.0 nm (night)	OI airglow
			545.0 nm (night)	Background