Kaguya’s HDTV and Its Imaging

Overview of the HDTV System

In addition to Kaguya’s 13 science instruments, the HDTV was unique in being specifically included to engage the public in the excitement of lunar exploration. Although other scientific cameras of Kaguya, such as the Terrain Camera and Multiband Imager, were designed to acquire high-resolution images of the area around the nadir, HDTV was optimized for off-nadir observation, giving an astronaut’s-eye view of large areas of the lunar surface.

The HDTV system on board Kaguya was developed by NHK (Japan Broadcasting Corporation). The system was assembled from consumer broadcast equipment that was modified for the space environment. It consisted of a camera unit and a data processing unit (Figure 2.1). The HDTV system weighed 16.5 kg; it was 460 mm wide, 280 mm high, and 420 mm deep, and its maximum power was 50 W.

The HDTV included both a wide-angle camera and a telephoto camera. For color (RGB) imaging each camera had three separate Panasonic IT charge couple device (CCD) detectors 1.7 cm wide and 2.2 million pixels. Each CCD sensor consisted of $1,920 \times 1,080$ pixels with a pitch of $5 \times 5 \, \mu m$. The shutter speed of each camera was set either manually or automatically. In automatic mode the shutter speed for each frame was based on the measured brightness distribution of the previous frame.

All images taken by the cameras were digitally compressed (DCT-compressed within the frame) and recorded into two onboard flash memories. Each memory had a capacity of 1 GB, capable of storing 1 min of high-definition video images with the frame rate of $1/30 \, s$ in the standard $(1\times)$ mode (1,800 frames).
Figure 2.1 Outside appearance of HDTV instrument. The telephoto camera faces this side, and the wide-angle camera faces the opposite side. The box on the right houses the data processing unit (Image courtesy of NHK)
Imaging could also be accomplished in three interval-recording modes. At 2×, 4×, and 8× modes, 2-min, 4-min, and 8-min-long videos were obtained with the frame rate of 2/30, 4/30, and 8/30 s, respectively. With the wide-angle camera the interval mode 8× was generally used for lunar feature observation because coverage of the lunar surface was maximized (ca. 720 km in latitude direction). Apart from video imaging, the HDTV cameras were often used in a still mode. The HDTV cameras can take ten frames at minimum. This mode was useful when download time was limited, such as the period just before Kaguya’s impact.

The wide-angle and telephoto cameras slanted 22.5° and 18.5°, respectively, below the spacecraft’s orbit (Figure 2.2), aiming in the backward and the forward directions of orbital

Figure 2.2 Fields of view and areas imaged by the telephoto camera (left) and wide-angle camera (right) at an altitude of 100 km
motion. The pixel resolutions at the closest point to the Moon (that is, at the bottom of the frame), at the altitude of 100 km, was about 65 and 43 m in the across-track direction and 230 and 658 m in the along-track direction, for the wide-angle camera and telephoto camera, respectively. These are higher spatial resolutions than the Clementine UVVIS and most of the Lunar Orbiter’s photographs of the 1960s.

The mission data of the HDTV were transmitted to the ground system in Japan via the X band transmitter on Kaguya. Data for a 1-min-long video (about 1 GB) required 20 min to be transmitted to Earth at the rate of about 7.6 Mbps.

Operation

On the way to the Moon, the HDTV telephoto camera captured its first video image of Earth, at the distance of 110,000 km on September 25, 2007 (Figure 3.1). After Kaguya entered lunar orbit, the HDTV cameras started imaging in late October 2007.

Kaguya was in a polar orbit of about 2 h period. As it orbited, the Moon rotated 1° in longitude to the west, meaning that the spacecraft returned to the original longitude on the 360th orbit (30th day), and the angle of sunlight on the Moon’s surface had changed 30° by that time. Thus, the angle of illumination of topography by sunlight was repeated about 6 and 12 months later. The ascending node of Kaguya’s orbit was on the lunar dayside from January to June, and was on the nightside from July to December. Kaguya turned over its position by 180° every 6 months, in April and October, to keep its single solar panel pointed at the Sun. For these reasons, the wide-angle camera was aimed northward from April to June and from October to December, and pointed toward the south for the rest of year (Figure 2.3). Consequentially, the HDTV camera needed one full year to image all locations on the Moon under good lighting conditions and with a good pointing direction.

Images of Earthrise and Earthset

True Earthrise and Earthset cannot be seen from most of the lunar surface because Earth is nearly stationary when observed from the Moon. Earthrise and Earthset, in which Earth looks
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Figure 2.3 This shows the positional relationship of the Sun, Earth, Moon, and Kaguya spacecraft as seen from the north. Beta ($\beta$) is the angle between the Sun, Earth, and the orbital plane of Kaguya. Omega ($\Omega$) is the angle between Earth, the Moon, and the orbital plane of Kaguya. The arrows indicate the pointing direction of the wide-angle camera.

Because the phase of Earth changes continuously as seen from the orbiting Moon there were only two chances for the HDTV to capture a full Earthrise and full Earthset each year, November and April, respectively (Figure 2.3). Full Earth means that nearly 100% of Earth’s surface is illuminated by the Sun. The HDTV successfully captured a video of the full Earthrise over the lunar south pole on April 6, 2008 (Figure 3.6).

The HDTV also succeeded in capturing a “Diamond Ring” of Earth from lunar orbit on February 10, 2009 (Figure 3.6). This phenomenon occurs when Earth moves in front of the Sun as seen from the Moon. The Diamond Ring happens only when the outer edge of the Sun is not completely covered by Earth. For Kaguya’s image a penumbral lunar eclipse was...
seen from Earth. Although Kaguya experienced partial and total solar eclipses, the HDTV could not image them because electric power for most of the instruments was available only from the solar panels, which were in darkness during eclipses and could not store the electricity.

Images of the Moon

Because the wide-angle camera and the telephoto camera were slanted toward the bottom of Kaguya, the HDTV provided a bird’s-eye view of the Moon landscapes, always looking toward the horizon. From an altitude of 100 km the bottom line of the wide-angle camera image covers about 136 km on the Moon (Figure 2.2). This is wide enough to cover most large craters, including Tycho and Copernicus. On the other hand, Kaguya also has a powerful “terrain” camera, with a spatial resolution of 10 m and swath width of 35 km at 100 km
altitude. The Terrain Camera acquired stereo images that were used to produce a global topographic map of the Moon. Its images, though, are too detailed for most non-scientists. The resolution of the HDTV cameras is between good Earth-based telescopic images and Kaguya’s Terrain Camera images and is perfect for giving a true feeling for being in low lunar orbit.

Shadows help to define topography. Most slopes on the lunar surface are less than 30°, so conditions necessary for rich shadow imaging of the equatorial regions occur only in 4 months – January, June, July, and December – when the Sun is low in the lunar sky (Figure 2.3). During the other months, there were few shadows in equatorial areas, but they were plentiful in middle- and high-latitude areas, which were thus targeted for imaging. This resulted from the slant angles of the HDTV cameras so that when the Sun was obliquely behind the spacecraft, landscape features were seen with few shadows, and when sunlight shined obliquely in front of the spacecraft, the landscape was seen with dramatic shadows. Therefore, light conditions of the northern hemisphere and the southern hemisphere of the same latitudes are different (Figure 2.5a–c). The relative qualities (i.e., “good,” “moderate,” or “bad”) of the imaging conditions for different latitudes in both cases described above are listed in Table 2.1. We tried to select the optimum period to image each selected feature.

The number of HDTV images acquired each month is shown in Figure 2.6. During the nominal operation period of the scientific instruments (from December 12, 2007, to October 31, 2008), fewer than ten images per month could be taken because the HDTV camera’s priority was the lowest among all the mission instruments. But before and after that period, much imaging was able to be performed. Altogether, 616 videos and 21 still images of the Moon were taken; their coverage is shown in Figure 2.7 (below).

Still Images from HDTV

HDTV videos are spellbinding but do not translate easily into still images. Two methods were employed to create images for this book. Dr. Rie Honda of Kochi University introduced the first method. A video sequence of HDTV contains 1,800 frames, each 1,080 pixels high by 1,920 pixels wide. Dr. Honda selects one specific horizontal line 1,920 pixels
Figure 2.5 (a) *Above*: Relations between *Kaguya*’s orbits and the Sun’s elevations. (b) *Above right*: Crater Meton (70°N), Sun elevation 20°; wide-angle camera facing the north pole. (c) *Below right*: Crater Neumayer (70°S), Sun elevation 20°; wide-angle camera facing the equator.
wide for every image. When these specific lines from 1,800 images are placed one above the other, a rectangular image of 1,920 pixels by 1,800 pixels results. If this image is stretched in the appropriate ratio, an image such as Figure 2.8a results. Such images are excellent to show the coverage of Kaguya’s HDTV and as an index to Kaguya HDTV videos.

The second method, conceived by one of the authors (Shirao), is simpler than the first one. The bottom part of an HDTV image continuously disappears as Kaguya moves above the lunar surface. To create a still image Shirao chose one image first, then connected it to the lower part of the previous image (Figure 2.8b). Then he would magnify the connecting image to match the scale of the bottom part of the first image. The magnification ratio is different horizontally and vertically, because the look angle changes gradually when approaching the topography. This action was repeated several times using Photoshop CS4, producing the “wide-view” images as in Figure 2.8c. This piecing together of strips from subsequent video frames accounts for the stair-step edges of the images in this atlas.

Strictly speaking our “wide-view” still images have several faults. Their look angle is a little different from the true one. Although magnification of each segment is constant on wide-view images, magnification of real wide-angle images changes gradually. Additionally, some pixels overlap or may be missing at the junctions in the wide-view images. Despite all of these defects, our wide-view images provide spectacular astronaut-eye panoramas of 100-km-wide swaths of lunar topography all the way to the horizon.

Table 2.1 Light condition of HDTV wide-angle camera

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G: good; M: moderate; -: bad
Figure 2.6 Kaguya HDTV imaging per month. HDTV acquired most of its imaging after the nominal mission was completed in 2009.
Figure 2.7 Yellow rectangles depict coverage of movies by wide-angle camera; blue boxes mark still images by wide-angle; and purple ones are movies by telephoto camera (Image courtesy of R. Honda)
Figure 2.8 (a) An example of strip images created by Honda’s method. (b) A sequence of trimmed images to create a wide-view image.
Figure 2.8 (c) finished wide-view image by Shirao’s method