Development and Flight Testing of an Onboard Video System for the KSLV-I

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Korea Space Launch Vehicle-I (KSLV-I) carrying the STSAT-2A satellite, made its maiden flight on August 25, 2009. Liftoff was from the Korea Aerospace Research Institute (KARI) launch site at the Naro Space Center in a southern coastal province of the Korean peninsula. A video telemetry system provided visual monitoring of flight critical events, as well as dynamic moving images, through two cameras equipped on the upper stage. This paper describes the development of the onboard video system consisting of two video cameras, a video compression unit and an RF transmitter meeting the requirements of the KSLV-I launch vehicle. During the flight, the ETTARS, an especially reconstructed small telemetry ground station for the KSLV-I, received the video telemetry data and simultaneously measured automatic gain control (AGC) signal levels from the receiver. The onboard video system achieved a 15fps video rate, flew with a 2Mbps data rate and transmitted data using NRZ-L PCM/FM in the S-band. Errors on real telemetry channels occurred as predicted by link budget equations based on thermal noise and multipath interference. According to error analysis, the BER versus SNR performance degradation from the laboratory reference was about 1dB, which is close to expected limit.

Key Words: Video Telemetry, KSLV (Korea Space Launch Vehicle), Flight Test

1. Introduction

Gathering rocket performance data has always been an important part of the launch process. Acceleration, audio, shock, temperature and vibration transducers have successfully been used to acquire vehicle performance data during the flight. While these transducers often provide adequate information, there are occasions when “a picture is worth a thousand words.”13

There has been a series of sounding rockets launched after the first launch in 1993 by the Korea Aerospace Research Institute (KARI) in South Korea. Korea Sounding Rocket (KSR)-I and KSR-II were developed to use a solid propellant system and KSR-III was developed to use a liquid propulsion system. With these sounding rockets, some scientific studies including ionospheric and ozone density profiles were obtained over the Korean peninsula.21 In the KSR series, onboard flight images have never been telemetered because the rockets were not equipped with onboard cameras. However, an onboard video system was developed for the Korea Space Launch Vehicle (KSLV)-I to monitor important flight events as well as dynamic motion inside the field of view (FOV) of the cameras in real time. The KSLV-I is the first Korean satellite launch vehicle launched at the Naro Space Center on August 25, 2009.

The configuration of the KSLV-I is shown in Fig. 1. The launcher consists of the first stage using a liquid propellant engine and an upper stage using a solid propellant engine. The mission of the upper stage is to inject the Science Technology Satellite (STSAT)-2A into a dedicated orbit at 300km x 1500km. For this objective, the domestic upper stage has numerous parts including a nose fairing system, an inertial and navigation system, an attitude control system, an electronics system and a flight termination system.21 As part of the electronics system, an onboard video system is placed on the upper stage. The purpose of this system is to monitor key flight events, including stage separation and the burning of the solid motor, through a downward-facing camera. It is also capable of acquiring critical images of the nose fairing jettison and payload separation from the upper stage using a camera that faces upwards.

In this paper, we introduce the development of the onboard video system for the KSLV-I. This system consists of two cameras, a video compression unit (VCU) and a radio frequency (RF) transmitter. To improve our own technologies, development was conducted applying by a series of procedures including requirements generation, conceptual and detail design, manufacturing and qualification testing using domestic technologies. Various environmental tests were also carried out at component and system levels before the video system was mounted on the KSLV-I. In the ground station, to receive the upper-stage instrumentation data and video data during the launch, a small-sized auto-tracking antenna system was reconstructed. This paper presents the establishment and operational results of a telemetry ground station with modern and traditional equipment. It then describes the flight test results, such as the occurrence of data errors according to the measured RF power levels, bit error rate (BER) versus signal-to-noise ratio (SNR) performance characteristics, flight images acquired from the onboard video cameras, and so on.
2. Onboard Video System

2.1. Overview

Design requirements of the video system were set from various launch constraints, and then design schemes and technologies were optimally adopted to develop each of the components. State-of-the-art technologies were used to monitor the launch process images as good as possible from the telemetry station.

It was necessary to apply the National Television System Committee (NTSC) system, which is the standard television format for South Korea, for the video signal system. The video camera acquires moving images with the NTSC signal under unknown brightness and color temperature levels. Because the camera lens looks toward the sun or dark space under unpredictable circumstances, the onboard camera also requires automatic exposure (AE) and automatic white balance (AWB) functions.

Video data has to be transmitted inside the 3MHz RF bandwidth in the communication link for the two camera signals at the same time. It is impossible to transmit two video signals using the analog frequency modulation (FM) method in the allocated bandwidth. Therefore, the VCU must use an image compression algorithm. Among the several compression technologies available, we adopted the Joint Photographic Experts Group (JPEG)-2000 standard, which has good error resilience in the link-drop condition for the video system.

For wireless communication applications using compressed video data, which is highly sensitive to even minor error, it is necessary to apply a channel coding scheme with a powerful burst-noise error correcting code. After inserting this excellent error correction code, an interleaving scheme is needed to allow for the correction of longer bursts. Meanwhile, before the pulse code modulation (PCM) data stream is modulated at the RF transmitter, a pre-modulation filter (PMF) is commonly used to reduce the energy contained in the sidebands of the modulated spectrum. Most existing filters are based on a constant cut-off frequency specification with 0.7 times the data rate. In the case of the VCU, a variable bandwidth PMF is included because we determine effective responses to very unusual circumstances, such as the change in PCM bit rate during the long-term development period.

The RF transmitter should modulate the filtered-out signal into the S-band frequency and amplify the modulated signal above 20 watts. For a simple modulation scheme, we adopted the direct FM modulation method for the unit. In addition, phase-lock loop (PLL) technique should be used to maintain excellent frequency stability with the temperature-compensated crystal oscillator (TCXO). Multistage driving and power amplifiers are utilized to obtain a high RF output.

Figure 2 shows the functional block diagram of the onboard video system. The VCU receives NTSC video signals from each camera and compresses using JPEG-2000 image coding technology. Then, signal processing such as video multiplexing, channel coding and pre-modulation filtering are accomplished inside the VCU. The RF transmitter modulates the filtered-out signal using the FM method and amplifies it with high power. Table 1 presents the key features of the onboard video system for KSLV-I.

2.2. Video camera

The onboard video camera has been developed to satisfy several design requirements as previously discussed. Figure 3 shows the functional block diagram of the camera that outputs a NTSC composite signal. It consists of a closed circuit television (CCTV) lens, a charge coupled device (CCD) sensor, a dedicated camera digital signal processor (DSP), a

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Table 1. Features of the onboard video system for the KSLV-I.

<table>
<thead>
<tr>
<th>Items</th>
<th>Key features</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Camera set</td>
<td>1 set facing upward</td>
<td></td>
</tr>
<tr>
<td>Field of view</td>
<td>57deg(H) x 44deg(V)</td>
<td></td>
</tr>
<tr>
<td>Camera signal system</td>
<td>NTSC standard</td>
<td></td>
</tr>
<tr>
<td>Video compression</td>
<td>JPEG-2000 algorithm</td>
<td></td>
</tr>
<tr>
<td>Bit rate</td>
<td>2Mbps</td>
<td></td>
</tr>
<tr>
<td>Bit representation</td>
<td>NRZ-L</td>
<td>IRIG</td>
</tr>
<tr>
<td>Data modulation</td>
<td>PCM/FM</td>
<td></td>
</tr>
<tr>
<td>Channel encoding</td>
<td>RS(255,223)</td>
<td>CCSDS</td>
</tr>
<tr>
<td>Randomizing</td>
<td>Pseudo-randomizing</td>
<td></td>
</tr>
<tr>
<td>Modulation bandwidth</td>
<td>3MHz</td>
<td></td>
</tr>
<tr>
<td>Peak deviation</td>
<td>+/-700kHz</td>
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<tr>
<td>RF frequency</td>
<td>2.2GHz to 2.3GHz</td>
<td>S-band</td>
</tr>
<tr>
<td>RF output</td>
<td>20W</td>
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Fig. 2. Block diagram of the onboard video system for the KSLV-I.
timing generator, a CCD signal amplifier, a bias generator and a power regulation device.

The CCD device is an interline solid-state image sensor suitable for NTSC color video cameras. It also has the features of 768(H)x494(V) effective pixels and a diagonal 8mm (Type 1/2) system with high sensitivity, low smear, low dark current, excellent anti-blooming characteristics and so on. The CCTV lens has a FOV of 57deg(H)x44deg(V) and a focal length of 6mm. Prior to mounting the camera on the launcher, the manual focus and mechanical iris of the lens are properly set and frozen. The timing generator is to generate and control all the timing signals of the camera. It controls the clock timing for electronic shutter speeds from 1/60sec to 1/100,000sec under DSP chip command in real time. In addition to basic camera signal processing functions, the dedicated camera DSP chip has an AE function, an AWB detection circuit and a synchronized signal generation circuit. It is capable of carrying out peripheral chip communication functions and controlling picture quality at 60Hz. As only luminance and chrominance (Y/C) components are handled by the DSP chip, an additional synthesis circuit creates the NTSC composite signal.

Figure 4 shows the onboard video cameras developed, including lamps and fixtures. There is a difference in fixture shape between two cameras because each is mounted at a different site. Each camera has a lamp in order to view internal images just before separation events, as the upward-facing camera is placed inside the nose fairing and the downward-facing camera is placed inside the interstage part. To protect each camera from shock environments, an absorber made of a rubber material was inserted between the camera body and fixture. The use of video-simplified IC chips and flexible PCBs has made it possible to design and manufacture a compact onboard camera.

2.3. VCU

Image compression is performed using a JPEG-2000 algorithm that has an intraframe image compression standard with good error resilience. Considering real-time processing, the low cost and simple configuration, a dedicated single-chip JPEG-2000 codec is used for each channel. The codec provides compression functions using a 32-bit reduced introduction set computer (RISC) processor as the system controller, a wavelet conversion engine, three entropy codecs, a built-in memory system and so on.

Following two independent image compressions, the video multiplexing and channel coding procedures are carried out as shown in Fig. 2. The channel coding scheme is comprised of four parts with an (n,k) Reed-Solomon (RS) encoder, an interleaver, a pseudo-randomizer and an attach sync marker (ASM). Table 2 shows the parameters and values of a (255,223) RS code implemented by the VCU. As each symbol is set to 8 bits, the number of symbols for an RS code block is calculated to be 255 symbols. The error correction capability for an RS code block is defined as 16 symbols. So an RS code block has 32 symbols for parity check and 223 symbols for information data. This means that if there are up to 16 symbols in the error data in an RS code block including the parity check data, an RS decoder can find the locations of the error symbols and correct all of the data errors.

Figure 5 shows the frame format for data transmission. First, there is a 4-byte frame synchronization code called ‘Frame Sync’. The transfer frame heading a ‘Frame Sync’ has a constant 1020-byte stream length that is rearranged with four RS code blocks, also called sub-frames according to interleaving depth 4.

The variable cut-off frequency PMF is comprised of a finite impulse response (FIR) digital filter, a digital-to-analog

| Table 2. (255,223) RS code parameters for the video data. |
|-----------------|-------------------|------------------|
| Items           | Values            | Description      |
| J               | 8 bits            | Number of bits for a symbol |
| n               | 255 symbols       | Number of symbols for an RS code block(2^1-1) |
| E               | 16 symbols        | Error correction capability for an RS code block |
| 2E              | 32 symbols        | Number of symbols for a parity check |
| k               | 223 symbols       | Number of information symbols for an RS code block(n-2E) |

Fig. 3. Functional block diagram of the video camera for the KSLV-I.

(a) Upward-facing camera  (b) Downward-facing camera

Fig. 4. Video cameras with lamps and fixtures for the KSLV-I.
conversion (DAC) block and a tunable 2\textsuperscript{nd}-order low pass filter (LPF) as shown in Fig. 6. It was designed and analyzed for each stage to satisfy the linear phase characteristics and magnitude frequency response of a 7\textsuperscript{th}-order Bessel LPF. When the PCM bit rate is changed, the cut-off frequency of the PMF is changed by a software programming function. The cut-off frequency of the FIR filter and DAC block is changed when the clock speed updates, and the cut-off frequency of the 2\textsuperscript{nd}-order LPF is changed when the voltage control parameter (\(V_c\)) configuration is updated. Figure 7 shows an external view of the VCU developed.

2.4. RF transmitter

An RF transmitter for video transmission has been developed in order to prevent interference with the second-stage telemetry and first-stage telemetry frequency, complying with Inter-Range Instrumentation Group (IRIG) standard.\(^3\) This component consists of four main parts, which include an FM modulation part, a driving amplification stage, a power amplification stage and a power-supply part. Each part is isolated by physical walls to prevent electromagnetic interference noise from transferring to another part. The block diagram of the RF transmitter is presented in Fig. 8.

The modulation part generates the center frequency in the S-band and modulates the filtered signals with the direct FM method using a voltage controlled oscillator (VCO). The PLL technique with a TCXO is used to maintain good frequency stability because the frequency of the VCO can drift easily under a variety of external environments. Frequency response was designed to within +/-1.5dB from 100Hz to 2MHz as alternating current (AC) coupling, and the deviation sensitivity was set to +/-350kHz/Vpp.

The three-stage driving amplification part boosts the VCO output signal up to the allowable power amplification level in the power amplification stage. The power amplification stage uses an amplifier, an isolator and a LPF to amplify the output to a sufficiently high level using an input/output matching circuit and an isolation circuit for protecting the reflected wave, etc. Figure 9 shows an external view of the RF transmitter for video transmission.
2.5. Qualification testing

Integrated functional testing was performed in a laboratory after component development of the onboard video system. Figure 10 shows a block diagram of the video test equipment (VTE) used for verification and evaluation. This ground equipment receives and decodes the compressed video data from the RF transmitter and displays the camera images. The VTE consists of a radio telemetry receiver (RTR), a video expansion computer (VEC) and a display component. There are major functions such as S-band RF reception, FM demodulation and bit synchronization in the RTR. The VEC has digital processing functions with forward error correction (FEC), video demultiplexing and JPEG-2000 decoding. FEC functions include reverse-pseudo randomizing, reverse-interleaving and RS decoding. Finally, two onboard camera images are displayed simultaneously on a computer screen.

Following functional testing of the video system, we carried out a variety of environmental tests according to the qualification level. They include hot and cold temperature tests, a vacuum test, pyro and half-sine shock tests, sinusoidal and random vibration tests and an electromagnetic compatibility (EMC) test.\(^{(2)}\) In the case of the EMC test, the components were applied at the space and launch vehicle level equivalent to MIL-STD-461E standards. Especially, the susceptibility test was performed in order to verify onboard video system function under the power level of the onboard transmitting sources. The radiation level of the video system was also precisely measured at the operation frequencies of the onboard receiving units.

3. ETTARS

A novel auto-tracking antenna system known as the Electronics Team’s Telemetry Auto-tracking Receiving System (ETTARS) was constructed to receive telemetry data and video data from the KSLV-I. An earlier antenna system was used as a mobile tracker system in several flight tests of the KSR series from 1993. However, most data-processing equipment except for the antenna assembly with antenna body and dish and the antenna controller were out of date and very inefficient. The latest equipment, smaller but more powerful, have replaced the old-fashioned devices. Figure 11 shows a block diagram of the ETTARS for the KSLV-I.

The Mini-Tracker control console in the antenna control room is still useful as a self-contained control unit that provides all of the power and driving signals necessary for the pedestal. The VTE with the RTR and VEC described in a previous section are utilized for video data processing in the ETTARS. The RTR has dual independent receiving channels, each with a set of RF front-end receiver, FM demodulator and bit synchronizer. Therefore, one channel of the RTR is used for receiving onboard video data and the other one is used for receiving upper-stage telemetry data. To extract, visualize and save measurement data from the upper stage, a Telemetry Test Set (TLMTS) notebook was created. AGC signals of the RTR are measured at 800Hz sampling rates for each channel. The AGC signals vary from 0V to +5V. This voltage means the RF power received from -110dBm to -10dBm. A camera at the edge of the antenna dish and a monitor in the control room were installed to view the direction the antenna moves to track the rocket. Figure 12 shows the antenna assembly of the ETTARS installed at the space center. Behind the antenna assembly is the launch pad of the KSLV-I on the flat ground of the mountainside. The antenna system uses a single-channel monopulse RF feed assembly with a six-foot mesh dish parabolic reflector.\(^{(15)}\) The tracker and feed assembly are designed to receive signals in the S-band range between 2200MHz and 2300MHz. The gain of the antenna for these frequencies is about 29.5dB. The 3dB beamwidth at 2200MHz is 5deg. It has a maximum slew speed of 30deg/sec, a maximum acceleration of 100deg/sec/sec, and a tracking accuracy of 0.1deg rms.
4. Flight Test Results

The onboard video system operated normally under the random and sinusoidal vibrations, and various temperature and vacuum environments during the flight. In the case of vibrations and temperature, measurements were taken at much lower levels than the qualification levels of the ground environmental test with 20G rms random and 12G sinusoidal vibration, and a hot temperature level of +70 degrees Celsius. For example, the box skin temperature of the RF transmitter was about +50 degrees Celsius at the end of the mission. Video telemetry data was transmitted using PCM/FM for the first flight and the AGC levels were recorded in the ETTARS. The AGC time constant was set at 0.1ms to capture as much data as possible. The AGC voltage samples were converted to the received power levels using a point-slope approximation obtained from a calibration procedure. The result is plotted in Fig. 13. The received RF level of the solid line has a similar trend, as a whole, when compared with the expected RF level shown by the dashed line.

From T0 (liftoff) to about T0+15s, the ETTARS antenna tracked the vehicle in manual mode because the antenna could not track in automatic mode around the time of liftoff due to low elevation angle, multipath interference, etc. The antenna elevation angle was -1deg at liftoff and +14deg at T0+15s, after which the antenna tracked the rocket in automatic mode throughout the end of the flight. Note that there were great fluctuations in both elevation and azimuth angles, from T0+75s to T0+140s, as the result of multipath interference derived from vapor trails. Therefore, the received power levels also varied with wide-ranging values, as shown in Fig. 13. After that, there were important events such as the nose fairing jettisoning at 216s and separation of the first and upper stages at 233s. Figure 14 illustrates the occurrence of frame synchronization (SYNC) errors per second of the video stream received. The noise floor for the RTR used was specified at -90dBm, and this point means the SNR is equal to 0dB. As the SNR decreased below 10dB, the number of frame SYNC errors increased rapidly.

The relation between the measured RF levels and data errors was analyzed in detail for only 5s over the fluctuation periods of the ETTARS antenna. The result is illustrated in Fig. 15: (a) received signal levels, (b) number of sub-frame errors per 0.1s, and (c) number of SYNC errors per 0.1s. The jumps in the error count indicate the occurrence of errors, and coincide in time with the drop in received signal level at the rate of about 3Hz. Nothing happens in any of the SYNC errors. The number of sub-frame errors is smaller than 25EA while the total number of sub-frames per 0.1s is about 97EA. In addition, the sub-frame error has normally just 1-byte for each sub-frame, 255 bytes. This means that the number of data errors is fairly infrequent, such as a maximum of about 25 bytes per approximately 24,735 bytes (255x97) for 0.1s during the level drop. Therefore, in the case of these data errors, it is acceptable that the occurrence of a sub-frame error of 1-byte was induced by a 1-bit error. Of course, all sub-frames of this figure where errors occurred could be corrected because a (255,223) RS decoder has the capability to correct errors up to 16 bytes per sub-frame.

Figure 16 illustrates the occurrence profiles of data errors when the SNR decreases from 15 to 7dB for about 40s: (a) SNR, (b) number of sub-frame errors per 0.1s with the first right axis, (c) number of byte errors per 0.1s with the second right axis, and (d) number of SYNC errors per 0.1s with the first right axis. It is clear from this figure that the occurrence of sub-frame errors and byte errors is much more sensitive to SNR values below 10dB. Additionally, we recognize that the number of SYNC errors starts to increase gradually when the SNR decreases below 10dB.

The BER versus SNR performance characteristics of the first flight are illustrated along with the experimental results conducted in laboratory in Fig. 17. In the well-designed non-return to zero level (NRZ-L) PCM/FM video system with a peak deviation equal to 0.35 times the bit rate and intermediate frequency (IF) bandwidth equal to 1.5 times the bit rate, a SNR of approximately 13dB resulted in a BER of $10^{-5}$. The experiment in the laboratory gives a reference performance under a stable environment without any wireless disturbance. The degradation from the reference performance for the first flight is about 1dB. The video system performed
very closely to the reference limit on the real telemetry channel.

Figure 18 shows the liftoff moment of the first flight of the KSLV-I climbing from the launch pad at the Naro Space Center. Some flight images from onboard video cameras are presented in Fig. 19: (a) downward image when stage separation started, (b) downward image after the ignition of the second-stage engine, (c) upward image when fairing jettison started, and (d) downward image viewing the satellite separated from the second stage.
5. Conclusion

An onboard video system consisting of two video cameras, a VCU and an RF transmitter was developed to meet many design requirements for the KSLV-I, the first Korean satellite launch vehicle. A robust CCD color video camera in a small package provides high performance utilizing a specialized camera DSP chip. A VCU including JPEG-2000 image compression allows the user to select the video frame rate and video quality. Additionally, the compression unit gives the system powerful forward error correcting ability and a variable cut-off frequency pre-modulation filtering scheme. An RF transmitter with a 20W output modulates the filtered video data with excellent frequency stability using PLL and TCXO. Environmental tests such as vibration, shock, vacuum, temperature and EMC were carried out at component and system levels before the flight testing. The ETTARS, a small telemetry ground station, was constructed to receive upper-stage instrumentation data and video data during the launch.

The KSLV-I, carrying the STSAT-2A satellite, lifted off on August 25, 2009, at 5:00 p.m. (KST). Liftoff was from the KARI launch site at the Naro Space Center in a southern coastal province of the Korean peninsula. The video telemetry system provides visual monitoring of flight critical events as well as dynamic motion through the use of upward-facing and downward-facing cameras at the same time. The onboard system achieved a 15fps video rate, flew with a 2Mbps data rate after (255,223) RS coding and transmitted data using NRZ-L PCM/FM in the S-band. The ETTARS received upper-stage instrumentation data in a 1MHz IF bandwidth and video data in a 3MHz IF bandwidth, and measured the AGC signal levels. Bit errors for the first flight test occurred in bursts and randomly. The number of sub-frames errors was 111,355EA throughout the receiving sub-frames. The number of sub-frame errors below 16 bytes per sub-frame was 81,820EA, and these were corrected perfectly by correcting 462,731 bytes. Therefore, the proportion of corrected sub-frames to total sub-frame errors is about 73%. By analyzing errors, we have also recognized that the BER versus SNR performance degradation from the laboratory reference is about 1dB, which is close to expected limit on the real telemetry channel.

References