Replacing 16 mm Airborne Film Cameras with Commercial-Off-The-Shelf (COTS) Digital Imaging

By Kris Balch,
EASTMAN KODAK COMPANY,
Motion Analysis Systems Division, San Diego, California

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ABSTRACT

For many years 16 mm film cameras have been used in severe environments. These film cameras are used on Hy-G automotive sleds, airborne weapon testing, range tracking, and other hazardous environments. The companies and government agencies using these cameras are in need of replacing them with a more cost-effective solution. Film-based cameras still produce the best resolving capability. However, film development time, chemical disposal, non-optimal lighting conditions, recurring media cost, and faster digital analysis are factors influencing the desire for a 16 mm film camera replacement. This paper will describe a new imager from Kodak that has been designed to replace 16 mm high-speed film cameras. Also included is a detailed configuration, operational scenario, and cost analysis of Kodak's imager for airborne applications.

The KODAK EKTAPRO Imager RO Imager is a high-resolution color or monochrome CCD Camera especially designed for replacement of rugged high-speed film cameras. The RO Imager is a record only camera. It features a high-resolution [512 x 384], light-sensitive CCD sensor with an electronic shutter. This shutter provides blooming protection that prevents "smearing" of bright light sources, e.g., camera looking into a bright sun reflection. The RO Imager is a very rugged camera packaged in a highly integrated housing. This imager operates off +28 VDC. The RO Imager has a similar interface and form factor is that of high-speed film cameras, e.g., Photosonics 1B. The RO Imager is designed to replace 16 mm film cameras that support rugged testing applications.

1. REQUIREMENT REVIEW

The Motion Analysis Systems Division of Eastman Kodak Company has been a supplier of high-speed video systems, for many years, to the US Government, DOD and various branches of the Armed Forces. In recent years, we have concentrated on understanding the imaging needs of the Range and Airborne Customer (ref. Photos on following page). Our understanding of these imaging needs is set within the context of replacing 16 mm film cameras with electronic imaging. The targeted film cameras are the Photosonics 1B, 1PL, and Stallix. Our understanding is as follows:

Value Drivers

- ❑ governmental mandate for reducing chemical film processing
- ❑ shorter time to view test results & need to facilitate faster data reduction of images
- ❑ improve the reliability of image content during an exercise with pre/post quick views
- ❑ direct electronic distribution of image data to multiple analysts or labs
- ❑ improve equipment reliability [no mechanical shutters or pin feeds]
- ❑ ease of rerunning a test if necessary [goof tolerant image capture]
- ❑ reduce skill level for setting up cameras & operating cost
- ❑ a camera that can serve multiple branches of the service will leverage their buying power for greater volume

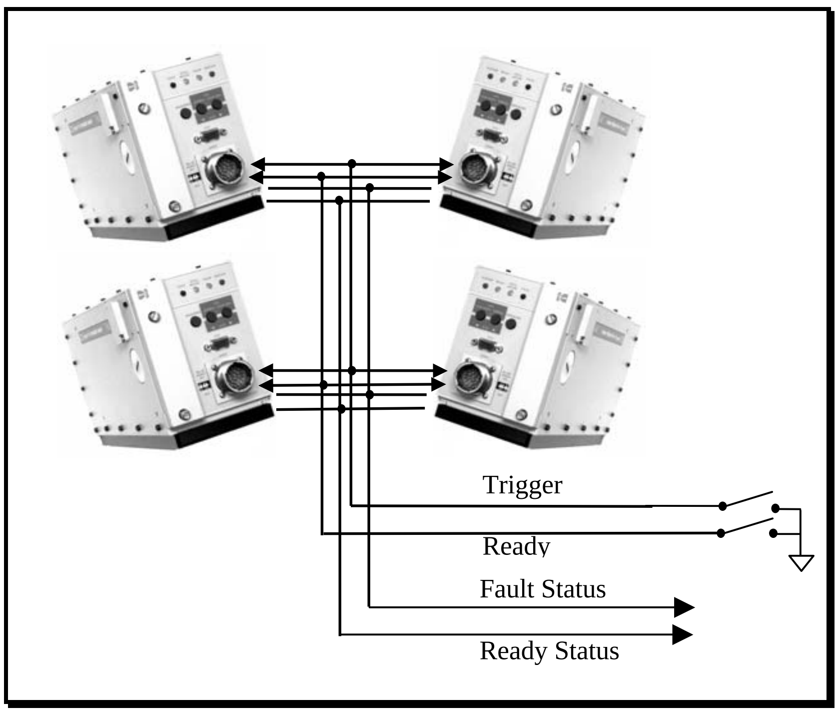
Customer Needs

- similar weight and size of current film cameras with a simple interface for dependable setup
- resolve 0.25 in. at 6 ft. or as close to this measurement as possible
- no loss of images or malfunction of the camera during Hi-G forces or high vibration
- multiple camera interface wiring needs to fit through 1-2 in gussets
- 10 second record time at 200 to 400 fps
- color is important for some users
- an event marker is an important feature and cameras need to be synchronized to IRIB B
- controls, cables, and storage devices need to exit the rear of the camera
- meet the wide range of environmental requirements [E.I. temp, shock, humidity]

2. INTRODUCTION

The KODAK EKTAPRO RO Imager is a stand-alone camera built into a thirteen pound, 4.3 x 5.5 x 12 inch housing, designed specifically for replacement of high speed film cameras. It produces high-resolution digital color or monochrome images that provide the features required for replacing Hy-G film cameras. Image playback and analysis can be performed on desktop computers. The RO Imager is a more efficient design because the playback function has been moved out of imager to the desktop computer. The imager also has the ability of displaying images LIVE at the record rate for ease of setup.

RO Imager stands for record only. The imager records up to 1000 full frames per second. It features a high-resolution, light-sensitive CCD sensor with an electronic shutter. This shutter provides blooming protection that prevents "smearing" of bright light sources, e.g., the imager looking into a spectral reflection. The RO Imager is a very rugged camera packaged in a highly integrated housing. This imager operates off +28 VDC. This imager has a redundant memory system that assures images can be archived during flight operations. The RO Imager is the same size as the most widely used 16 mm film cameras. Recorded digital images are read through a fast serial interface or a removable storage module. The RO Imager is controlled through a simple dedicated hardwired interface, an RS-485 interface, or a 10BaseT Ethernet interface. The RO Imager is a cost-effective replacement for high-speed film cameras.



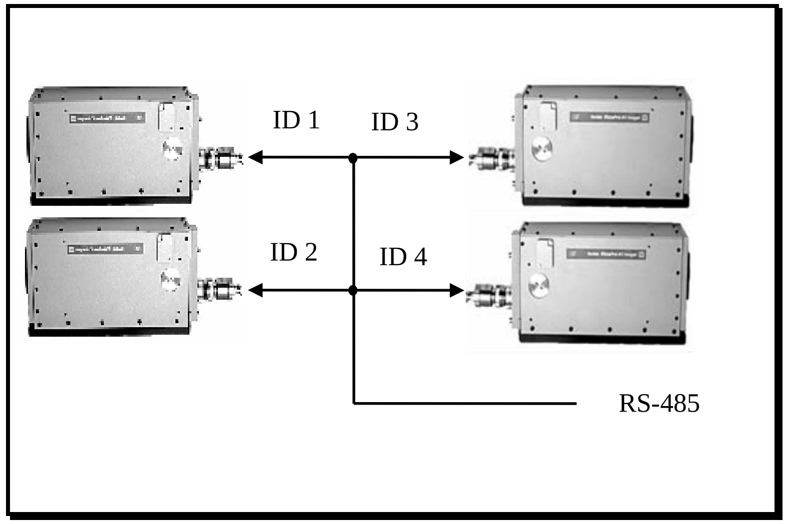
The RO Imager design is based on Kodak's high-resolution interline CCD sensor. The sensor resolution is 512 x 384. The pixels are 16 μm x 16 μm square. The pixel pitch is the same in both horizontal and vertical directions. This square pixel pitch is ideal for computer-aided image analysis. The color sensor has a color filter array [CFA] deposited on the surface. The CFA that is arranged in a Kodak proprietary matrix, is called Bayer. A Bayer pattern consists of a blue, green, red, green pixel arrangement in a 2 x 2 matrix. After capture, the images are processed through a Bayer Color Algorithm on a computer to produce 24-bit color images of superb quality. The RO Imager is also available with a monochrome sensor for higher resolving power and light sensitivity.

The RO Imager can capture either 512 frames or, with optional memory, 1024 frames. The RO Imager digitizes the captured image to eight bits and stores the image data into internal DRAM memory. All RO Imagers that have 512 frames may be upgraded to the optional 1024 frames. Whether the imager has 512 frames or 1024 frames, it is the same size.

The RO Imager is designed to operate similar to a film camera. Prior to recording, the RO Imager is in sleep mode or standby. A signal is sent to the imager to wake it up from a low-power state to a ready-to-record state. The time from standby to ready mode is two seconds. This two-second delay assures that the CCD sensor, imager electronics, and communication are all in sync. After the imager is in the ready mode, a trigger signal will start recording. The first image recorded will be frame 0. The imager continues recording until the end of memory. The images are now in memory. The RO Imager can be programmed to automatically download the images to a removable flash disk (solid state). Otherwise, the RO Imager will wait in a hold mode until instructed to download the images.

The RO Imager has three methods for communicating. The simplest is a hardwired interface shown on the next page in a multiple unit configuration. This interface provides hardwired control of the imager without the use of a computer. The RO Imagers can be bussed together with the lines as a wired-or network. In this networked configuration, all imagers can be initialized and triggered. The Imager status can be monitored from a common set of lines that indicate each imager's state by their DC voltage.

The second method of communicating with the imager is the RS-485 interface. The RS-485 interface is used to configure and control the imager. The RS-485 serial interface can be bussed together for networking multiple imagers. Some RS-485 commands are global, meaning all imagers recognize the command at the same time. Other commands will require addressing individual RO Imagers through the RS-485 interface.



The RS-485 interface when bussed is shown in the figure to the right. Imagers are uniquely identified by the ID programmed by the user. The RS-485 interface can be driven from a PC using a RS-485 card. The distance that can be driven is over 4000 feet.

The third interface is an optional 10BaseT Ethernet physical link. This interface also networks imagers together to a common cable. An Ethernet Hub needs to be attached to each physical cable in order for the local network to communicate with the imager. Commands or Images can be transferred through the high-speed serial interface to the imager.

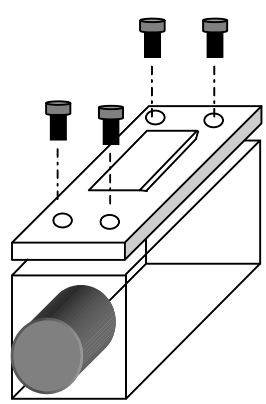
The RO Imager is shown in the photo to the right. The RO Imager has one main connector. All system power, hardwired signals (Ready, Trigger, Ready Status, and Fault), RS-485, Ethernet, and wired-or fault indicators are through this connector. This connector is a round military style.

3. TECHNICAL APPROACH

The RO Imager has been designed for extreme environments. The operation of the RO Imager is similar to that of the 16 mm film cameras. This similarity will enable the transition from airborne film cameras to a commercial-off-the-shelf (COTS) solution for digital imaging. The RO Imager is the COTS solution for airborne separations imaging. Described below are the technical details for implementing the RO Imager as an airborne camera.

Mounting & Wiring

The RO Imager uses the same mounting holes as the Photosonics 1B camera. However, the airborne applications use the Photosonic 1PL camera and dovetail mount. Therefore, a simple adapter plate with a flanged dovetail and mounting holes that match the RO Imager will allow existing mounts to be used. Shown below is the simple drawing of such a plate.

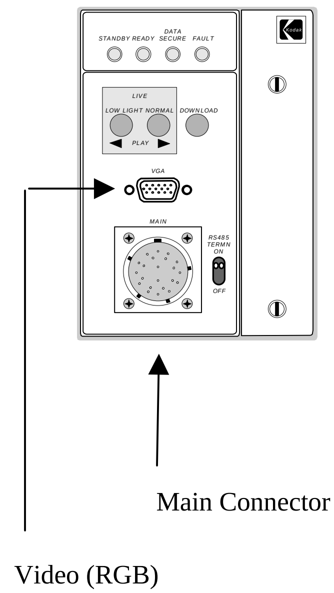


The RO Imager adapts to either a C-mount or a box mount for the lens. Both of these lens mounts can support a lens cage. A lens cage will constrain the lens to remain at the initial lens settings while in Hy-G airborne flight. The four holes on the front of the RO Imager are used to attach the box mount. These same holes can be used to attach a custom lens cage.
The RO Imager has a removable access door on the rear panel. This door is used to access the removable flash disk. To assure that the door remains in place during flight, the retaining screws should be drilled and locked in position with wire.
Multiple RO Imagers are designed to be controlled through a simple four-wire interface. For the airborne application, this interface can be simplified to a two-wire interface. This interface and power are distributed through a single connector.

Imager Connector

This connector carries Imager primary power, serial control, Ethernet connections, status lines, external sync input, Ready command input, and Trigger command input. However, for an airborne application, not all of these signals are required. There are several possible wiring configurations applicable for airborne imaging with multiple cameras. Shown below is the full wiring configuration for the electrical connection to the RO Imager.

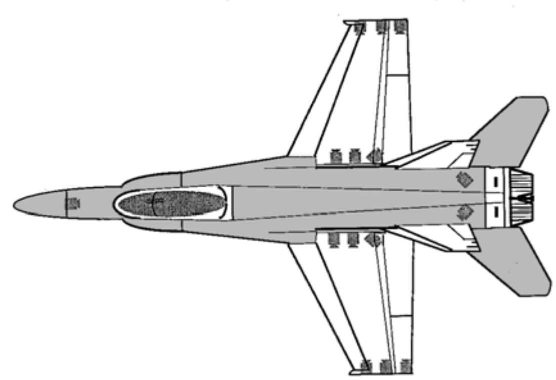
Pin	Signal Name	Function
T	Ethernet Rx +	Ethernet receive and transmit lines. The Ethernet connection is 10Base-T using TCP/IP protocol. RO Imagers respond to the ASCII command set. RO Imagers, D-Boxes, J-Boxes, and their host computer must use a dedicated Ethernet network. No other devices should be on the network.
B	Ethernet Rx -	
C	Ethernet Tx +	
U	Ethernet Tx -	
M	Exposure Out	TTL level output that is high as each frame is exposed.
Z	Exposure Out Return	
N	External Sync	Input a TTL low to high transition to record a frame when a RTE EXT command is in effect. See page 3.12 for details.
a	External Sync Return	
L	Fault Status	Outputs closure to indicate a fault has occurred that prevents the Imager from making a recording.
Y	Fault Status Return	
G	Ready	A TTL low or contact closure between these two lines puts the Imager in the Ready State. Trigger input starts a recording.
W	Ready Return	
K	Ready Status	A closure that indicates that a Ready command has been received and the Imager is ready to make a recording.
J	Ready Status Return	
F	RS-485 Rx +	RS-485 receive and transmit lines. A serial communications link that carries control commands from the user to the RO Imager via a D-Box and/or a J-Box. RO Imager's responds to the ASCII command.
V	RS-485 Rx -	
D	RS-485 Tx +	
E	RS-485 Tx -	
H	Trigger	A TTL low or contact closure input will start a recording if the Imager is in the Ready State.
X	Trigger Return	
P	Vbb (+28 VDC)	Primary power input.
R	Vbb (+28 VDC)	
A	Ground	Primary power ground.
S	Ground	
b	Transmit Enable	
c	Transmit Enable Return	



Example of a Configuration (Same connection as the 16 mm film cameras, Photosonic 1PL)
One of the most widely used 16-mm film cameras in airborne applications is the Photosonic 1PL. The wiring for Photosonic 1PL is shown below.

1PL	**Photosonic Camera**	**RO**	**Imager**	**Comments**
Pin	Function	Pin	Function	
A	28 VDC	P,R	28 VDC	
B	28 VDC Return	A,S, W	28 VDC Gnd & Ready Return	
C	Remote Start	G	Ready	Set RO Imager into Standby
D	115 VAC (heater)			No Connection
F	115 VAC Neutral (heater)			No Connection
N	115 VAC			No Connection
P	115 VAC Neutral			No Connection
K	IRIG B Hi			
U	IRIG B Lo			
J	IRIG B Shield			
S	Event Marker, 28 VDC	H	Trigger	Use to start recording
V	Event Marker, 28 VDC Ret	X	Trigger Return	
L	Case Ground			

Shown to the right is an F-18 with its standard placement of high-speed film cameras. The same placement will work for the RO Imager. Using the existing wiring is possible. However, the use of existing wiring depends on the change of assignment for the cable. Specifically, the 115 VAC is not required. The RO Imager does not have IRIG B input. However, the RO Imager can be synchronized to a time source. More will be discussed on this synchronization method in the next section.

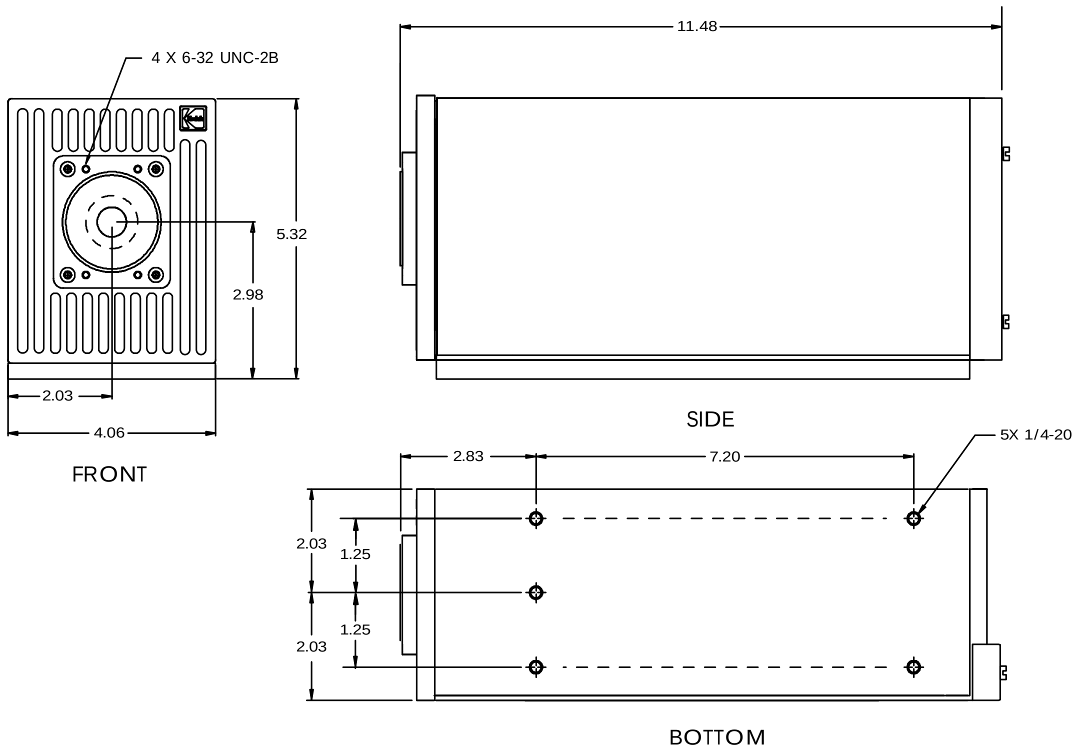


Communication with the RO Imagers is through either the RS-485 interface or the Ethernet interface. The RS-485 interface is best for commanding the RO. However, if images are to be downloaded to a central source for storage or playback, the Ethernet interface can support these functions, as well as control.

Communication to the RO Imagers can be accomplished through a dedicated PC. This PC is essentially a rugged industrial computer the size of a small computer.

4. PHYSICAL INTERFACE

Imager 13.5 lbs., Mounting plate 1.2 lbs.

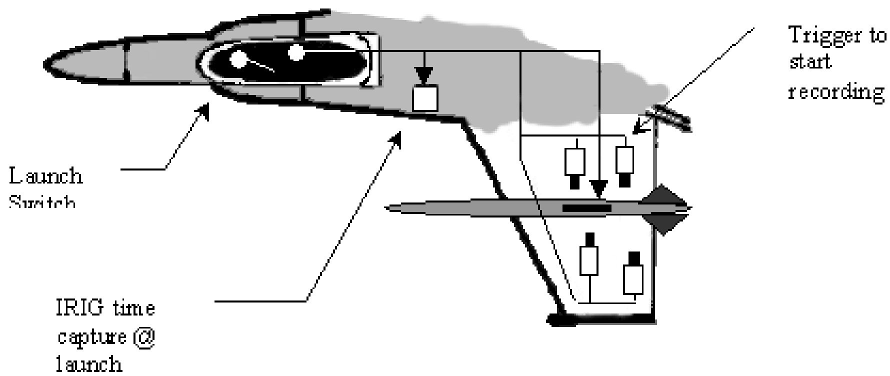


5. A FILM CAMERA OPERATIONAL SCENARIO

It is possible to use the RO Imager in a configuration that emulates a high-speed film camera. To make the RO work with existing wiring, there are a few voltage potential changes. In addition, a commercial IRIG generator can be used to synchronize the range IRIG time to the images at the time of the trigger.

1. The Remote Start signal should be open (i.e., open relay contact) when the imager is not to be activated (Standby). Just prior to recording the test, Remote Start should be closed to the +28 VDC Return. This closure will put the imager in Ready mode.
2. Add a 10 k-ohm ½ watt carbon resistor to the Remote Start signal in the imager interface cable as shown below.
3. The Event Marker +28 VDC signal should be open (i.e., open relay contact) when the imager is not to be recording. To start recording immediately, the Event Marker +28 VDC signal should be closed to the +28 VDC Return. This closure will put the imager in Record mode.
4. Add a 10 k-ohm ½ watt carbon resistor to the Event Marker +28 VDC signal in the imager interface cable as shown below.
5. The two retaining screws on the removal door on the back of the RO Imager should be drilled to secure them with wire during flight. The same should be done to the four screws for lens box mount on the front of the RO.
6. The RO Imager does not have IRIG (B or C) input. Therefore, to synchronize to range timing, an alternative approach must be taken. The RO Imager has very precise frame timing. Once Triggered (Event Marker +28 VDC), the RO Imager starts recording the images well under one microsecond. This timing is over 100X the accuracy of IRIG B

timing. Multiple RO Imagers can be synchronized together in a configuration that will assure each RO Imager is precisely recording in synchronization all other RO Imagers. Therefore, the task of synchronizing to IRIG becomes one of noting (recording) the time of the IRIG at the Trigger of the RO Imagers. The trigger frame will always be frame 0 for the RO Imagers. Each (N) frame thereafter is precisely N x 1/frame rate. Capture of this IRIG time can be accomplished by use of a commercial IRIG record unit, or an auxiliary IRIG unit, onboard the aircraft that is manually (electronically) triggered simultaneously with the Event Marker +28 VDC. Shown below is a pictorial block diagram of several RO Imagers, IRIG Receiver, and Pilot interface.



At the time of Weapon launch, the IRIG unit saves the time in its memory. This time corresponds to the Trigger time or Frame (0) in all the RO Imagers because they are all precisely in unison during record. Each image in the RO Imager has the time from frame (0), the frame number, shutter speed, date of recording, test number, and other important parameters embedded as data. After the recording, the images are safely saved automatically to the inserted Memory Module (PCMCIA flash memory). Each image is stored as a file on the Memory Module. Therefore, if the RO Imager is programmed to record 500 frames, there will be 500 files stored on the Memory Module.

After the aircraft lands, the ground crew unloads the RO Imager Images & the IRIG launch time. The IRIG launch time then can be used as an offset to each RO Imager recorded time. This offset can be appended to the image file along with other user defined data (see the appendix for the RO Imager file format). This method of post-appending the timing is as accurate as sampling the IRIG time for each frame during recording. This method saves valuable storage space and simplifies the wiring. Shown below is an example of this appending of the IRIG B timing (unit = 100 µsec) to RO Imager image frames taken at 1000 fps.

Before Appending Image Data

IRIG Time Captured at Launch (Days, hundredth, tenth, unit) 31 0 3 1

Frame Number	RO Real-Time	RO Elapse Time	RO Undefined space (IRIG)
0	0 0 0 31 2 97	0 0 0 0	0 0 0 0
1	1 0 0 31 2 97	0 0 0 1	0 0 0 0
…………	…………	………..	……….

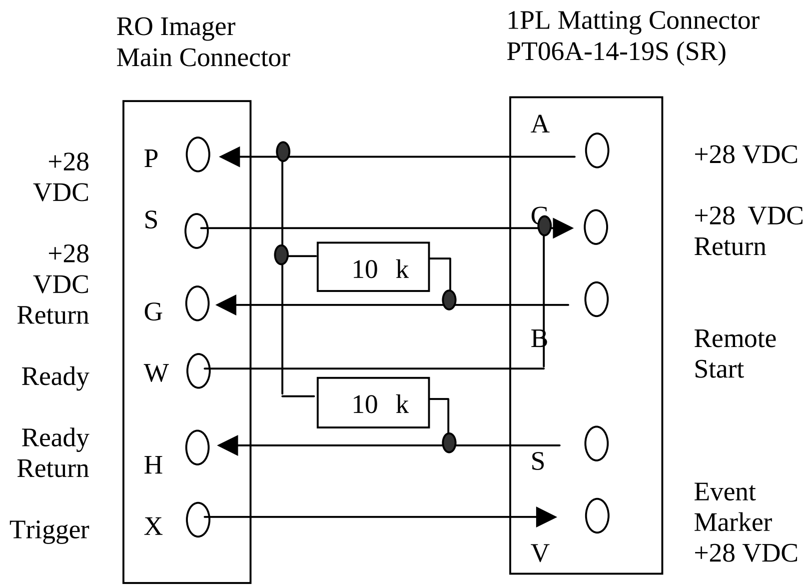
After Appending Image Data

IRIG Time Captured at Launch (year, month, days, hundredth, tenth, unit) 97 2 31 0 5 1

Frame Number	RO Real-Time	RO Elapse Time	RO Undefined space (IRIG)
0	0 0 0 31 2 97	0 0 0 0	31 0 5 1
1	1 0 0 31 2 97	0 0 0 1	31 0 6 1
…………	…………	………..	……….

The following drawing and procedure illustrate the steps necessary to emulate the 1PL with the RO Imager.

Pre Flight Setting for RO Imager
Through the Control Panel software, set the following: frame rate, exposure, date, Imager ID, starting frame number for download, ending frame number for download, and sequence number (test number). These settings will be saved during power off.

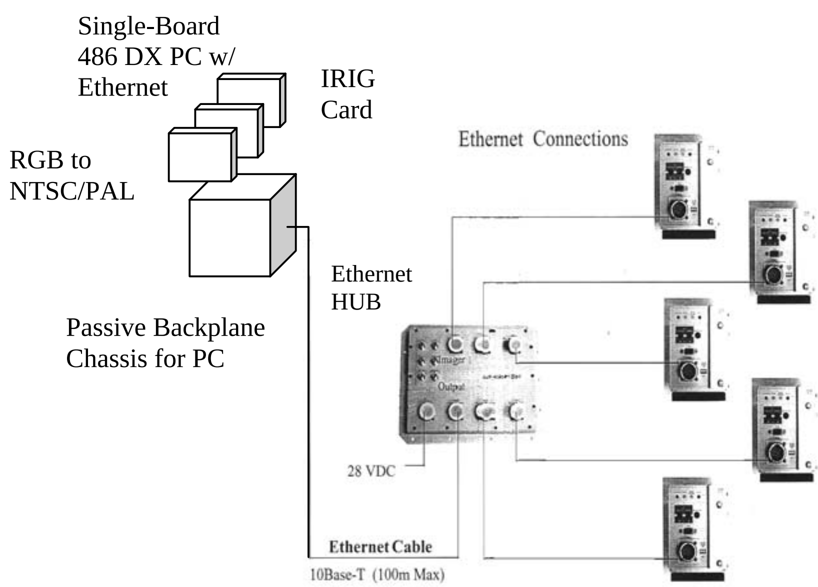


Power Up Sequence
(from 1PL matting connector)
Apply +28 VDC to Pin A. Hold Remote Start, Pin B and Event Marker +28 VDC, Pin S open circuit. RO Imager is in a Standby mode.

Setting the RO Imager into a Ready mode (from 1PL matting connector)
Ground or close circuit Remote Start, Pin B (can be momentary). RO Imager will remain in Ready mode awaiting a Trigger signal for 60 seconds, thereafter it returns to Standby mode.

Triggering the RO Imager into a Record mode (from 1PL matting connector)
Ground or close circuit Event Marker 28 VDC, Pin S (can be momentary). RO Imager will start recording images immediately and continue until the end of memory is reached. RO Imager then will automatically download specified images into the Flash Memory (two images per second). After all images are downloaded, another set of pictures can be taken by removing power to +28 VDC, Pin A and reinitiating the Power On sequence shown above.

It is possible to use the RO Imager in a network configuration that allows the pilot to download either live digital video or recorded digital video. This operational scenario is very similar that of a film camera except an Ethernet 10BaseT interface is used to link the RO Imagers to the single-board PC computer. Shown below is the block diagram (connectivity) for Ethernet and RO Imager. Images would still need converting from the PC VGA video port to the VGA-to-NTSC/PAL converter. However, the VGA Multiplexer would not be required since all video will be transmitted through the Ethernet link. In place of the VGA Multiplexer there needs to be an Ethernet Hub. Again, many possible commercial Ethernet Hubs can be modified for airborne applications. It is also possible to use the distribution box (J-Box) with an Ethernet HUB that is built for use with the RO Imagers.



Basic Steps for setting up RO Ethernet Communications with Windows NT

1. Setup the Ethernet Card Services for the Ethernet card you are using. This process is handled by the software provided by manufacture of the card or via the drivers provided by Windows NT. Follow the cards documentation.
2. Install the TCP/IP basic protocol; refer to Windows NT 4.0 online documentation.
3. Choose an IP address (i.e., 100.11.7.87). This address must begin with 100 and otherwise be unique for each RO Imager as well as the controlling computer.
4. Set the Subnet mask address to 255.0.0.0.

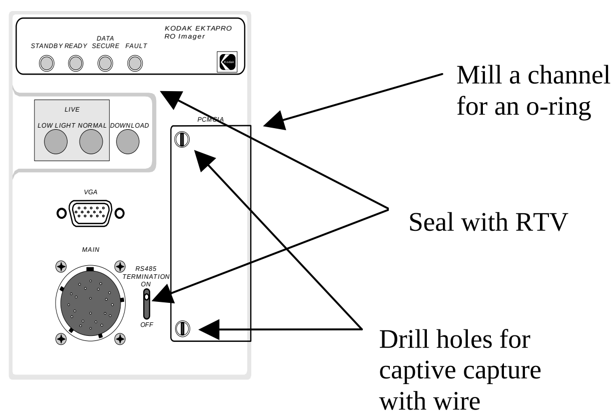
6. ADDITIONAL MODIFICATIONS TO THE RO IMAGER

The RO Imager was designed to replace 16 mm film cameras used on automotive crash sleds. Some modifications may be necessary to the RO Imager that will assure long reliable operation in airborne applications. These modifications made by the end-user are not covered under warranty. These modifications can be made without disassembly of the RO Imager.

1. Seal around the LED lights and the RS-485 Termination switch with RTV. The closing of the gaps around the LED lights will better seal the imager against water vapor.

2. Remove the Memory Module door and have a small channel milled into the inside face of the door. This channel should be designed to retain an o-ring. When the door is put back in place, the area will be sealed from water vapor.

3. While the Memory Module door is off, drill holes into the two rear screws at a right angle. These holes will allow securing the screws with wire so they cannot spin off accidentally.



7. FINANCIAL IMPACT

The comparison of financial impact of high-speed photography vs. high-speed digital imaging is presented in the table below. The comparison is based on 1 year operation for 1 plane with 18 cameras, 2 flights a day over 7 days a week. In addition, an error rate of 1 in 50 test is assumed for a misfire failed capture (premature camera starts, failed launch, etc.). In support of the test, assume 120 ground personnel @ an average rate of $25/hr. The greatest cost saving from digital imaging is the elimination of the recurring expense of film & film processing. In addition, the opportunity to rerun a test by resetting the RO Imager while in the air is very important and cost effective. There have been many occasions where the film was expended on a test that still had the safety set on the weapon.

FILM Solution	COST	DIGITAL Solution	COST
(18) 1PL cameras	$115,740	(18) RO Imagers*[1]	$799,425
(18) 200 ft film Mag's	$93,240	---------------------------	$0
(18) Adapter Cables	$4500	(18) Adapter Cables[2]	$3600
(18) IRIG Timing Interface	$83,160	(1) IRIG B Generator	$5000[*4]
(18) BCD Numeric Data	$36,900	(18) BCD Numeric Data	$0
(18) Variable Shutter Option	$8730	(18) Variable Shutter Option	$0
(13,140) 200 ft. rolls of HS film, EASTMAN EKTACHROME High Speed Film 7250 including processing	$722,700 [$55/roll (avg. $42 - $76)]	(18) Memory Modules (one time cost)	$121,590
(1) film reader & analyzer	$200,000	(1) Image Workstation	$46,000
(1) year service for 12 cameras*[3]	$7200	(1) year of service for 12 Imagers	$0
(8) Misfires including ground support cost	$96,000	(4) Misfires including ground support cost*[5]	$0
TOTAL	$1,368,170		$975,615

[*1] RO Imager discounted for USG and 15% for quantity purchase.
[*2] Custom cables using Main connector to 1PL connector.
[*3] Four hr service (lube and repair) @ $25/hr each camera every 3 months.
[*4] IRIG B Time Code Generator VME card, Single board VME PC, and card cage.
[*5] Assumes ordnance is not expended. RO Imagers can be reset without landing for a 2nd try.

8. CONCLUSION

The 16-mm film cameras have been used in severe environments. The time has come to replace these 16-mm film cameras with electronic imaging. Today's technology, the RO Imager, can meet the needs of the airborne testing community. Below is our outline on the value drivers and needs for the airborne application. We evaluate how well we meet these needs.

Value Drivers

1. **governmental mandate for reducing chemical film processing:** No chemicals required with the RO Imager.
2. **shorter time to view test results is required:** Images can be viewed while airborne with the addition of a VGA-to-NTSC converter box (COTS unit) setup.
3. **need to facilitate faster data reduction of images:** Images are digital and can be immediately analyzed with higher timing precision, then film.
4. **improve the reliability of image content during an exercise with pre/post quick views:** Images can be view while airborne or immediately upon landing.
5. **direct electronic distribution of image data to multiple analysts or labs:** Images are digital and in a standard format.
6. **improve equipment reliability [no mechanical shutters or pin feeds]:** Shutter is all electronic and there are no moving parts too fail in a recording.
7. **ease of rerunning a test if necessary [goof tolerant image capture]:** The RO Imager can be reset while airborne. This reset allows for rearming and a 2^{nd} chance at a miss release.
8. **reduce skill level for setting up cameras:** The RO Imagers are very easy to setup and operate.
9. **reduce operating cost:** The zero-base return for capital investment can be within one year. This return on investment depends on the amount of test conducted during a year.
10. **a camera that can serve multiple branches of the service will leverage their buying power for greater volume:** The RO Imager is discounted for USG purchase and there are volume discounts.

Customer Needs

1. **similar weight & size of current film cameras with a simple interface for dependable setup:** The RO Imager is within 2 lbs. of the 16 mm film cameras. The RO Imager is slightly longer than the film cameras, but its front profile is smaller.
2. **resolve 0.25 in. at 6 ft. or as close to this measurement as possible**: To resolve a 6 ft. FOV at ¼ in. resolution requires 576 x 576 pixels. The RO Imager is 512 x 384.
3. **no loss of images or malfunction of the camera during Hi-G forces or high vibration***:* The RO Imager has been proven in a very Hy-G automotive crash application.
4. **multiple camera interface wiring needs to fit through one to two inch gussets***:* The hardwired trigger and ready lines more than satisfy need to fit through a one to two inch gusset.
5. **10 second record time at 200 – 400 fps:** No. With 1000 frames in the RO Imager at 200 fps, it can record for 5 seconds.
6. **color is important for some users***:* Both monochrome and color are available.
7. **an event marker is an important feature and cameras need to be synchronized to IRIB B***:* The event marker is frame (0) and the IRIG time can be accurately synchronized to the RO Imagers with the addition of a single- board computer and an IRIG generator PC card.
8. **controls, cables and storage devices need to exit the rear of the camera***:* All exit the rear of the imager.
9. **meet the wide range of environmental requirements [e.i., temp, shock, humidity]***:* Some minor modifications are required for wet humidity.

In conclusion, we believe the RO Imager is well suited to replace the 16-mm film cameras used in airborne applications. With a few simple modifications, a true COTS solution for airborne ordinance testing can be achieved. The author wants to thank William R. Balch, Katherine S. Marsh, and Wendy Telford for their help on the paper.