Developing a Super Slow-Motion Camera for HD

Background

Slow motion replays are now widely accepted as an integral part of television sports coverage. Indeed, many sports now rely on these replays to help game officials judge close plays and questionable calls.

To create a slow-motion replay which appears smooth, it is necessary to have a camera and a recording system which is capable of shooting faster than the normal 50 or 60 fields or frames per second rate. Capturing more pictures than normal then playing those out at the standard speed gives you smooth motion at a reduced speed of action rate.

This was the thinking behind the development of the Grass Valley LDK 23 which set the standard for live, super slow-motion system, or super slo-mo. The LDK 23 shot at three times normal speed, producing 75 or 90 frames a second depending on video format, giving perfect motion at one-third normal speed, for 3X super slo-mo.

The important point here is that the technology existed for this to happen within a live production without complex processing or delay. With a special super slow- motion server, the 3X output could be recorded, then played back instantly at variable speeds. The recording could go on indefinitely; normally super slo-mo server channels are permanently recording, capturing the entire game.

Without this approach, viewers had to put up with jerky motion, or there was a significant delay while complex processing and rendering took place to estimate the in-between pictures. This did not produce satisfactory results and was of no practical value in the world of fast action sports because of the processing delay.

Today the broadcast market sees a number of very high-speed cameras: speeds as high as a million frames a second have been quoted. But these are limited to very short recording durations – a fraction of a second in the case of the highest speeds – and the outputs need to be downloaded and processed before they can be used. This makes them attractive for very specialized shots, but not a practical proposition for live applications.

Sports broadcasters are accustomed to the idea of 3X super slo-mo, and directors routinely call for replays instantly. They are an established part of the language of televised sports productions.

Sports productions are leading the migration to HD for broadcasters around the world. Audiences expect landmark events – like the 2006 FiFA World Cup, The Super Bowl, Euro 2008 (European football), and the 2008 Olympics and Paralympics – to be broadcast in HD, and increasingly there is an expectation that other, more routine sporting events should also be available in HD.

This all leads to a significant demand for an HD super slo-mo system. The development of such a camera, though, faces a number of technical demands if it is to meet the uncompromised quality standards that viewers expect of HD. This paper looks at some of these design challenges and how they have been addressed by Grass Valley engineers in the LDK 8300 Super Slo-Mo HD Camera.

Signal-to-Noise Ratio

The majority of high-end professional television cameras use three 2/3-inch CCDs as its image sensors, with CMOS sensors beginning to make their appearance. In this context it does not matter whether the imager is CCD or CMOS, though, as both achieve the same end result.

The imager sensor is a chip on which there are a large number of photosites. These photosites convert light energy into electrical energy: they collect photons falling on the photosite and output a signal which is proportional to the number of photons collected. In the imager's output amplifier, the signal charges will be converted into a proportional output voltage. The output voltage from the imager is extremely low, and has to be immediately amplified before being converted from analog to digital for downstream processing (all imager sensors are analog devices).

The imager output is directly proportional to the amount of light falling on it, but it is also directly proportional to the length of time that it is exposed to that light. It is counting photons: if you reduce the time that you are counting photons then of course you reduce the number of photons which hit the imager. Shooting at three times the normal frame rate means that the imager is exposed for one-third of the normal time for each frame. This reduces the total amount of light on the image sensor, and the output from the imager degrading the signal-to-noise ratio at the front end of the camera.

One possible solution would be to use a special imager, developed with low signal-to-noise as its primary design requirement. The disadvantage of this would be that its pictures would not visually match the other standard-speed broadcast cameras being used during the event.

This would probably be unacceptable even if the output of the camera was only used for slow-motion replays. But in practical situations, the super slo-mo camera is used as part of the broadcast program and differences in image quality, certainly in HD, would not be tolerable.

Furthermore, having a standard-speed camera alongside the super slo-mo camera is not an acceptable solution either. The additional capital and operational costs of camera, cable, and operator would add to the production budget, and in many sports applications there is only one perfect spot for the camera, not two spots side-by-side.

For those reasons, Grass Valley engineers decided to use the same head block in the Grass Valley LDK 8300 Super Slo-Mo HD Camera as used in its standard-speed equivalent, the LDK 8000. An added benefit is the use of DPM – dynamic pixel management – to create native 1920x1080 and 1280x720 resolutions from the same imager without compromise.

In the LDK 8300, ultra low-noise electronics minimize the impact of noise. In 3X operation it achieves a signal-to-noise ratio of 54 dB, significantly better than other slow-motion cameras available on the market and an acceptable noise floor for HD.

Another design decision taken in the LDK 8300 was that it should offer native 2X as well as 3X super slo-mo. Some sports – basketball, for instance – are so fast that there is no time between plays to replay a shot at three times its length before the live game has moved on.

One of the reasons for providing the additional 2X setting is that this can easily be recorded by super slo-mo recorders in use today, and provides the director the opportunity to call for slow-motion shots during fast-moving events. The LDK 8300 achieves this by using the clock at the camera head so that no additional electronics processing is required. This gives a 50% increase in the exposure time for each frame, with a consequent increase in output from the imager and improvement in the signal-to-noise ratio.

Whether shooting at 2X or 3X, the standard-speed output for live use is created at the camera control unit. The sophisticated algorithms which blend the two or three video phases into the standard-speed output also improve the signal-to-noise figure by a further 3 dB. The result is that the LDK 8300 can be intercut seamlessly with the LDK 8000 camera, in HD, without any visible differences to the audience.

Data Rate

It is well known that uncompressed HD, as 720p or 1080i, has a data rate of 1.5 Gb/s. However, if you are shooting at three times the normal frame rate, you are faced with a data rate of 4.5 Gb/s.

To accommodate this data rate, Grass Valley developed a new fiber system. It uses either SMPTE hybrid fiber cables or two cores of standard single mode dark fiber cables, and operates securely over distances of up to 13,000 ft/4000m including the delivery of power to the camera. With local power at the camera head, even longer distances can be covered.

The base station is specifically designed to unpack the triple frame rate video (for 3X speed), carry out the necessary processing, then offer the output as three parallel HD-SDI signals to an external recording device (2X speed is output as two parallel HD-SDI signals). As already noted, the base station also creates a very high-quality standard (1X) speed output for live use simultaneous with the 3X or 2X.

This requires two sets of algorithms: one for progressive and another for interlaced image capture. The camera always operates at the native rate and format of the production, so if the requirement is for 1080i, then that is what is generated in the camera head electronics. As can be readily appreciated, creating a single realtime stream of interlaced HD video from three interlaced frames per output frame calls for very complex mathematics and consequently a great deal of processing power in the base station.

It is very difficult to create smooth slow-motion in interlaced formats, and this is an issue that broadcasters have to address. For the sort of action events that require super slo-mo, 720p provides far superior results and is a much better origination format in this application. However, it is important that the technology does not impose restrictions on the operational requirements of the production company or broadcaster, so the processing power and capability is included to create a very high-quality realtime 1080i output as well.

While interest is now emerging for working at 1080p50/60 formats, users will be glad to know that the design of the LDK 8300 is prepared for this standard should it come into common use. The main challenge will be the data rate between the camera and the base station: transmitting 9 Gb/s without jitter or glitches, even over fiber, is a very significant challenge. Grass Valley engineers are working on a new, universal transport standard which will accomplish this.

In transmission and processing, latency is an important issue, especially when cutting between the standard speed output of an LDK 8300 and a traditional LDK 8000 HD camera, and the entire fiber transmission system has been designed for minimum processing delays**.**

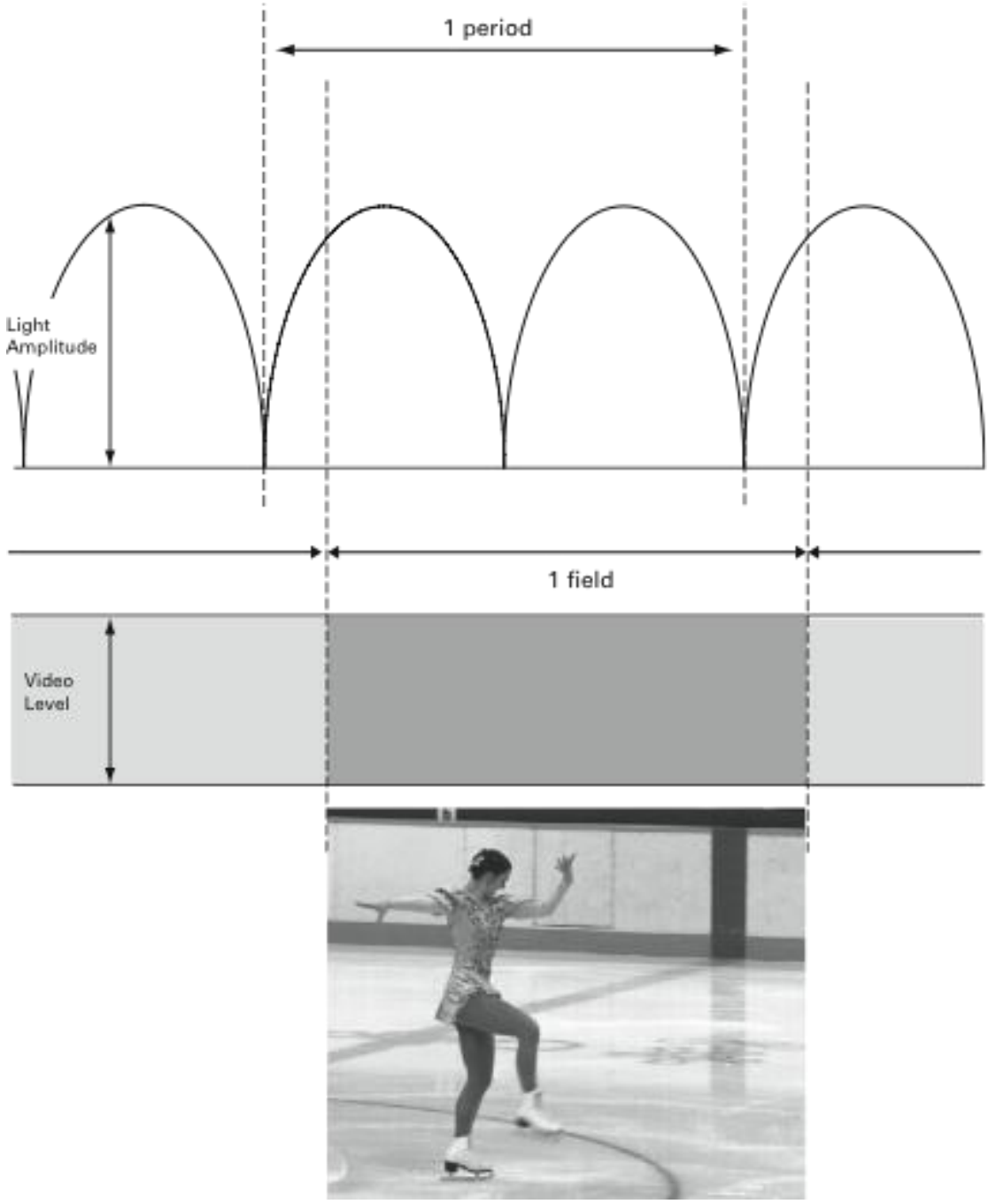
Making super slo-mo systems fit seamlessly into production environment is also a primary consideration. Camera set-up and shading can be controlled from a standard operational control panel (OCP), so matching Grass Valley super slo-mo cameras to Grass Valley standard-speed cameras is simple. Grass Valley's camera control system uses Ethernet to link the OCP panel and the camera's base station together, and LDK 8000 and LDK 8300 cameras can be controlled on the same network.

Flicker

When sporting events are played under artificial lighting, there is another important issue to consider: flicker.

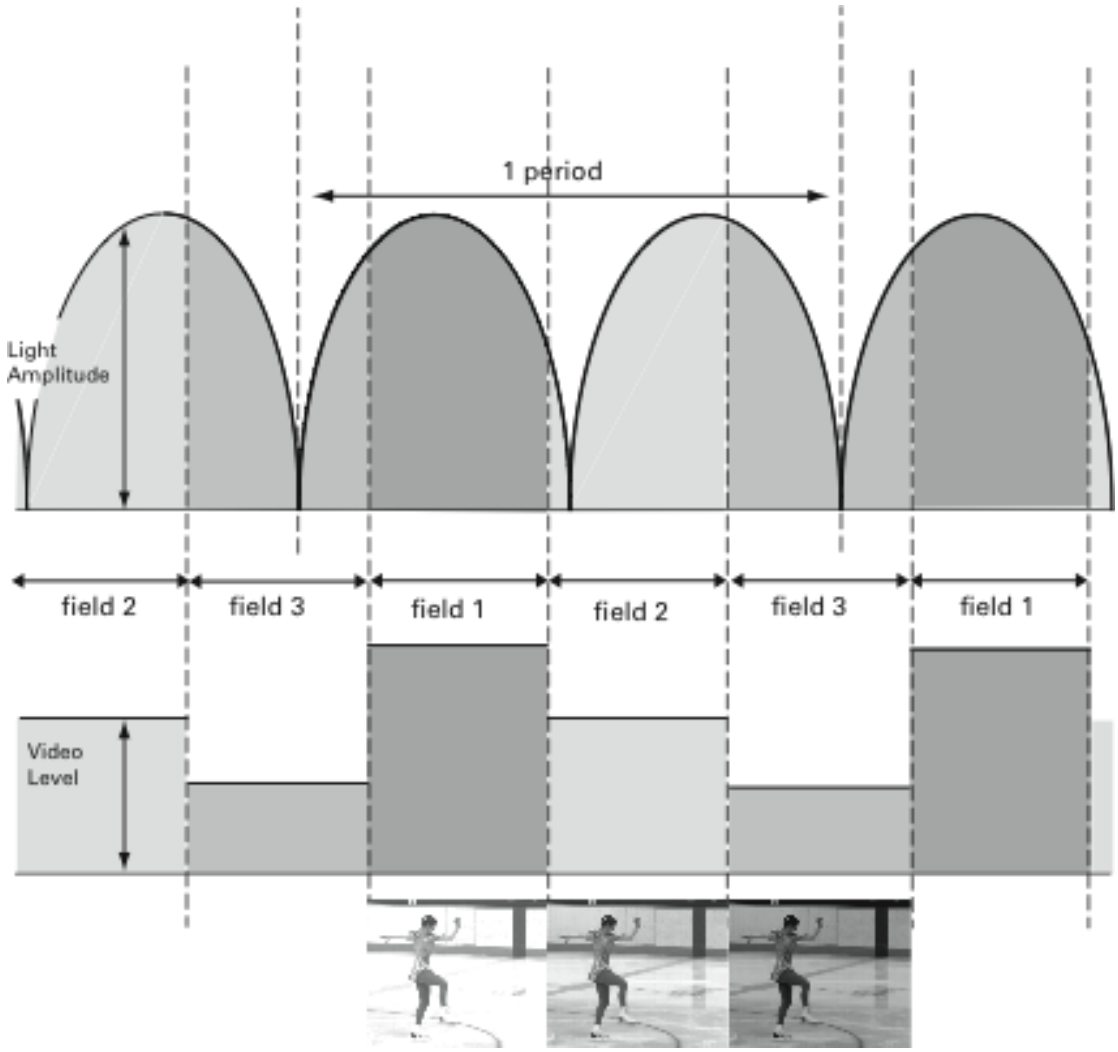
While the eye automatically integrates the output of many different types of artificial lighting so that the level appears constant, they remains cycling with the mains power frequency. Typically this is not an issue with television cameras either: a 50 or 60 fields per second camera under 50 or 60 Hz lighting, respectively, will always receive the same amount of light – effectively integrating the illumination over a complete cycle - so the picture will appear stable.

As the diagram below shows, this is the case even if the lighting and the cameras are not synchronized: provided they are operating at the same frequency, the light will be integrated over a field of the video to provide a constant level of illumination.



But when shooting at 150 or 180 frames per second, successive frames will receive a different amount of light because each will capture a different part of the power sine wave. When slowed down, these changes in light levels will appear as a visible and distracting flicker.

The diagram below illustrates the different levels of light received in each field by a 3X super slo-mo camera under artificial lighting.



This flicker appears not just with single-phase lighting but also with two- or three-phase lights and discharge lamps.

While other high-speed cameras ignore this problem, and as a result produce a very disturbing flicker under artificial lighting conditions, Grass Valley has developed a unique compensation system to eliminate it. And a simple automatic gain control is not sufficient for high-quality results: players moving quickly through the frame would fool the detectors and actually risk introducing flicker rather than reducing it.

Grass Valley's solution is AnyLight™, a system of sophisticated algorithms running in the signal processing unit. Control is important: any image processing of this nature risks introducing motion blur which would be unwanted. AnyLight has five presets (including off) which allows the engineers to precisely dial in the amount of correction required for each set-up.

These presets are:

- **optimal** - no flicker reduction, for use in optimal lighting conditions
- **good -** artificial lighting with minor amplitude changes, including incandescent or well-balanced three-phase lighting, and mixed daylight and artificial lighting

- **fair** – when there are significant amplitude changes, such as under fluorescent lights
- **poor** – for lighting with major amplitude changes, like HMI, MNHD, gas discharge lamps, and neon
- **extreme** – which results in a completely flicker-free image but does introduce an increased level of motion blur: this setting should be used only when there are extremely challenging lighting conditions

The LDK 23 Mk II standard definition super slo-mo camera introduced flicker compensation and rapidly became regarded as the industry benchmark for slow-motion. Qualitative evaluations of AnyLight in the LDK 8300 HD camera suggest that it is an even more effective implementation.

Obviously the AnyLight processing, like the signal blending for the standard speed output, has to be done in real time. It is equally important that it, too, is performed with very low latency to ensure there are no jumps in the action, particularly when cutting from a standard-speed LDK 8000 camera to an LDK 8300.

Conclusion

Super slo-mo replays have become such a regular part of the vocabulary of television sports and events that it is impossible to imagine life without them. Broadcasters, producers, and directors migrating to HD are aware that their audiences expect the same production values that they have grown accustomed to with SD, which means delivering super slo-mo, with the same replay speeds and operational convenience, but with the higher quality of high definition.

The practicalities of television outside broadcast coverage, though, are such that super slo-mo cameras have to provide a live realtime output as well as sending the high-speed output to a server for replay. So most of the design constraints are centered on ensuring that the camera output, whether live or in slow-motion replay, matches in image quality and colorimetry the standard-speed broadcast cameras used elsewhere on the production.

We can summarize the design challenges, therefore, as:

- the ability to capture full resolution HD pictures at 2X and 3X normal speed
- identical image quality from the optical block and camera head, and comparable signal-to-noise ratio
- a transport system to carry the high data rates (4.5 Gb/s for today's HD) over standard cables and practical distances including those pre-installed in sports venues
- a means of minimizing the effect of lighting flicker in slow-motion replays
- advanced signal processing to create a smooth, stable, and clean realtime signal from the high-speed video, even from an interlaced output

- maximum commonality between components and operations for standard-speed and super slo-mo cameras, including lens and viewfinder mounts, and operational control and master control panels.

Meeting all these challenges was demanding, and Grass Valley waited until all issues were addressed and resolved before bringing the LDK 8300 to market.

The LDK 8300 Super Slo-Mo HD Camera was first used on the Euro 2008 football championships in June 2008. At both that event and in Beijing later that year, production companies had the opportunity to directly compare the performance of the LDK 8300 with its competition: the widely held view was that the LDK 8300 not only met, but exceeded all of the imposed technical and operational requirements and, thanks to its very low noise and flicker reduction, creates a visibly superior image.

In North America, the LDK 8300 recently debuted at the center-court camera position during the 2009 Western Conference Finals of the National Basketball Association (NBA), providing extraordinary super slo-mo replays of the action as well as supplying realtime shots of the play-by-play announcers. The LDK 8300 then continued with the NBA as the "hero" camera during the 2009 NBA Championship Finals.