Super Motion System

By L. J. Thorpe, T. Nakamura, and K. Ninomiya

A radically new television field-acquisition system designed to enhance the capture of motion is described. The Super Motion system is comprised of a new genre of color television camera and a new VTR system. The motion judder and image blur associated with conventional TV pictures when played on a standard slow-motion recorder have been overcome. This is accomplished by shooting the scene with a camera whose frame rate is three times as high as that of a normal 525/30 camera. New technologies incorporated in the system — mixed-field pickup tubes, fiber-optic transmission, digital processing and standards conversion, and high-speed C-MOS digital LSI chips to encode RGB *to NTSC—are described.*

Since the introduction of the Type-C 1-in. videotape recorder, slow-motion video replay has gained wide popularity by permitting close examination of movement in sports, science, and drama. Increasingly, it is even used as a special effect in commercials and drama. Dynamic tracking (DT) technology (essential to this facility) has become an indispensable element of this format. This slow-motion ability is eagerly sought within smaller-format systems, such as 3/4-in. and the new 1/2-in.

In the film domain, the problem is tackled by increasing the shutter speed to multiples of the normal 24 frames/sec (camera frame rate). When the film is subsequently projected at a fixed speed of 24 frames/sec, the motion is reproduced at a rate proportionally slower (by the same multiple as the shutter was increased) but with the same quality as would be seen in the projection of a normal-speed picture. The viewer is looking at all of the original high-speed frames, over a longer period of time, and thus sees slow motion with higher temporal resolution.

The Super Motion system was developed to solve a specific problem associated with conventional slow-motion playback of television recordings. Sony Broadcast Products presented a paper entitled "The Development of the Super Motion System" at the 126th SMPTE Technical Conference in November 1984. This paper dealt in some detail with the theory of the special VTR employed. The emphasis of this article will be on the special Super Motion camera.

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The Slow-Motion Problem

While adding immeasurably to the production capabilities of today's VTR, the technical quality of conventional 1-in. Type-C slow-motion playback is fundamentally flawed. TV cameras shoot at a fixed field rate of 60 Hz, and thus deliver to the VTR a finite number of video "snapshots." This is a relatively slow taking rate, particularly when fast motion is involved, and much motion resolution is inherently lost.

The Type-C VTR can be controlled to play back the recorded tape at any linear speed between still-frame and normal speed of 24.4 cm/sec. To replay in slow motion, the appropriate intermediate speed is set, and for the VTR to produce a standard 525/60 NTSC output, the video head must trace the same track multiple times (this multiple varying according to speed of slow-motion replay). The limited number of frames recorded initially is thus further reduced, causing increased motion impairment.

There are two important aspects relating to the impaired quality of the reproduced slow-motion image:

- *The resolution of the motion itself.* The clarity and smoothness of the movement, which is purely a function of the system's temporal resolution.
- *The quality of a given picture frame.* The spatial resolution of that frame, which is obviously adversely impacted by the fact that the subject is in motion for the brief period during which the frame is being exposed or scanned, and complicated further by the finite integration time of today's photoconductive pickup tubes.

These two factors contribute directly to the subjectively disturbing phenomena that mar conventional Type-C slow-motion playback. The specific symptoms are:

- *Staccato motion.* A direct result of inadequate temporal resolution and the repeat field mechanism employed in Type-C slow-motion playback.
- *Picture blur.* Associated with the frame rate of the taking camera and the finite integration time of the pickup devices used.

It has long been recognized that the poor reproduction of movement (typified by the erratic or staccato nature of this motion), particularly when the playback is substantially slowed down, is subjectively a much more disturbing aspect. The associated problem of picture blur actually alleviates this problem by masking the jerkiness via the integration or blurring phenomenon. In playback of many sports activities, the split-second relative motion (as in racing) or the beauty of form (as in gymnastics) is primarily impaired by the poor time resolution of the system.

The Super Motion system was developed specifically to improve the first of these problems. That is, it is designed to substantially enhance the fluidity of the slow motion (also incidentally reducing the motion blur), rather than to improve the clarity of a stop-action freeze-frame picture.

Fundamentals of the Super Motion System

The Super Motion system emulates high-speed photography in the video domain. This is accomplished by shooting the scene with a camera operating at a frame rate that is three times as high as that of a normal TV scan rate (30 frames/sec). The Super Motion camera runs at 90 frames/

sec. In 1/30 sec, it therefore photographs three sequential video frames in place of the one single frame captured by a conventional camera. If an object is in motion, three snapshots of the progress of that motion are captured, rather than just one, in 1/30 sec.

The BVP-3000 Super Motion camera scans 525 television lines at a 90-Hz frame rate, or 180 fields interlaced 2:1. To record subsequently this unusual signal and play it back as a standard 525/30-Hz NTSC signal, so that it will deliver an appropriate signal into the existing TV signal, requires the process of standards conversion. The 90-Hz frame rate must be converted down to the 30-Hz standard. This conversion is accomplished in the camera control unit (CCU) prior to recording.

The elevation of the camera frame rate, while keeping the number of scanning lines constant at 525, has important repercussions on two key facets of camera design: pickup device technology and bandwidth. The bandwidth consideration is important because it forces us into the realm of high-definition television.

The minimum bandwidth required to reproduce all of the information within a specific TV standard is given approximately by the following expression:

$$f_{max} = \tfrac{1}{2} KANf_F \frac{(1 + 1/K_h)}{(1 + 1/K_v)} \quad (1)$$

where K is the Kell factor, generally assumed to have a value of approximately 0.7; A is the aspect ratio; N is the total number of scanning lines in a single interlaced frame; f_F is the frame repetition rate; K_h is the horizontal retrace ratio; and K_v is the vertical retrace ratio.

As a basis for examination, it is useful to consider first the 525/30 NTSC system where the relevant parameter values are as follows:

$A = 4/3 = 1.33$
$N = 525$
$f_F = 30$
$K_h = 63.5/10.9 = 5.8$
$K_v = 262.5/21 = 12.5.$

which produces for f_{max} a value of:

$$f_{max} = 1/2 \times 0.7 \times 1.33 \times 525 \times 30 \times 1.08 = 4.17 \text{ MHz}$$

This equation defines the minimum bandwidth to cater to a given line number, frame rate, and aspect ratio, and it fits nicely with the generally accepted 4.2 MHz for the NTSC signal.

In the Super Motion camera, all parameters are assumed to remain the same, except f_F which now becomes 90, and this produces:

$$f_{max} = 1/2 \times 0.7 \times 1.33 \times 525 \times 90 \times 1 = 12.6 \text{ MHz}$$

The significant fact is that there is a proportional relationship between the frame rate of a camera and the bandwidth of which it must be capable. In conventional TV color cameras, the originating *RGB* set is actually wider than the 3-dB minimum of 4.2 MHz for the NTSC system, being more typically 6 or 8 MHz to allow proper aperture-correction schemes to be employed and to produce full bandwidth for picture processing, etc., within a studio. The Super Motion camera has been designed with a bandwidth closer to 18 to 20 MHz.

In one sense, the Super Motion camera is a high-definition camera. All of the design techniques — the wideband pickup requirements, higher scanning rates, and wideband preamplifier and video processing — are those required, for example, in an 1125/60 HD camera. The use of that bandwidth, however, is quite different.

In an HDTV camera, as we normally speak of it, the wide bandwidth is employed to gain radical improvements in the spatial resolution, for example, to double the horizontal and vertical spatial resolution as in the 1125/60 system. That same bandwidth, however, can just as well be applied to the third important dimension of TV, the temporal or time dimension. This is the premise of the Super Motion camera. The spatial resolution is essentially that of today's NTSC signal, and all of the bandwidth is employed to sustain the demands of the higher frame rate (Eq. 1). Thus, in its deployment of bandwidth, the Super Motion system is a variation on the theme of high definition — high temporal definition.

In discussing the special processing required, we refer to a set of three high-speed fields occupying the same time duration as a TV field in a conventional 525/60 camera. Each of the high-speed pictures is expanded in time in the standards conversion process, and is then separated into three individual pictures. Each of these reconstructed fields is recorded in real time on a specially designed high-speed Super Motion VTR. The three original high-speed fields from the camera totalled 1/60 sec in time. Their recorded time, on tape, now totals 3/60 sec. Therefore, playback of the tape at standard Type-C speed (24.4 cm/sec) will reproduce the original picture with one-third the speed of motion. This picture has all the resolution of a normal 525/60 camera/recorder combination, running at normal

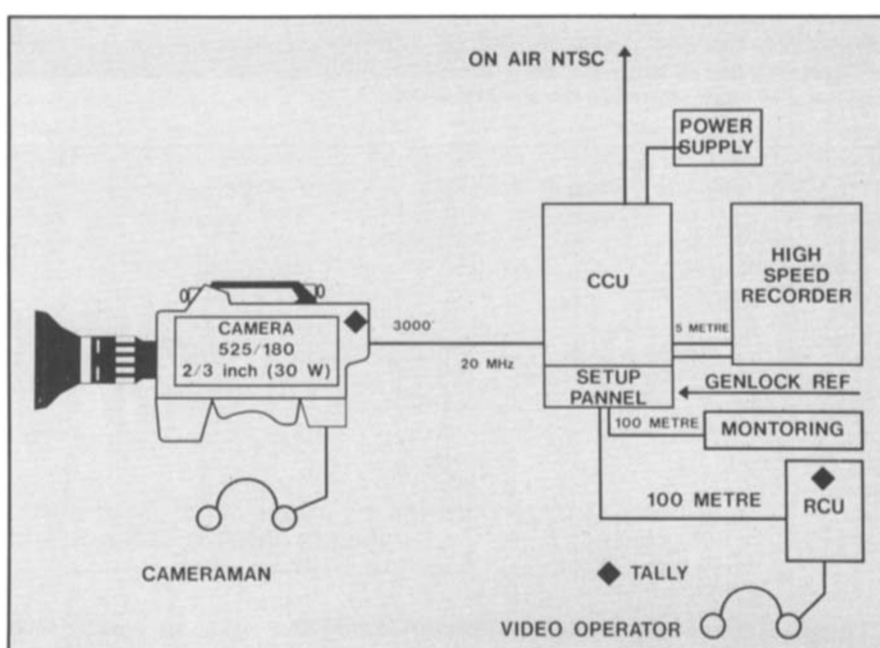

Figure 1. Super Motion system basic architecture.

speed, but with the important addition that the VTR plays back three times the number of frames.

Operational System Requirements

The camera and the VTR have certain operational system requirements which form the foundation for much of the system architecture. These requirements were pivotal in making key design decisions in the camera processing and VTR recording methods. Briefly stated, they are as follows:

- The final output from the system will be a 1-in. recording, fully meeting Type-C SMPTE specifications and capable of playback on any standard Type-C machine, regardless of manufacturer.
- The camera system will deliver a fully standard 525/30 NTSC video output, in real time, capable of feeding directly to air.
- The system will be genlockable so that it can be incorporated into a total TV system.
- The camera head will be portable to allow for hand-holding or shoulder mounting, thus permitting mobility in a crowded sports environment.

While the recording process is specialized, the playback is standard. The camera is also specialized (in that it runs at higher scanning rates), but the CCU can simultaneously deliver a standard NTSC output and the required signals for the special high-speed recorder. Figure 1 shows a block diagram of the total Super Motion system.

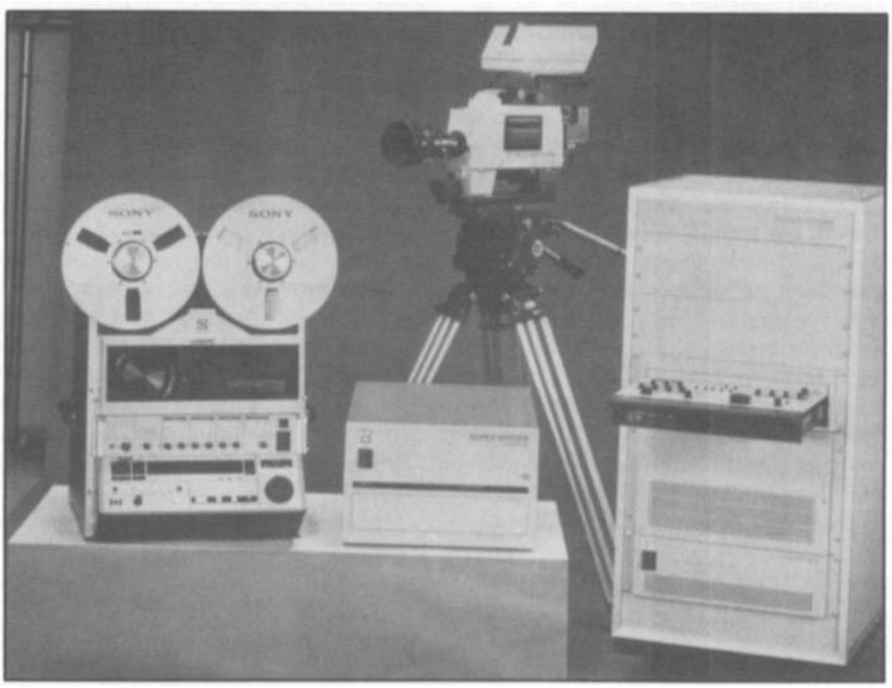

Figure 2. BVP-3000 camera system and BVH-2700 VTR.

In addition to these prime requirements, there are other key operational requirements, as follows:

- The camera head will also be capable of operation with large field lenses and a large studio-type viewfinder to permit a more traditional type of sports coverage with the camera mounted on a tripod.
- The CCU and VTR will be connected via a short multi-core cable, so that these units can be located together in a mobile van for operational control convenience.
- Existing test equipment such as waveform monitors and picture monitors will be used for operational adjustment and maintenance.
- The camera head will connect to the CCU via a single cable capable of being extended to 1 km length, again for operational flexibility in the field.
- The CCU operation will be as conventional as possible to minimize operator training requirements.
- A separate remote video operator panel will allow flexibility in camera control.
- The Super Motion VTR is capable of playing back any standard Type-C tape. That is, the machine can be used as a normal playback machine when not required for Super Motion effects.
- The Super Motion VTR uses standard time code and is fully compatible with the RS-422 remote-control system employed by standard Sony 1-in. VTRs.

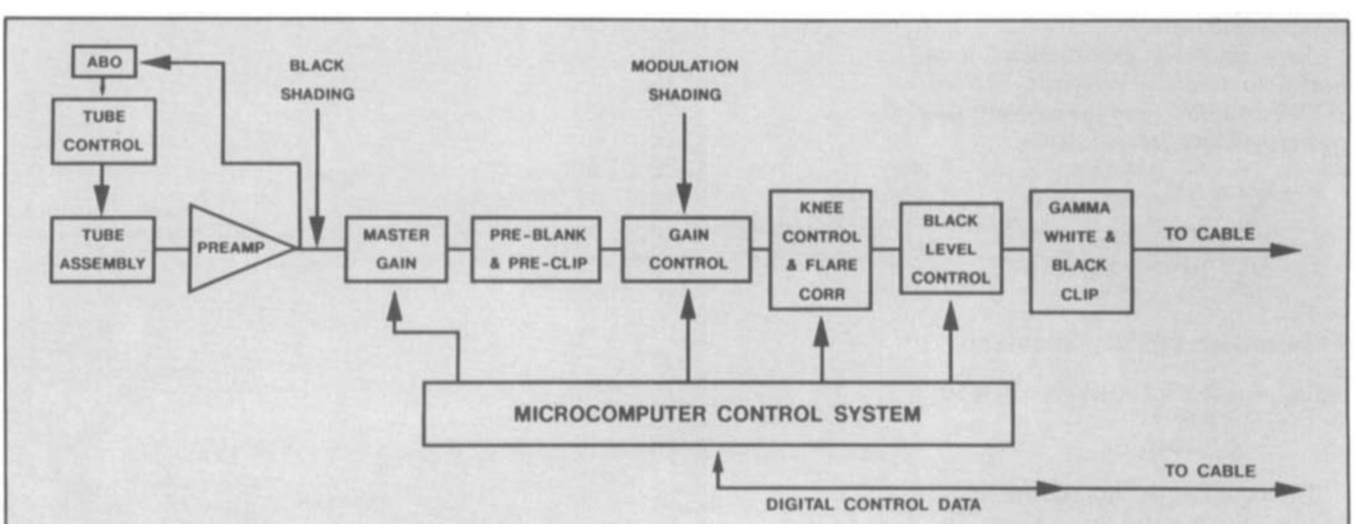

Figure 3. BVP-3000 camera-head video channel.

Figure 2 is a photograph of the system.

Super Motion Camera System

The Super Motion camera head is relatively simple. Figure 3 shows the basic details of one of the *RGB* video channels. It is an *RGB* camera employing three ⅔-in. mixed-field Plumbicon pickup tubes. Following preamplification, the wideband *RGB* signals first undergo basic linear processing: black-and-white level normalization and balancing, black-and-white shading corrections, and linear matrixing. This is followed by nonlinear processing such as black-and-white clipper and gamma correction. These three wideband 20-MHz analog signals are then fed to the camera cable for delivery to the CCU.

Within the CCU, the final processing is performed on the *RGB* signals. They are then standards-converted, and the three high-speed frames are individually separated into three parallel 525/60 video signals. Because the CCU is almost entirely digital, it is called the digital processing unit (designated DPU-3000).

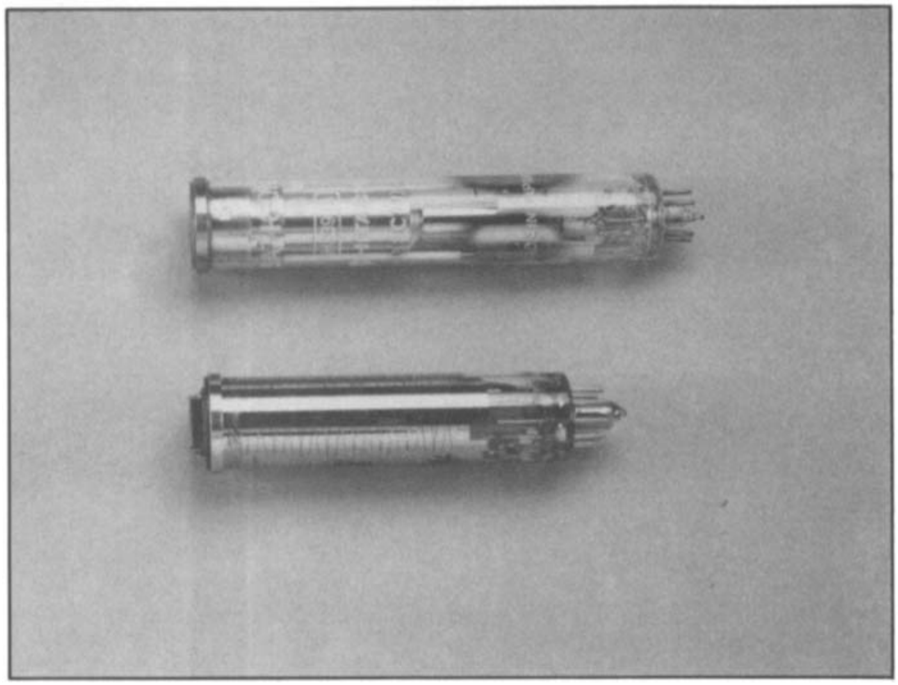

Figure 4. Short mixed-field compared with standard ⅔-in. tube.

Camera Head

Because the camera is still required to scan 525 lines within every high-speed frame, the horizontal scanning must also be increased in speed. That is, to scan 525 lines (two fields) in 1/90 sec instead of 1/30 sec, the horizontal scan rate must be increased to 47 kHz (15.734 × 3 kHz). Horizontal scanning is, even today, extremely difficult to accomplish satisfactorily at the standard rate of 15.734 kHz using conventional magnetic deflection techniques. It would be virtually impossible at three times this rate.

Sony's recently introduced mixed-field tube, however, employs totally electrostatic deflection while retaining a dc magnetic focusing system. This new electron optical system was developed specifically to permit precision deflection for high-definition tubes operating at, for example, an 1125/60 scanning rate. A new diode gun and a new target layer also contribute to the very small beam capability. High corner resolution is a major benefit of this new tube, in that much better orthogonal landing of the beam all over the raster can be maintained with this technology.

This pickup tube research, which initially centered on a 25-mm tube for an 1125/60 HD camera, was also subsequently directed to produce a smaller ⅔-in. mixed-field tube (Fig. 4). This tube was developed to support future portable HDTV camera development, and with appropriate refinements, a high-performing version was produced to form the primary pickup element for a new range of 525/60 standard broadcast cameras currently being introduced by Sony (BVP-360, BVP-3A, BVP-30, and BVP-150). This same ⅔-in. tube is employed in the Super Motion BVP-3000.

Camera Sensitivity

The BVP-3000 employs a standard high-performance, high-index, prism-splitting block. It interfaces with all lenses currently available for the standard BVP-300 and BVP-3A/30 series cameras. Optical efficiency is therefore identical to that of Sony's standard three-tube broadcast cameras. The efficiency of transformation of the light lumens on the individual tube faceplate to signal current output requires some explanation.

The output signal current from a pickup tube is given by:

$$I_s = dQ/dt \qquad (2)$$

or approximately by:

$$I_s = \Delta Q/\Delta t \qquad (3)$$

where ΔQ is the total charge removed in one field; and Δt is the period of one field.

In the Super Motion camera, the total charge removed is one-third that of a conventional camera, assuming constant lumens of light on the faceplate in either case. The total scanning period for one field is also reduced by a factor of three, so the ratio of $\Delta Q/\Delta t$ remains constant. Hence, the signal current level from a pickup tube is essentially independent of scanning speed.

The total noise generated in the front-end preamplifier is represented by an effective root-mean-square (RMS) noise current according to:

$$I_n \sqrt{\int_o^B \bar{i}_n^2 \, df} \qquad (4)$$

where the incremental noise current squared is:

$$\bar{i}_n^2 \propto \pi^2 f^2 [C_o + C_{iss}]^2 R_e \qquad (4a)$$

where C_o is the output capacitance of the tube assembly; C_{iss} is the input capacitance of the field-effect transistor (FET); R_e is the equivalent input resistance of the FET; and B is the bandwidth.

This RMS noise current thus has the familiar triangular noise spectrum represented in Fig. 5. In the downconversion employed in the camera DPU, the high-frequency noise is also converted down. Thus, the effective triangular equivalent noise current becomes as shown. The total equivalent noise current is in-

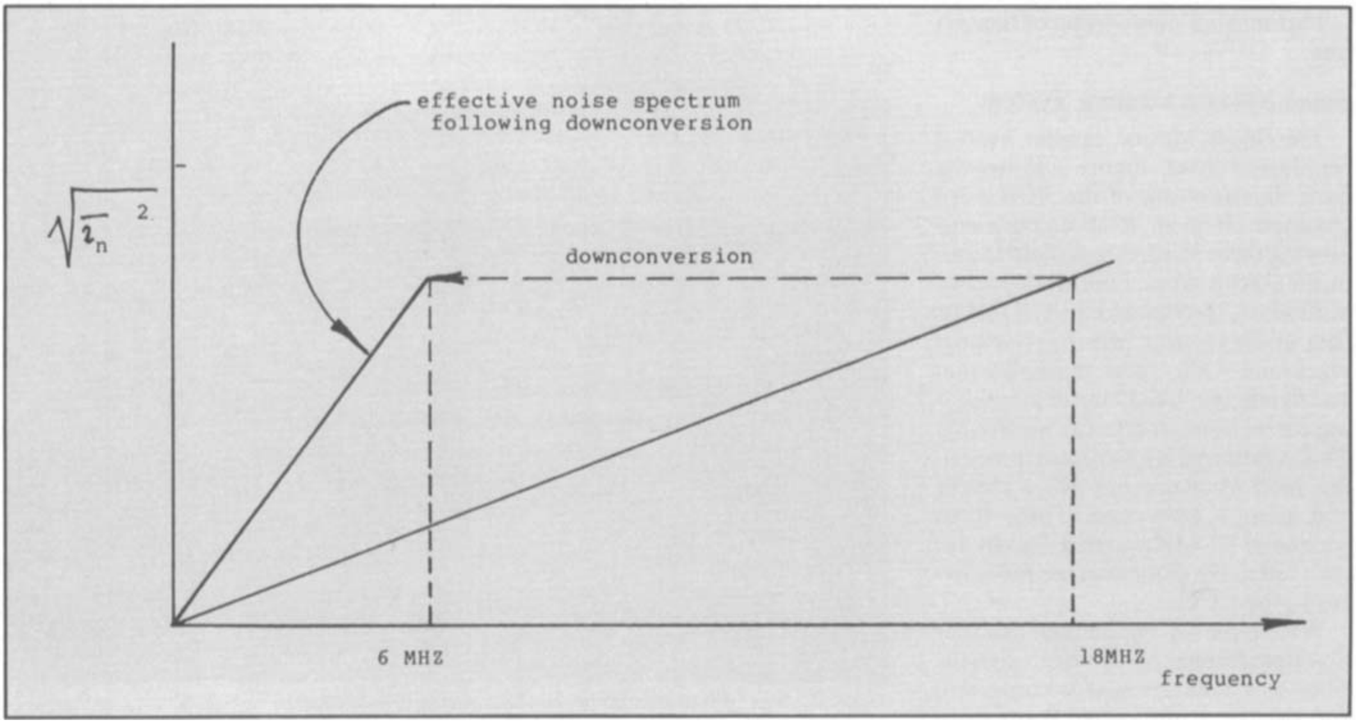

Figure 5. Process of noise downconversion in the Super Motion system.

creased approximately by a factor of three, thus degrading the camera signal-to-noise ratio (SNR) by approximately 9 dB. This deterioration is alleviated, however, by use of a new FET developed by Sony, which has a lower C_{iss} and a lower R_e. This same FET employed in a normal camera would produce an SNR in excess of 60 dB for a 4.2-MHz bandwidth. The Super Motion BVP-3000 system has an output SNR of about 51 dB for a 4.2-MHz bandwidth with a green signal current of 200 nA.

The capacitive lag (for constant light level and output signal current) is increased by a factor of three as a result of the high-speed scanning. This effect is reduced somewhat in the BVP-3000 by the use of a totally new mixed-field Plumbicon tube that features a diode gun and a low-capacitance photoconductive layer. Bias light is also operated at a higher level than in a normal ⅔-in. camera.

Camera Processing Unit

The wideband 20-MHz *RGB* analog signals are received from the camera cable into the DPU-3000 camera processing unit (Fig. 6) and are passed through a variable equalizer that can be switched to compensate for the particular cable length employed. Where fiber-optic link is used, this equalization is automatic.

The three video signals are then fed to three A/D converters. These are Sony designed and manufactured large-scale integrated (LSI) circuits designated CX-20116, which have a capability of 100-MHz maximum sampling rate but are operated here at a 43-MHz rate (or 12 × 3.58-MHz subcarrier). It is an 8-bit system.

The digitized video is then passed through a digital aperture-correction system, both horizontal and vertical, and is then delivered to a field memory system. This is a large digital memory organized into a bank of nine separate field memories (Fig. 7). This memory bank converts the single 180-field/sec video into three separate and distinct 60-field/sec signals. Each of the *R, G,* and *B* 8-bit parallel digital signals enters its memory bank as a serial sequence of high-speed fields. Each of these component video signals (which go into memory as a 525/180 scanning format) is subsequently clocked out at the slower 60-field rate.

The input high-speed fields, which are serial in time, are read out in par-

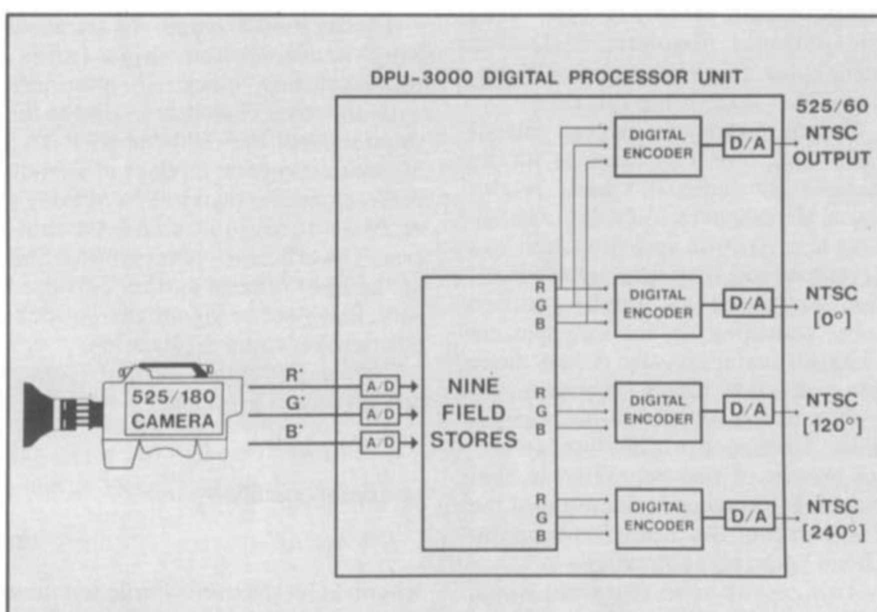

Figure 6. Block schematic of the DPU-3000 camera system.

allel according to the scheme shown in Fig. 7. That is, high-speed field 1, for the red video, is clocked out of memory block 1A as a 525/60 scanning format. Field 2 is clocked out 1/90 sec later from memory block 2A, also as a 525/60 signal. Similarly, field 3 comes from memory block 3A, delayed by a further 1/90 sec. Field 4 comes from memory block 1B and so on. These signals are clocked out of memory at 14.3 MHz (4 × 3.58-MHz subcarrier). Thus nine separate digital video signals are produced at a converted scanning rate of 525/60 — three red, three green, and three blue. Each original high-speed 180-Hz serial set of three fields becomes three parallel individual standard 60-Hz fields, displaced in time relative to each other (Fig. 8).

The next step is to formulate three encoded NTSC-type video signals from these three sets of *RGB*. Each set of time-coincident *R*, *G*, and *B* is matrixed, filtered, and encoded, all in the digital domain. A number of custom-built (by Sony) low-power digital C-MOS LSI chips perform this encoding (Fig. 9). Each of the three encoders is formulated from combinations of four basic LSI chips:

CX-23059	*Y,I,Q* matrix chip
CX-23056	*I,Q* filter and *Y* delay chip
CX-23057	*I,Q* modulator and sync mixer blanking chip
CX-23058	delta delay block

Three of the labeled chips are self-explanatory. The delta delay block LSI is required to match data timing

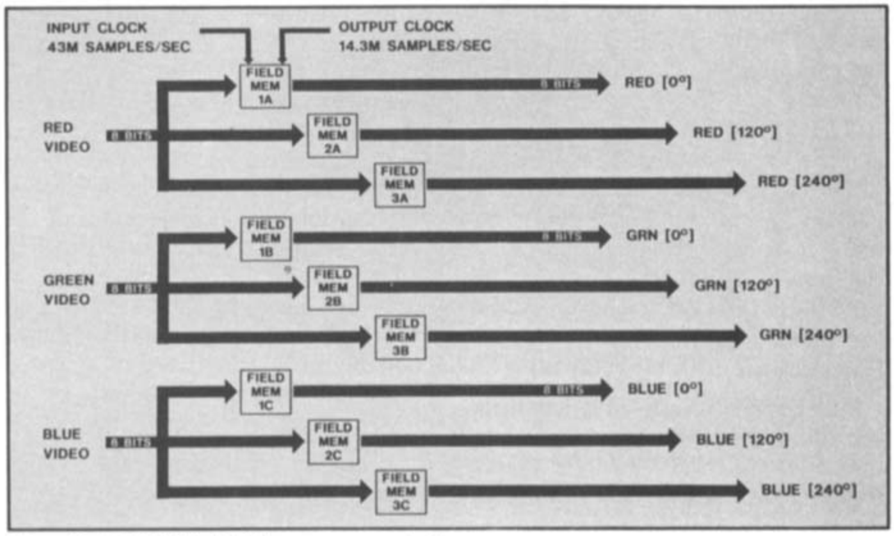

Figure 7. DPU-3000 digital memory organization.

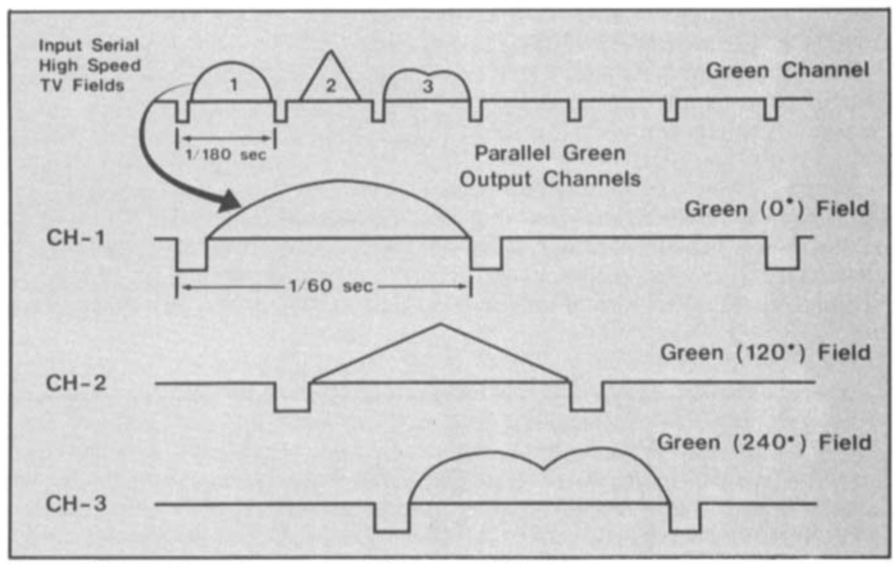

Figure 8. Separation and expansion of high-speed TV fields.

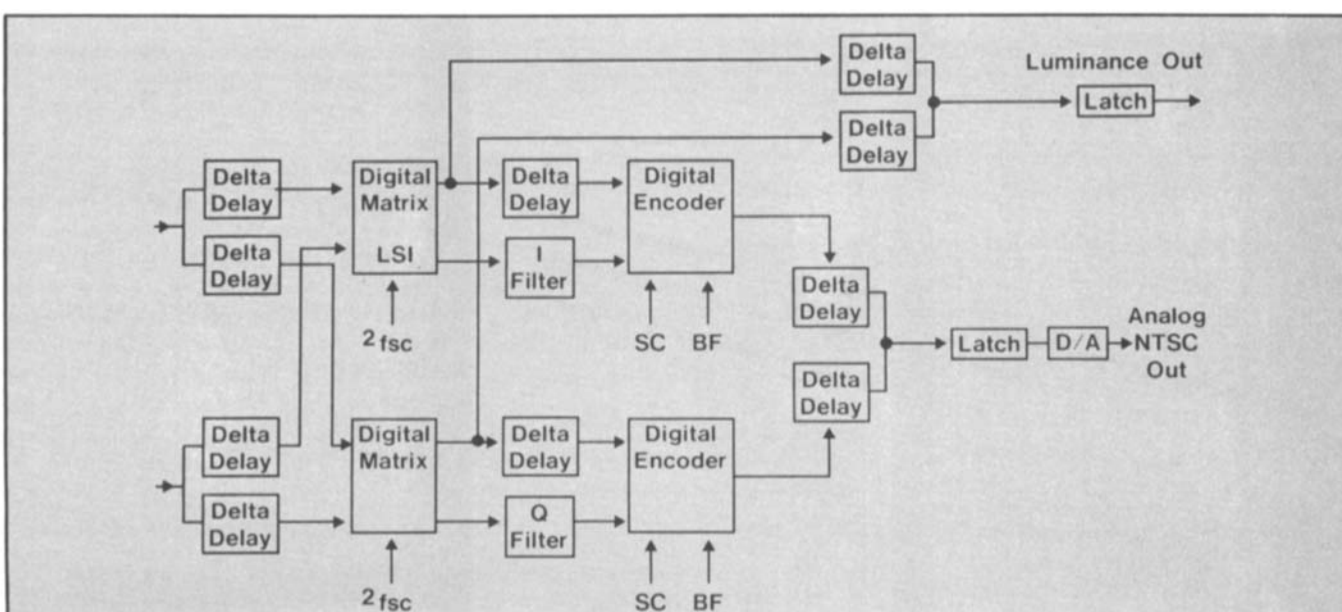

Figure 9. Digital encoding using LSI building blocks.

between the other LSIs. The low-power C-MOS devices employ pipeline techniques to overcome speed limitations.

The DPU-3000 arranges the three channel signals so that the correct color field sequence is recorded. This encoding is performed in the digital domain to ensure absolute equality of the three luminance and chrominance signals.

Super Motion BVH-2700 VTR

The Super Motion VTR has three recording heads, each positioned on the scanner at 120° relative spatial separation. During recording, the drum rotates at 60 Hz, and each of the three heads is separately driven by its previously described respective individual video signal from the DPU-3000 (Fig. 10). The BVH-2700 has a parallel three-channel recording system in contrast to the single video recording channel employed in a standard Type-C recorder.

The recording tape linear speed is 73.2 cm/sec, or three times that of a conventional Type-C recorder (3 × 24.4 cm/sec). The use of three record heads, at three times normal longitudinal recording speed, allows three times the amount of information (of a normal Type-C recorder) at standard scanner speed. Three video tracks are recorded per revolution of the scanner. Recording of the three fields takes place simultaneously because of the spatial 120° displacement of the three heads and the corresponding 120° relative time displacement of the three incoming video signals. Figure 11 indicates the recording methodology. The adherence to essential Type-C writing speed allows:

- Employment of current video recording technology
- Basing the BVH-2700 on a proven tape transport system
- Enhanced flexibility of the system (can play back all Type-C recordings).

The substantial increase in longitudinal tape speed, by a factor of three, actually increases the writing speed by about 2% above that of Type-C. The precise Type-C footprint on tape is carefully ensured by an increase in the helix angle, also by about 2%.

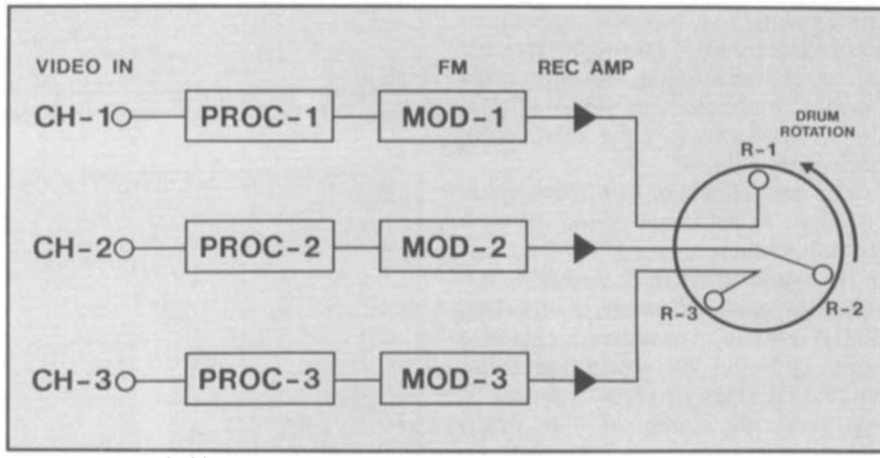

Figure 10. BVH-2700 drum with three recording heads.

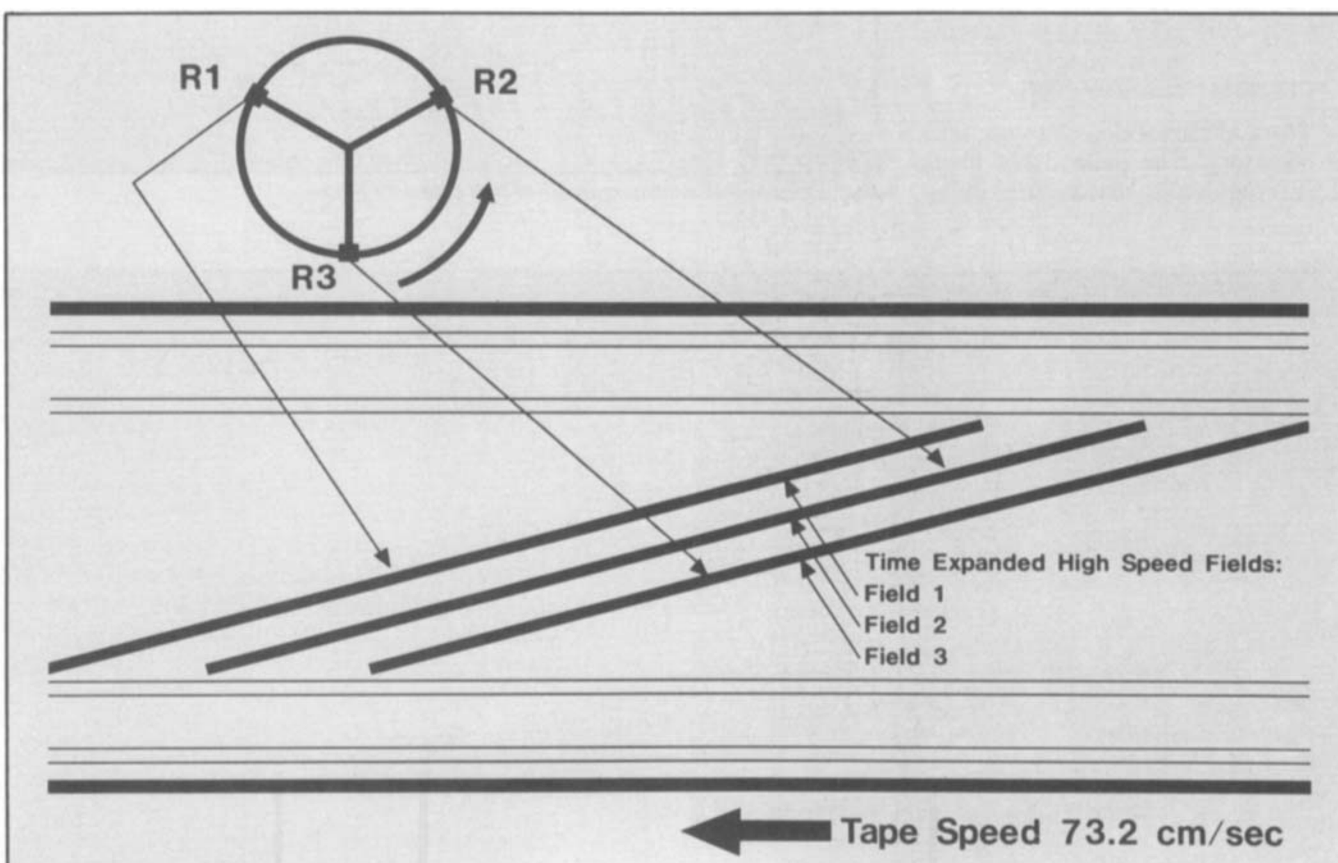

Figure 11. BVH-2700 recording method.

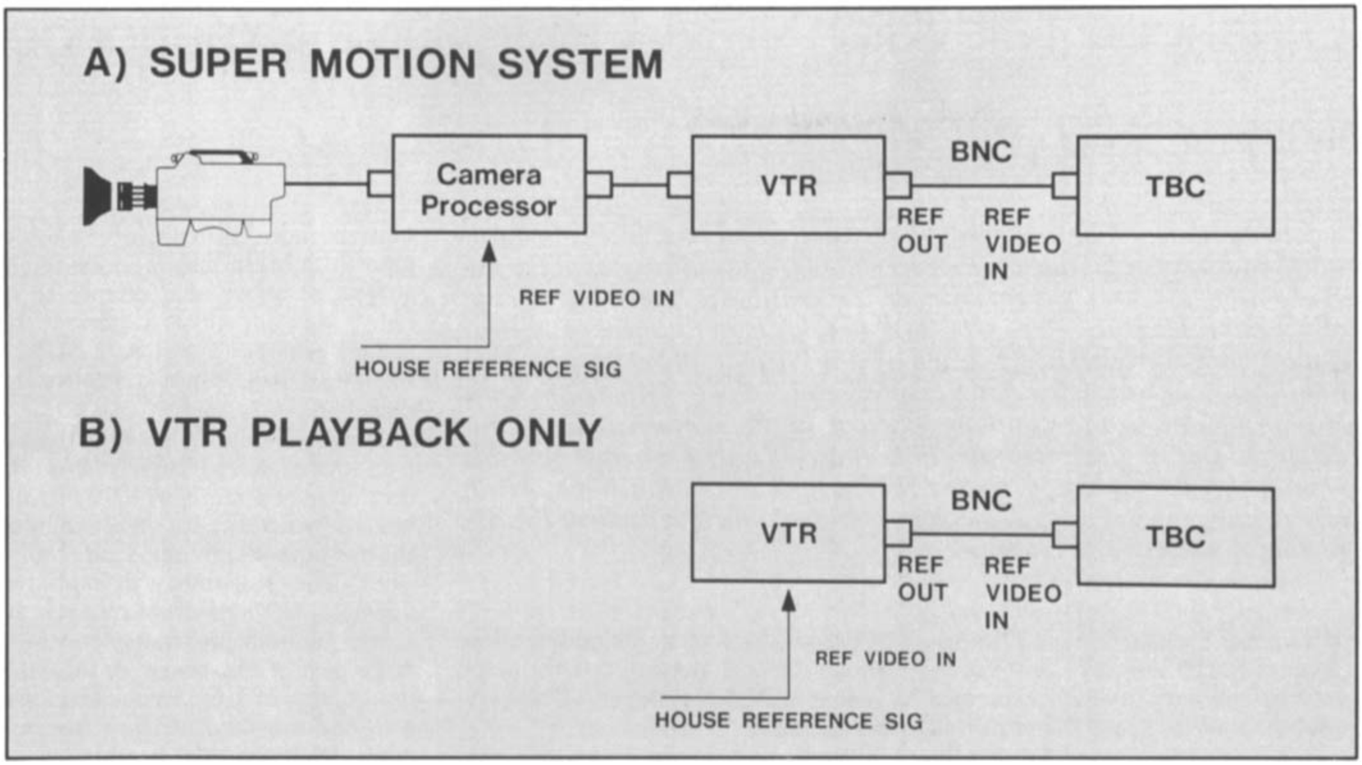

Figure 12. Operational configurations for the BVH-2700: (a) Super Motion system; (b) VTR playback only.

This, coupled with an effective reduction in head speed, guarantees the correct Type-C track angle on tape.

To reduce the head speed appropriately, one of two approaches is possible: a reduction in the drum diameter or a small amount of time compression of the incoming record video. The former expedient could cause difficulties in recovering sufficient signal for stable vertical sync detection. The time-compression technique, using the digital techniques of the Betacam system, was therefore employed. This solved the potential problem of still-frame playback and allowed the generation of the proper head-speed vector.

There are two operational configurations for the BVH-2700 VTR system. When it is employed in the Super Motion configuration (Fig. 12a), the recorder operates in the high-speed mode during recording, as described above. In playback, one head is used to separately trace one track at a time. The requirements are essentially those of a Type-C VTR except in the area of still-mode. In playback, with the VTR running at one times standard playback speed of 24.4 cm/sec, the result is one-third slow-motion playback, with full NTSC bandwidth pictures and greatly enhanced motion portrayal.

For real-time playback, the tape must travel at three times normal speed, in which instance the VTR will play back every third video track and display a picture identical to that from conventional Type-C recording techniques. If variable slow motion is required, this utilizes field-repeat methods similar to standard Type-C. Because we are starting with three times the number of fields, the clarity of motion remains substantially improved all the way down to still-frame. Even at very slow speeds and still-frame, the picture clarity is considerably improved because of the shorter exposure time of the frame. Image blur, due to prolonged subject movement within a given frame, is considerably reduced because of the 5-msec (approximately) field time. Most of the residual image blurring is a consequence of the inherent integration characteristics of the pickup device over that time period.

The BVT-2700 time-base corrector (TBC) is similar to that employed with a standard Sony Type-C machine. It has a wider correction window to meet the extended DT requirements of slow-motion playback on the BVH-2700.

Figure 12b shows the second configuration, where the BVH-2700 VTR and the BVT-2700 TBC can be used to play back any Type-C tape, independent of the DPU-3000 processor. Thus, the BVH-2700 system can be used as a normal Type-C playback machine. It cannot be used to record a standard NTSC signal.

Conclusion

The Super Motion system was specifically developed to alleviate the most pressing limitation of conventional slow-motion playback in television, the poor portrayal of movement. The system was *not* designed to address exclusively the clarity of a still-frame picture. HDTV technology permitted the design and practical implementation of a high-frame-rate camera. The high frame rate of 90 Hz, compared to the standard 30 Hz, dramatically elevates the capture of fast motion and preserves, in slow-motion VTR playback, a superb fluidity and smoothness of movement. This has been verified in a considerable number of sports events covered by the Super Motion system during the past year.

A novel method of separating and recording all of the captured high-speed video frames, while maintaining absolute adherence to Type-C recording specifications, was developed. This imbued the system with an important operational flexibility. High-definition technology, digital video processing, and Betacam technology, along with further refinement of DT technology, all coalesced to produce the Super Motion recording system.