9000 has evolved over two years of design effort and epitomizes the sophistication of design effort applied by the engineering team.

Summary

The purpose of the servo system in any tape recorder is to control precisely all moving elements, including tape, as control references require. Designing a precision control system begins with basic mechanical elements capable of operating precisely. Operating parameters of the servo loops must then be chosen to optimize the signal-to-noise ratio of loop error signals, and at the same time, to keep carrier frequencies high enough to support the required loop bandwidths (Fig. 5). This was done on the IVC-9000 transport and servo system. The final performance of these various servos is reflected in the time-base stability of the demodulator output. The peak-to-peak time base error of 0.2 μs is well within the 1-μs window of the time-base corrector.

An Analysis of Quadruplex and Helical-Scan Video Recording

By JEROME L. GREVER

In recent years, there have been a number of changes in the field of videotape recording — in the technology and in user requirements. In view of these changes, an RCA engineering team was assigned the task of evaluating whether future high-quality video recorder designs should be quadruplex or helical scan. This paper reports on the results of that investigation and gives some thoughts on video recording in the future.

NEARLY 18 years ago, the quadruplex videotape recorder was introduced to the broadcasting industry. Today, 7,000 quad machines are in use around the world — about 4,000 are in the U.S.A. And these machines are compatible — a tape recorded on an Ampex VR-1200 in Miami will play very well on an RCA TR-70 in Chicago. Or, a tape recorded in Hamburg, Germany, can be played to-air in Sydney, Australia.

Since 1956, quadruplex machines have undergone many improvements and the quality of today's video recording is quite high. However, during the last several years, many users have indicated a need for video recorders that are simpler to operate and that are more cost-effective — equipment that costs less to purchase and to operate. We at RCA recognized it was necessary to fully address these considerations and to make a scientific and objective judgement as to the optimum video recorder configuration in light of present and anticipated future requirements. Accordingly, we engaged in development work in areas that impact the cost and the complexity of the equipment. Many parameters were studied and trade-offs were evaluated. Following is a summary of what was learned during the course of that investigation.

Quadruplex vs Helical Scan

The first major question was whether our future high quality video recorders should be quadruplex or helical scan. Putting it another way, RCA management asked the Engineering Department, "Should we embark on the design of a high quality helical scan VTR?" In order to answer that question, a comprehensive evaluation of the key design parameters of both types of recorders was initiated.

In the design of a videotape recorder, a great many areas must be considered including reliability, maintainability and a host of operating features. In the course of the study it was decided that these items, although important, can be specified in overall design objectives and are not closely related to whether the recorder is quadruplex or helical scan. Other items, however, could be dependent upon the type of scanning and the investigation was focused on them. They are:

- Video Signal-to-Noise ratio
- Operating cost
- Manufacturing cost (purchase price)
- Head-to-tape interface
- Segmentation error
- Interchangeability
- Compatibility

In these areas, trade-offs can be readily made. For example, the designer can elect to improve the characteristic of interchangeability by suffering an increase in manufacturing cost. Or, he could decide to reduce operating cost at some sacrifice in signal-to-noise ratio. Let us review each of these areas.

Video Signal-to-Noise and Operating Cost

Signal-to-noise ratio is probably the most important performance parameter of a videotape recorder. It is also closely related to operating cost by virtue of track width and head scanning speed. Therefore SNR and operating cost will be treated together.

As shown in Fig. 1, the signal is recorded on the magnetic tape in a track whose width is equal to one dimension of the magnetic head. As the head scans the tape, the signal is recorded as a varying intensity of magnetic flux on the tape. The wavelength is proportional to the head scanning speed and the signal frequency being recorded. Analysis will show that the playback signal output is proportional to the track width and that the signal output increases with increasing wavelength. For short wavelength recording, as in video recording, the signal output increases with an increase in head scanning speed, but not linearly. Further, the tape noise increases as the square root of the track width. The combination of these factors causes the video SNR to increase approximately as the square root of the amount of tape used per unit of time.

The level of signal playback or SNR is also governed by characteristics of the tape. Figure 2 is the familiar hysteresis or B-H curve of a magnetic material. The amount of excitation required (H) and

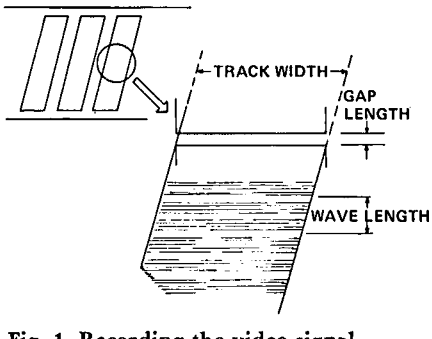

Fig. 1. Recording the video signal.

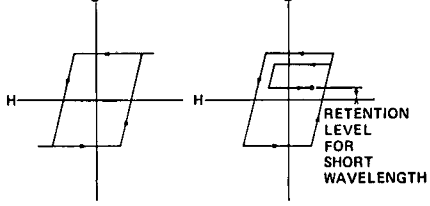

Fig. 2. B-H curve of magnetic tape.

Presented on 18 October 1973 at the Society's Technical Conference in New York by Jerome L. Grever, Electronic Recording Equipment Dept., RCA Corp., Camden, NJ 08102.

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the degree of magnetic strength retained (B) are related to the shape and size of the curve. For high-frequency signals the retained magnetic strength is not the peak value as shown on the left diagram but is the lower value shown on the right because of a phenomenon known as minor looping. The width of the B-H curve indicates the coercivity of the tape. The conventional magnetic tape for quadruplex recorders has a coercivity figure of 300 oersteds. If tape of higher coercivity is used, as is done with most helical recorders, a higher signal output is obtainable as shown in Fig. 3.

Now, with the foregoing in mind, let us look next at the amount of tape or the tape area used per unit amount of signal information. A convenient unit of measurement is the television field and Table I shows a tabulation of tape area required per TV field for quadruplex operating at 7½ and 15 in/s (19.05 and 38.10 cms), for three kinds of helical recorders using 1-in (25.4-mm) wide tape and a helical using 2-in (50.8-mm) tape. Also tabulated are SNR figures when using tapes of 300 or 500 oersted coercivity. SNR figures shown for the three helical machines are lower than the manufacturers' published figures by 1.5 dB. The figures are stated in this way in order to make a meaningful comparison between quadruplex and helical recorders. The quadruplex figures result from measuring the SNR by use of a wideband rms voltmeter. The SNR of helical-scan recorders is normally measured by using a gated noise meter with lowpass and highpass filters. This latter method yields a SNR approximately 1.5 dB higher than the former. Therefore 1.5 dB was subtracted from the manufacturers' SNR figures in order to make an accurate comparison.

Signal-to-noise ratio vs tape usage (tape area per TV field) is plotted in Fig. 4. This graphically illustrates that SNR is not dependent upon whether the tape format is quadruplex or helical — both types of recorders fit the same curve. Conclusions that were drawn at this point are:

(1) Many of the helical-scan recorders in use today rely upon high coercivity (high-energy) tape to achieve a usable SNR.

(2) Quadruplex can achieve a high SNR at 7½ in/s using high-energy tape.

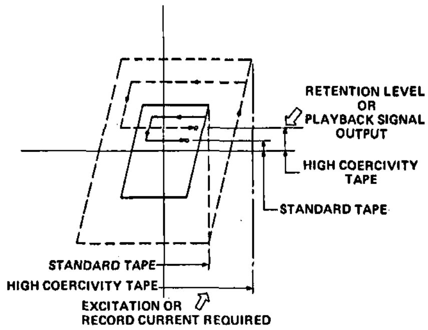


Fig. 3. Standard vs. high coercivity tape.

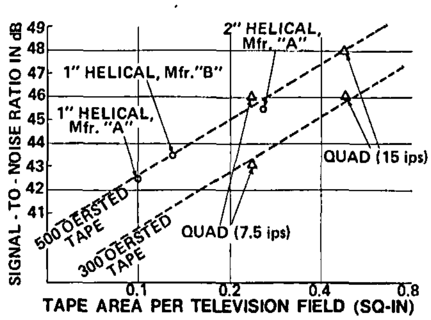


Fig. 4. Signal-to-noise vs. tape area.

(3) Comparing very new helical-scan recorders to quadruplex operating at 7½ in/s, the newest 1-in machine uses 25% less tape and the recently introduced 2-in machine uses 5% more tape than quadruplex.

(4) Older format helical recorders use less tape than quadruplex but their signal performance is inferior.

(5) If one were to design a new recorder to have a given SNR performance, the tape usage would be the same regardless of whether the machine were quadruplex or helical scan.

Another factor in operating cost is the wear of the video scanning head. With quadruplex recorders the average cost per hour is $1.80 although many users realize 90¢ an hour or less. For the higher quality helicals on the market, scanning head costs range from 20¢ to 60¢ per hour, depending upon type of machine and upon the environment. These differences accrue from the fact that helical head-to-tape pressure is substantially less than with quadruplex. Conclusion is that helicals have a clear advantage over quadruplex in the cost of video head wear.

Manufacturing Cost or Purchase Price

The image of inherently lower manufacturing and purchase costs has been associated with helical recording since its inception. This is primarily because the early products were intended for minimum cost lower performance applications. Since the capital cost of equipment is an item of major importance, our engineers conducted a detailed study of the manufacturing cost of a quadruplex and helical recorder which would be designed to have equal characteristics of performance, operating features, reliability and maintainability. Each recorder type was broken down into subsystems as shown in Fig. 5. In this case the helical recorder was a single-head type, which is the most economical helical configuration.

These same subsystems are listed in Table II. We have converted the manufacturing cost figures into percentages using the cost of the quadruplex system as the reference. Note that the total cost differential is 9%. This 9% helical cost advantage is primarily related to the use of fewer magnetic heads with therefore fewer record and playback circuits, and to slightly lower cost mechanical assemblies. The pricing of recently introduced helical recorders tends to verify the accuracy of our analysis — for example, one of the new helical machines is priced at approximately $87,000.

Our conclusions on manufacturing cost:

(1) If one were to design a helical and a quadruplex recorder having essentially equal characteristics, the helical should cost about 9% less.

(2) If the cost differential between a helical and a quad recorder is more than about 9%, we believe it likely that some important characteristics would be lacking in the helical machine. It would probably be deficient in one or more of these areas: performance; operating features; reliability; and maintainability.

Head-to-Tape Interface

Our engineers have made detailed theoretical and experimental studies of head-to-tape contact. In the quadruplex system, depicted in Fig. 6, intimate and accurate contact is made possible by a small diameter wheel penetrating into tape held precisely by a vacuum guide.

Table I. Tape Usage vs Signal-to-Noise Ratio.

	Tape width, in (mm)	Tape speed, in/s (cm/s)	Head scanning speed, in/s (m/s)	Area per TV field, in² (mm²)	Signal-to-noise ratio, dB 300 Oe	500 Oe
Quadruplex	2 (50.8)	15.00 (38.10)	1560 (39.624)	.450 (290.32)	46	48
Quadruplex	2 (50.8)	7.50 (19.05)	1560 (39.624)	.225 (145.16)	43	46
1-in Helical Mfr "A"	1(25.4)	6.90 (17.53)	723 (18.364)	.103 (66.45)		42.5
1-in Helical Mfr "B"	1 (25.4)	9.62 (24.43)	1000 (25.400)	.123 (79.35)		43.5
1-in Helical Mfr "C"	1 (25.4)	12.61 (32.03)	1124 (28.550)	.168 (108.39)		Spec. not available
2-in Helical Mfr "A"	2 (50.8)	8.00 (20.32)	1570 (39.878)	.236 (152.26)		45.5

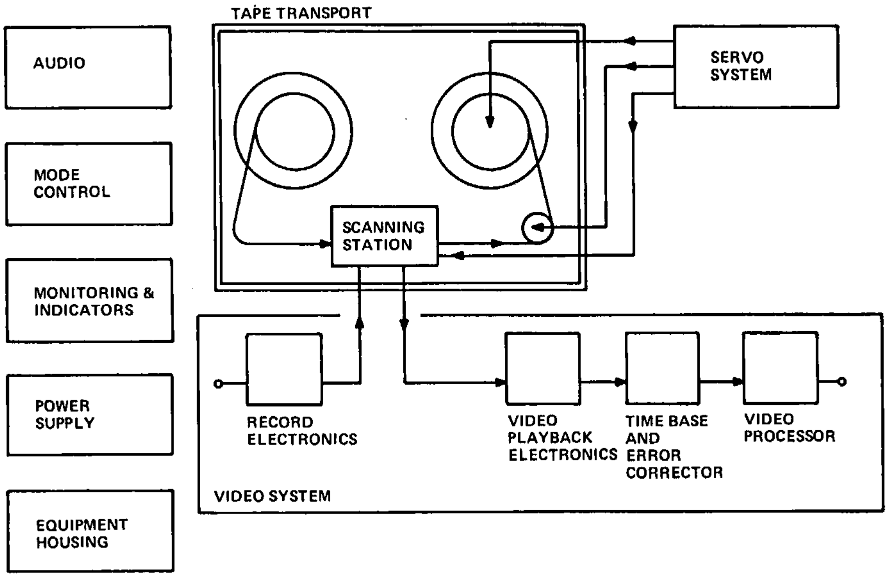
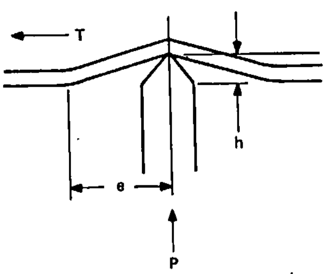
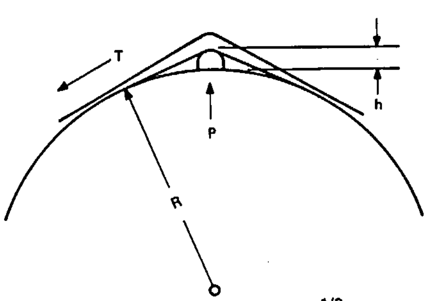


Fig. 5. Basic block diagram of a video recorder.



P: PRESSURE ON HEAD $P \approx T\frac{h}{e} = 0.03\,T$
T: TAPE TENSION
e: 1/2 OF VACUUM GUIDE SLOT WIDTH e = 0.061"
h: POLE TIP PROTRUSION h = 0.002"

Fig. 6. Quadruplex head-to-tape configuration.



P: PRESSURE ON HEAD $P \approx T\left(\frac{h}{2R}\right)^{1/2} = 0.016T$
T: TAPE TENSION
R: DRUM RADIUS R = 3.50"
h: POLE TIP PROTRUSION h = 0.002"

Fig. 7. Typical helical head-to-tape configuration.

Table II. Manufacturing Cost of Equivalent Quadruplex and Helical-Scan Recorders.

	Quadruplex		Single-head Helical	
Video Subsystem				
Record electronics	6		4	
Playback electronics	9		7	
Time base and error corrector	15		15	
Video processor	2.5		2.5	
		32.5%		28.5%
Servo Subsystem				
Headwheel	6		6	
Capstan	4		4	
Reel	1		1	
Guide or tension	1.5		1	
		12.5		12.0
Tape transport (including motors and audio heads)		17.5		15.0
Video head scanning station		5.0		3.0
Audio electronics		7.5		7.5
Mode control		2.5		2.5
Monitoring-indicator subsystem		10.0		10.0
Power supply and equipment housing		12.5		12.5
Total		100.0%		91.0%

This arrangement provides consistent high quality recording with a low drop-out rate.

Typical helical-scan geometry is shown in Fig. 7. The normal head-to-tape pressure is about one-half that of quadruplex which leads to more dropouts with helical, especially as the tape wears.

• COEFFICIENT OF ELONGATION BY TEMPERATURE:

$K_T = 1.5 \times 10^{-5}/°F$

• COEFFICIENT OF ELONGATION BY HYGROSCOPIC VARIATION:

$K_H = 1.1 \times 10^{-5}/\%$ R.H.

MISTRACKING DUE TO TAPE ELONGATION

• TRACKING ERROR EXPRESSED AS % OF TRACKWIDTH:

$$\text{TRACKING ERROR (\%)} = 100\,\frac{S(TK_T + HK_M)\sin\alpha\cos\alpha}{W_T}$$

S: LONGITUDINAL TAPE DIMENSION COVERED BY ONE TRACK
T: TEMPERATURE CHANGE
H: HUMIDITY CHANGE
W_T: TRACK WIDTH
α: TRACKING ANGLE WITH RESPECT TO THE LONGITUDINAL EDGE OF TAPE

Fig. 8. Tracking error due to dimensional instability of tape.

Furthermore, unless the tape is floated on an air film around the scanning assembly, head-to-tape pressure will vary along the length of the videotrack because of friction between the tape and the stationary surfaces of the scanning assembly. These pressure variations would be translated into fluctuations of frequency response in the FM system which in turn would cause chroma level flutter.

Segmentation Error

A disadvantage that exists in quadruplex recorders and not in single head helical-scan machines is related to the fact that the quad system dissects a television field into a number of segments. If the four head-channels are not properly equalized by the operator, a picture defect known as banding can result. This is not considered a serious problem when using modern velocity error and chroma amplitude correctors.

Single-head helical-scan recorders do not exhibit banding because an entire TV field is recorded on a single-track scan. However, two-head segmented-scan helicals may have another type of picture defect which is a fluctuation of the chroma amplitude at the TV field rate — the eye sees this as color flutter, more visible in high-chroma areas of the picture.

Interchangeability

In order to achieve reliable interchange of tapes between recorders at different times and in different environments, it is necessary to have a high degree of dimensional stability between the tape and the video scanner. The base material of magnetic tape is Mylar (a trademark registered by E. I. duPont de Nemours) and its physical characteristics are well known. Its coefficients of elongation as a function of temperature and humidity are such that serious dimensional changes can occur due to these factors. Figure 8 gives equations for elongation of Mylar tape and for the attendant degree of mistracking. Added to these temperature and humidity induced instabilities are

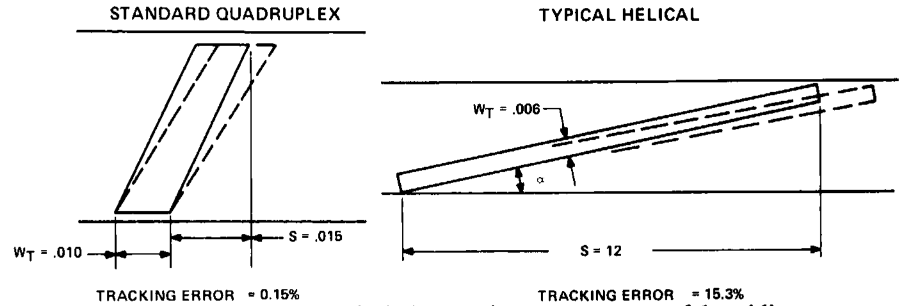


Fig. 9. Tracking error due to typical changes in temperature and humidity.

dimensional changes due to variations in tape tension.

Dimensional instability will result in mistracking of the recorded track by the scanning head. The degree of mistracking is proportional to the change of tape length covered by one head scan. Using the equations given in Fig. 8, we can calculate the tracking error for some fairly typical environmental changes — a temperature change between recording and playback from 50° to 80° Fahrenheit and relative humidity change from 30% to 80%. The results of the calculation are given in Fig. 9. The environmental changes will cause a very small tracking error in a quadruplex system — only 0.15%. However, in a helical-scan recorder, the degree of mistracking will be quite large — 15%.

Unfortunately, these are not the only factors which affect tracking. The fairly large helical tracking error depicted in Fig. 9 is added to a tracking error due to tape tension variations and to mechanical tolerances of the video scanner. The combination proves to be a rather serious problem to keep under control. Another unfortunate circumstance of the helical tracking problem is that a simple control track phasing adjustment will not compensate for the tracking error. Nor will an automatic control track phasing device. The situation is a dynamic one which changes along the length of the video scan. A rather sophisticated tape length servo would likely be required to significantly reduce the tracking error.

Our conclusions regarding interchangeability are:

(1) The quadruplex format is essentially immune to tracking errors due to environmental factors and tape tension variations. As a result, quadruplex recorders exhibit a high degree of interchangeability under extreme variations of temperature, humidity and tape tension.

(2) Helical recorders, by the nature of their format, are highly susceptible to tracking problems and are not reliably interchangeable.

Compatibility

In considering the use of helical-scan recorders for broadcast and educational applications, the lack of a standard format is a rather serious problem — there are nearly as many formats as there are manufacturers and hardly ever are any two compatible. There appears to be no solution to this problem in sight, even in the long term. On the other hand, world-wide compatibility of quadruplex is an established fact.

Conclusions

That is the last of our seven major areas of investigation. The final step for our engineers was to weigh all of the pros and cons and make an overall judgment as to the better approach for the design of future video recorders. It was concluded that quadruplex is the preferred approach because its advantages — especially reliability of tape interchange and compatibility — substantially outweigh the helical advantages. Following is a listing of advantages accruing to each design:

Helical-Scan Advantages	*Quadruplex Advantages*
Video head cost	Interchangeability
Manufacturing cost, 9% lower than Quad	Compatibility
	Head-tape interface

Signal-to-noise ratio, tape usage and segmentation error do not appear on this list because future recorder designs would be essentially equivalent in these areas. In a later section of this paper I will describe a development which will eliminate segmentation error in quadruplex recording.

In summary, we have concluded that quadruplex is the better approach for high-quality recording for today and for the future — at least for the next 5 to 10 years. In the longer term, beyond 5 to 10 years, we believe a radically different method of recording could supplant both helical and quad. In the interim, for broadcast and other high-quality applications, we believe that helical recording does not offer enough to the industry to justify a move in that direction.

The Future of Quadruplex

What are our views of quad recording for the next 5 to 10 years? We see major product innovations in the future and a continual improvement of performance and features in certain areas. For example, in order to realize the full potential of recent years' technological advances, a modification of the present SMPTE standard for video recording should be considered. As we see it, these modifications to the standard would be slight and could be such that compatibility would be maintained between today's quadruplex equipment and future recorders which employ the modified format. This brings us to the much publicized Quad II.

Quad II is a proposed modification to the video recording standard. As we view it, Quad II relates only to 625-line recorders — machines used in Europe, Australia, etc. Except from the academic viewpoint, it should not affect users in the U.S.A. For 525-line recorders, RCA is proposing a modified format which we have dubbed Quad IA. The IA terminology is used to connote a minor departure from the current video recording standard. This, by the way, is RCA's terminology and we haven't yet suggested that title to the SMPTE. (We assume most readers are aware that the present quadruplex recording standard was promulgated by the SMPTE.) RCA plans to make a formal proposal on the Quad IA format to the appropriate SMPTE committee.

The entire picture can be depicted in Table III. Quad I is the present video recording standard and, although there are some small differences between 525- and 625-line systems, we can approximately represent both by the figures in that column.

First let's address tape speed: Whereas all Quadruplex reel-to-reel recorders in use today have switchable tape speed

Table III. Proposed Modifications to Quadruplex Video Recording Standard.

	Quad I	Quad IA 525-Line	Quad II 625-Line
Tape speed, in/s	15 (primary) $7\frac{1}{2}$	$7\frac{1}{2}$ (primary) 15 (special)	$7\frac{1}{2}$ (primary) 15 (special)
Tape coercivity, Oe	300	500	500
FM deviation, MHz	7–10	7–10	9–12
Pilot tone	No	Yes	Yes
Program audiotracks	1	1*	2
Cue track	1	1	1
Compatible with Quad I	—	Yes	Yes

* Provision for stereo

of $7\frac{1}{2}$ and 15 in/s, 90% of these machines are operated at 15 in/s. This is understandable since performance at 15 in/s has been decidedly superior in the past. However, technological advances in servomechanisms, video head materials and other areas allow $7\frac{1}{2}$ in/s performance at essentially the same level as the industry has been achieving at 15 in/s. So, we should cut tape costs in half by moving toward $7\frac{1}{2}$ in/s as the primary recording speed and providing 15 in/s for special purposes such as mastering and dubbing where extra-high SNR is important. In both Quad IA and Quad II, a minor change in the standard format would be required. For example, we will propose a slightly wider videotrack and perhaps a change in signal pre-emphasis.

Next, tape coercivity: High energy tape of 500 oersteds is not readily available for quadruplex recorders. However, since higher SNR can be achieved with these tapes, RCA will urge the tape manufacturers to start supplying 500-Oe tape on a more readily available basis.

FM deviation: In 625 line systems, beats or moiré in the picture has been a rather serious problem. Accordingly, for Quad II we are proposing a super-high-band deviation range of 9–12 megahertz. Since moiré is no problem in 525-line systems we will recommend no change in this parameter for Quad IA.

Pilot tone: Here, we would propose the use of a continuous wave signal added to the recorded video signal, which, on playback, would be used to correct for amplitude and phase errors, thereby essentially eliminating all traces of banding. This will simplify the operation of quad machines because less attention will need be paid to manually adjusting the four channels for optimum playback. We have a pilot tone system operating in our Camden, N. J. laboratory and are very pleased with its performance. As part of RCA's overall plan, there will be a simple and straightforward modification for existing quadruplex recorders to allow them to ignore the pilot tone when these machines are required to play Quad IA or Quad II tapes.

Program audio: For Quad II we are proposing two program audio channels for bilingual use — to allow, for example, the recording of German and French on the same tape. For Quad IA we are not proposing two audiotracks, although it is possible that some users will want to record stereo, quadraphonic, or something, in the future. To that end, we would propose a somewhat wider audiotrack on which stereo signals could be recorded in multiplexed form or possibly a method of splitting the audiotrack in a way that would be compatible with Quad I tape and machines. And, there would still be a cue track as in the existing standard.

Finally, Quad IA and Quad II machines would have provisions for playing tapes which had previously been recorded on the present format (Quad I). This would preserve compatibility between present tape libraries and future Quad IA/Quad II machines.

Now, about standardization activity. For a relatively short period of time, RCA and others in the industry have been considering the possibilities of a modified quad format. Two committees have already been formed to discuss the matter on an organized industry basis. An SMPTE Ad Hoc Committee was organized March 23, 1973 and the International Electrotechnical Commission formed a committee on June 22, 1973. The SMPTE Committee has been very active, having had two meetings and four telephone conference calls in the first seven months.

That's where things stand today. At this point there shouldn't be much doubt in the reader's mind as to the course RCA is on — and, we believe, for sound technical reasons. Our engineering development programs, along with a great deal of field experience, indicate that quadruplex is the way to build high quality video recorders for the foreseeable future.

Edit. Note: *Due to the exigencies of the production schedule for the* Journal, *discussion among the authors of the papers above which was not possible at the Conference is being obtained in writing for publication in a subsequent issue of the* Journal.