The United States Digital Advanced Television Broadcasting Standard

Robert Hopkins

Advanced Television Systems Committee
1750 K Street NW, Suite 800, Washington, DC

ABSTRACT

A demonstration of high definition television (HDTV) was given in the United States in the early 1980's. It inspired the imagination as to what might be seen, someday, in the homes of television viewers. Now, some fifteen years later, we are on the verge of adopting a new television broadcasting standard. In the near future, the Federal Communications Commission is expected to make its final ruling on the new technology. The new standard will be 100% digital, something nobody would have guessed watching those early demonstrations.

This paper will briefly review some key technical debates. The debates were related to HDTV production standards and analog HDTV broadcasting during the 1980's. They began to shift focus in 1990 as the first digital HDTV broadcasting proposals were made public. More recently, the debates have centered on the tremendous flexibility that can be obtained with a digital broadcasting system. The Digital HDTV Grand Alliance system, that has been under study in the FCC's Advisory Committee on Advanced Television Service and documented by the Advanced Television Systems Committee, will be highlighted. Current status of the technical standard will be explained. To conclude, comments on the future potential of this new television broadcasting technology will be offered.

Keywords: advanced television, ATV, digital broadcasting, high definition television, HDTV, ATSC, Grand Alliance

1. INTRODUCTION

In the early 1980's, it was conventional wisdom that high definition television (HDTV) broadcasting would be possible only from satellites; and, of course, the broadcast signal would be analog. In the United States, there seemed to be little interest in HDTV broadcasting, or satellite broadcasting. There was a budding interest, though, in HDTV production. The first time many engineers saw HDTV pictures was at the Society of Motion Picture and Television Engineers (SMPTE) Winter Television Conference in San Francisco in February 1981. The Japanese Broadcasting Corporation (NHK) provided a demonstration of the 1125-lines, 60 Hz HDTV system they had been developing. Shortly after the SMPTE Conference, the equipment was taken to New York and Washington, DC for more demonstrations.

With HDTV just over the horizon, many in the United States began to think that the time for a single world-wide standard had arrived; and a future HDTV standard offered

---

Published in the Proceedings of SPIE Volume CR61, Standards for Electronic Imaging Technologies, Devices, and Systems, January 1996, pp. 193-216.
Paper presented in San Jose, California, February 2, 1996.

that opportunity. Because there was only one system under development, it was thought that system could become the single standard.

2. ADVANCED TELEVISION SYSTEMS COMMITTEE (ATSC)

In 1983 it was becoming clear that something was going to happen with HDTV. It was also clear that the standards issues were broader than any one standards organization. As a result, the Electronic Industries Association (EIA), the Institute of Electrical and Electronics Engineers (IEEE), the National Association of Broadcasters (NAB), the National Cable Television Association (NCTA), and the Society of Motion Picture and Television Engineers (SMPTE) formed the Advanced Television Systems Committee, the ATSC, to serve as an over-sight committee. All of the various constituents of the United States television industry were invited to become members of the new organization.

The purpose given to the ATSC through its Charter was to explore the need for and, where appropriate, to coordinate development of voluntary national technical standards for advanced television systems. Also, where useful and appropriate, the ATSC Charter calls for submission of its voluntary standards to the American National Standards Institute for consideration as American National Standards and to the Federal Communications Commission for regulatory consideration. With regard to international issues, ATSC was charged with developing proposed United States national positions for presentation to the appropriate department in the United States Administration.

ATSC immediately became involved in the international discussions related to HDTV production standards. The biggest impediment to achieving a single standard has been the 50 Hz / 60 Hz difference. While this may not be a technical problem today the way it was in the early days of television, everybody, it seems, is afraid to make that kind of change because of backward compatibility. But, there also may be national political reasons that prohibit world-wide agreement, even if the 50/60 Hz problems go away. In any event, for some combination of these reasons, the efforts for a single world-wide HDTV production standard suffered a defeat at the Consultative Committee on International Radio (CCIR) Plenary Assembly in Dubrovnik in 1986.

The United States, Canada, and Japan were pushing the CCIR to adopt the 1125/60 system as a single world-wide HDTV production standard. Others, however, especially some Europeans, were very concerned that this would lead directly to a single broadcasting standard, one based on 60 Hz; and they certainly did not want a 60 Hz broadcasting standard! After Dubrovnik, the interest in HDTV began to shift from production to broadcasting.

3. HDTV BROADCASTING DEVELOPMENTS IN THE 80'S

3.1 Europe

Shortly after Dubrovnik, Europeans established an HDTV satellite broadcasting project called Eureka 95, or EU95. Governments were heavily involved in the project. Terrestrial broadcasting was not considered, primarily because no new television spectrum was available. It was assumed that conventional PAL and SECAM terrestrial broadcasting would continue, perhaps with compatible enhancements.

A new signal format, multiplexed analog components (MAC), had already been developed in Europe and was being implemented for satellite broadcasting. It was a 625-line signal and represented a moderate improvement in quality compared with PAL and SECAM. In the MAC format, luminance and chrominance components are kept separate and time-compressed. There were several different versions (C-MAC, D-MAC, and D2-MAC) under development, though. The outcome of EU95 was a new signal format called HD-MAC. It was a compatible enhancement of the already existing MAC family.

3.2 Japan

In its development of the 1125/60 system, NHK designed a satellite broadcasting system called MUSE (multiple sub-Nyquist sampling encoding). Essentially, this was a time-multiplexed analog component system that was sub-sampled in a quincunx pattern. After four fields, the entire signal was transmitted.

Because terrestrial spectrum is not available in Japan, terrestrial broadcasters supported the development of enhancements to the NTSC system. These developments were staged in phases, with each phase representing continued improvement. Even the final phase, though, is not HDTV.

3.3 United States

In the United States, the Federal Communications Commission (FCC) was on the verge of re-assigning some television spectrum for land-mobile use. Broadcasters, of course, were opposed. If HDTV required greater bandwidth than NTSC, and if potential television channels were going to be used for other purposes, where did that leave the broadcasters? There was general belief that the alternative media (cable, satellite) could and would deliver high definition programs to the public.

Broadcasters, through the National Association of Broadcasters (NAB) and the Association for Maximum Service Television (MSTV), sponsored a demonstration of HDTV broadcasting from a terrestrial TV station in Washington, DC to show feasibility and to stimulate interest in looking at the issue. Two contiguous 6 MHz channels, 58 and 59, were used as a single 12 MHz channel. The demonstration was very successful.[†] Shortly thereafter, some 55 broadcasters petitioned the FCC to initiate a Notice of Inquiry (NOI) to determine what options broadcasters would have.

The FCC did initiate an inquiry and formed an industry Advisory Committee on Advanced Television Service. In the process, the FCC also coined the term ATV for "advanced television." The term was used to cover a variety of improvements to

[†] NHK demonstrated a terrestrial microwave delivery system at the same time.

television, ranging from simple enhancements of NTSC to full high definition television.

4. ADVISORY COMMITTEE ON ADVANCED TELEVISION SERVICE

The Advisory Committee was authorized for two years and asked to "...advise the Federal Communications Commission on the facts and circumstances regarding advanced television systems for Commission consideration of technical and public policy issues." In addition, the Advisory Committee was asked to "...recommend policies, standards and regulations that would facilitate the orderly and timely introduction of advanced television services in the United States."

The Advisory Committee existed for more than eight years, through three Administrations and four FCC Chairmen. Hundreds of volunteers participated in the work of the Advisory Committee. Issues such as planning factors and user requirements were laid out early. Other issues, such as technical standards and implementation details, took more time. Technical proposals were requested, then examined in excruciating detail. One key requirement was that the proposals had to be implemented and demonstrated — paper proposals were not sufficient.

Within months, there were twenty-some proposals for advanced television systems. The Advisory Committee volunteers took their jobs seriously, critically examining every proposal. Ones which lacked substance eventually disappeared. The number of surviving proposals declined rapidly.

The private sector fully supported the Advisory Committee. For example, broadcasters formed the Advanced Television Test Center (ATTC) in 1988 to test proposed systems. The Cable Television Laboratory (CableLabs) was formed by the cable television industry in 1988. One stated purpose of CableLabs was to test the proposed systems; indeed, they built a test facility at the ATTC location. The Advanced Television Evaluation Laboratory (ATEL) in Canada offered to perform the subjective assessment tests.

4.1 Early proposals

Early in the process, there seemed to be a preponderance of views that a high definition broadcasting system should be compatible with NTSC. Two types of proposals fell in this category, 1) NTSC receiver-compatible systems and 2) augmentation systems. The NTSC receiver-compatible signal, with 6 MHz bandwidth, would appear to be NTSC to an NTSC receiver, but would contain "hidden" information to enhance the picture on an ATV receiver. The augmentation signal would be broadcast in a separate channel and "added" to the 6 MHz NTSC signal in the ATV receiver. While both approaches had the advantage that NTSC receivers would not be made obsolete, both had the disadvantage that NTSC, with its inefficient use of the spectrum given today's technology, would continue indefinitely.

Some "visionaries," led by Zenith and MIT, began to talk more openly about a third possibility, a totally new spectrum-efficient 6 MHz signal, incompatible with NTSC receivers. The NTSC receiver-compatible proposals were thought to be deficient because the improvements were not adequate. The augmentation proposals were thought to be deficient because extra spectrum was required. By adopting a new 6 MHz system, and simultaneously broadcasting programs using NTSC during a transition period, 1) the compatibility problem would be solved, 2) the spectrum efficiency problem would be solved, and 3) the improvement problem would be solved. This procedure is analogous to the early years of AM/FM radio simulcast. People began to realize that if you had to use two channels, it could be done in such a way that you could eventually re-claim the first channel. By this time, all proponents of augmentation systems had dropped out. Simulcast was beginning to gain favor. But it was still an analog signal.

4.2 Digital proposals

Digital broadcasting was first proposed by the General Instrument Corporation in 1990, about one week before the deadline for submitting proposals to the Advisory Committee. Almost everyone had believed digital broadcasting would not be possible for many years into the future. After examining the General Instrument proposal very carefully, most people began to believe digital broadcasting would be possible. Less than one year later, all remaining HDTV system proponents, except one, had modified their proposals to be digital systems. Within another year, the last two enhanced NTSC system proponents dropped out. This left five systems under consideration, all HDTV, and four of them were all-digital.

The competitive phase of the Advisory Committee work was well underway, and it had been quite successful.

Meanwhile, in Europe, it became clear that the analog HD-MAC program was not the proper direction. Many laboratories began to investigate digital broadcasting privately. Eventually, the HD-MAC program ended and the Digital Video Broadcasting (DVB) Group, dominantly a private sector organization, was formed to lead the investigations on digital television broadcasting. The DVB emphasis was, and continues to be, standard definition television (SDTV) rather than HDTV.

In Japan, an analog HDTV satellite service was initiated using the MUSE system. Consumers could purchase HDTV receivers, but at a premium price. The NHK entry in the American process continued to be analog.

4.3 First-round testing

The first round of testing began at ATTC in July 1991 and finished at ATEL in November 1992. Test reports were published for each of the five HDTV systems, about one thousand pages each. The Advisory Committee working groups were kept busy analyzing the test data.

These reports went to a meeting of Advisory Committee leaders, called the Special Panel, in early 1993. The participants in the meeting were the chairs of the multiple Advisory Committee groups, plus a few others that were added to ensure that various industries were represented. The meeting lasted four days. At the conclusion of the meeting, it was agreed that only digital systems should receive further consideration. It was agreed also that none of the four digital systems was clearly superior to the others. So, the Special Panel recommended that various improvements — improvements that the individual proponents had suggested would make their system superior to all others — should be implemented and then the systems should be tested again.

One clear message that came from the test results and discussions at the Special Panel meeting was that digital HDTV broadcasting in a 6 MHz channel was not a fantasy, it was a reality.

The Special Panel recommendations went to the Advisory Committee in February 1993. The Advisory Committee adopted the recommendations. Both references 1 and 2 contain the full report. Summaries of the report are available as references 3 and 4. But, the Advisory Committee also strongly suggested that the proponents should pool their resources and make a "Best of the Best" proposal.

Three months later the Digital HDTV Grand Alliance was formed. And thus began the cooperative phase of the Advisory Committee work.

5. DIGITAL HDTV GRAND ALLIANCE SYSTEM

Members of the Digital HDTV Grand Alliance are AT&T, David Sarnoff Research Center, General Instrument Corporation, Massachusetts Institute of Technology, Philips Electronics North America Corporation, Thomson Consumer Electronics, and Zenith Electronics Corporation. Shortly after the Grand Alliance was formed, a new combined system proposal was made. The Advisory Committee, through its Technical Subgroup, evaluated the proposal and made a number of suggestions. In two areas (audio and RF transmission), the Grand Alliance decided to perform tests to determine the superior approach, and then made decisions based on the tests. The Grand Alliance shared its test results with the Technical Subgroup, and, in each case, the Technical Subgroup concurred with the Grand Alliance.

This section gives a summary of the Grand Alliance system parameters. Further technical details on the Grand Alliance system may be found in references 5, 6, and 7.

5.1 Video

5.1.1 Scanning formats

The original proposal made by the Grand Alliance included two HDTV scanning formats. The first was based on 960 vertical lines with interlaced scanning at 60 Hz and progressive scanning at 30 Hz and 24 Hz. The second was based on 720 vertical lines with progressive scanning at 60 Hz, 30 Hz, and 24 Hz. For both formats, picture rates at 1000/1001 times the integer values were included also to enhance interoperability with NTSC systems where the field frequency is 59.94 Hz. Subsequently, the Grand Alliance, based on suggestions made by the Technical Subgroup, replaced the 960-line format with a 1080-line format at the same picture rates.

During 1994 and 1995, great interest was shown in adding SDTV formats to the specification. After a number of meetings, it was agreed by the Technical Subgroup that two formats, based on 480 vertical lines, should be added. The resulting set of ATV scanning formats is shown in Table 1. In the table in the Picture Rates column, the letter “I” means interlaced scanning and the letter “P” means progressive scanning.

Table 1. ATV system scanning formats.

Vertical Lines	Horizontal Pixels	Aspect Ratio		Picture Rates*			
1080	1920	16:9		60I		30P	24P
720	1280	16:9			60P	30P	24P
480	704	16:9	4:3	60I	60P	30P	24P
480	640		4:3	60I	60P	30P	24P

* Picture rates also at 59.94, 29.97, and 23.98 Hz

5.1.2 Video compression

The Grand Alliance proposed the use of MPEG-2 Video[8] compression using the Main Profile at the High Level (the proposed formats were all High Level). They also said they were considering the use of syntax not included in MPEG-2 if significant improvement in bit rate reduction could be demonstrated. After further study, the Grand Alliance decided to maintain MPEG-2 compatibility by not including non-MPEG-2 syntax. Later, as noted in the previous section, the Advisory Committee added scanning formats which fall within the Main Level of MPEG-2, and this specification was changed to be simply MPEG-2 Main Profile.

5.2 Audio compression

The original proposal of the Grand Alliance did not specify an audio bit rate compression system. The Grand Alliance performed tests on competing audio systems and concluded that the AC-3 system, provided by Dolby Laboratories, had the highest performance. The system provided by Philips was selected as a backup system.

The audio system supports five full-quality channels with a low-frequency effects (subwoofer) channel. This sixth channel is often referred to as 0.1 channel for a total of 5.1 channels. The sampling rate is 48 kHz. The compressed data rate is 384 kbps for the 5.1 channel service. Several services, in addition to the main audio service, can be provided. Examples are services for the hearing or visually impaired, dynamic range control, and multiple languages.

5.3 Transport

The Grand Alliance proposed that the multiplex and transport follow a constrained subset of the MPEG-2 Systems[9] transport stream syntax. The Technical Subgroup concurred.

5.4 RF transmission

The original Grand Alliance proposal did not include a specific RF transmission system. The Grand Alliance performed tests on a vestigial sideband modulation (VSB) system and a quadrature amplitude modulation (QAM) system. The VSB system showed superior performance and was selected by the Grand Alliance. It uses 8-level VSB with a 16-level VSB high data rate mode for media which can support the higher data rate (e.g., cable).

6. ATSC DIGITAL TELEVISION STANDARD

In June 1992, ATSC proposed to the FCC that ATSC would fully document the standard for the ATV system and make that information available to the FCC. The anticipation was that the FCC would treat the standard similar to the way the *ATSC Ghost Canceling Reference (GCR) Signal Standard* was handled. In the case of the GCR, after a long study and test period, ATSC adopted a standard and submitted it to the FCC. Subsequently, the FCC adopted the standard and placed it in their Rules.

The *ATSC Digital Television Standard*,[10] based on the Grand Alliance proposal, was adopted in two stages. The full standard, except for the SDTV video formats, was adopted in April 1995; the SDTV video formats were adopted six months later. The *ATSC Digital Television Standard* consists of four normative annexes, one each for video, audio, transport, and RF transmission. In addition, there is an informative annex related to receiver issues.

Because the video and transport portions of the *ATSC Digital Television Standard* are based on the MPEG-2 video and transport standards, the *ATSC Digital Television Standard* is simplified in these areas by making reference to the MPEG-2 standards and listing constraints to those standards.

For the audio portion of the *ATSC Digital Television Standard*, a different approach was required. The Grand Alliance adopted the Dolby Laboratories AC-3 system, which was not the subject of any standard. The ATSC took on this documentation task and the resulting document is the subject of the *ATSC Digital Audio Compression Standard*.[11] The treatment of audio, then, in the *ATSC Digital Television Standard* is handled by making reference to the *ATSC Digital Audio Compression Standard* and listing constraints to that standard.

The remaining portion of the *ATSC Digital Television Standard*, RF transmission, is handled by fully specifying the 8 VSB and 16 VSB subsystems in the subject annex.

ATSC has adopted a third related document, the *Guide to the ATSC Digital Television Standard*.[12] This document has been written as a tutorial to assist persons not familiar with the technology.

The ATSC documents listed in references 10, 11, and 12 are available on the World Wide Web at `http://www.atsc.org` and by anonymous ftp at `ftp.atsc.org`.

7. GRAND ALLIANCE PROTOTYPE TESTING

During the period of April through August 1995, the Grand Alliance prototype was tested at ATTC, CableLabs, ATEL, and in the field. The prototype was designed before the 480-line formats were added to the ATV system specification, and supports only the high definition ATV formats, i.e., the 1080 x 1920 and 720 x 1280 formats. Selected portions of the test results are presented in this section. The information was taken from the "Final Technical Report" of the Advisory Committee.[13] In many cases, the measured values are compared with "target specifications." In general, those target specifications were derived by using the best measured value from the four original digital systems (DigiCipher, DSC-HDTV, AD-HDTV, and CCDC).

7.1 Resolution

Static resolution was measured using an electronic circular zone plate. Dynamic resolution was measured using an electronic radial resolution pattern that was held stationary, and rotated at 0.5, 1.5, and 5.0 revolutions per minute. The test results are shown in Table 2. In general, the results conform with expectations. The vertical chroma resolution for the 1080 x 1920 format was about 20% lower than anticipated, but that occurred because the Grand Alliance prototype employed field-based, rather than frame-based, vertical chroma decimation. The horizontal dynamic chroma resolution decreased about 20% more than expected at the highest rotation rate, probably because of coarse quantization under the stressful condition. The vertical resolution for the 720 x 1280 format was about 20% lower than anticipated. In this case, the anticipated results may have been too aggressive; vertical resolution for the progressive scan format was predicted to be 90% of the number of vertical lines.

Table 2. Resolution of the Grand Alliance prototype.

	Measured Value		
1080 x 1920	**H**	**V**	**D**
Static Resolution, Luma (c/aph)	460	400	540
Static Resolution , Chroma (c/aph)	250	140	260
Dynamic Resolution, 5.0 rpm, Luma (c/aph)	500	200	540
Dynamic Resolution, 5.0 rpm, Chroma (c/aph)	135	100	135

	Measured Value		
720 x 1280	**H**	**V**	**D**
Static Resolution, Luma (c/aph)	320	275	400
Static Resolution , Chroma (c/aph)	180	180	230
Dynamic Resolution, 5.0 rpm, Luma (c/aph)	300	210	360
Dynamic Resolution, 5.0 rpm, Chroma (c/aph)	170	160	183

7.2 Scan conversion between HDTV scanning formats

Subjective assessment tests were run at ATEL to determine the quality loss when a 1080I signal is transmitted, but displayed on a 720P monitor rather than a 1080I monitor; and the quality loss when a 720P signal is transmitted, but displayed on a 1080I monitor rather than a 720P monitor. The only sequences that were selected for assessment were ones in which expert observers were able to see differences. Furthermore, on two of the motion sequences, a more critical portion of the sequence was used for assessment than was used in the “quality, basic material” test.

In the case of transmitted 1080I signals, tests were run using two still pictures and four moving sequences. Of these six sequences, two are considered “basic material,” two are considered “graphics,” and two are considered “noise and cuts.” The average measured quality difference between the 1125-line studio reference and the test signal without format conversion (i.e., 1080I was transmitted and displayed as 1080I) was -0.54 grade on the CCIR Five-Point Continuous Quality Scale. The average measured quality difference between the studio reference and the test signal with format conversion (i.e., 1080I was transmitted and scan converted in the receiver for display as 720P) was -0.58 grade. Therefore, the quality loss due to scan conversion was 0.04 grade (i.e., scan converting for the 720P display showed a loss of quality of 0.04 grade compared with the 1080I display).

In the case of transmitted 720P signals, tests were run using one still picture and six moving sequences. Of these seven sequences, four are considered “basic material,” one is considered “graphics,” and two are considered “noise and cuts.” The average measured quality difference between the studio reference and the test signal without format conversion (i.e., 720P was transmitted and displayed as 720P) was -0.51 grade. The average measured quality difference between the studio reference and the test signal with format conversion (i.e., 720P was transmitted and scan converted in the receiver for display as 1080I) was -0.69 grade. Therefore, the quality loss due to scan conversion was 0.18 grade (i.e., scan converting for the 1080I display showed a loss of quality of 0.18 grade compared with the 720P display).

The difference seen by the non-expert viewers was very small, much less than had been anticipated. The expert observers characterized the conversions as slightly poorer than when presented in the original format. They said the quality loss was manifested as a slight loss in resolution and a slight increase in noise.

7.3 Video quality

To determine the quality after video compression, twenty-six different sequences were used to test the system. Table 3 is a summary of the results. All test categories were well within the target specifications. Recognizing that the target specifications were based on the “Best of the Best” of the four original digital systems, the Grand Alliance system is clearly the superior system in both the 1080I mode and the 720P mode.

Table 3. Quality of the Grand Alliance prototype measured by non-expert viewers.

	Target Specification	Measured Value	
		1080 x 1920	**720 x 1280**
Quality, Basic Material	≤ 0.3 Grade below reference	-0.12 Grade	-0.11 Grade
Quality, Noise & Cuts	≤ 1.0 Grade below reference	-0.40 Grade	-0.50 Grade
Quality, Graphics & NII	≤ 1.0 Grade below reference	-0.06 Grade	-0.04 Grade
Quality, 24 fps Film	≤ 0.25 Grade below reference	-0.04 Grade	-0.01 Grade

In the first round of testing, the DigiCipher system, across all sequences, was found to be 0.3 grade lower in quality than the reference (0.3 for stills and 0.3 for motion sequences), DSC-HDTV was 0.9 grade lower in quality than the reference (0.5 for stills and 1.2 for motion sequences), AD-HDTV was 0.3 grade lower in quality than the reference (0.3 for stills and 0.3 for motion sequences), and CCDC was 1.0 grade lower in quality than the reference (0.5 for stills and 1.3 for motion sequences).

In the second round of testing, the Grand Alliance system, across all sequences, was 0.15 grade lower in quality than the reference in both the 1080I mode (0.0 for stills and 0.2 for motion sequences) and the 720P mode (0.1 for stills and 0.2 for motion sequences). It should be noted that in the second round of testing, 10 image sequences were retained from the first round and 16 new sequences were selected, many of which are more critical than those in the first round. The Grand Alliance system performed better than the systems from the first round, despite the inclusion of the more critical sequences.

In detail, in the 1080I mode, nineteen of the twenty-six sequences were statistically indistinguishable from the reference. For the seven sequences that were statistically significant, the average quality loss was 0.4 grade. One sequence, M49 (Picnic with Ants), which consists of a central still image with noise encroaching from the sides, is known to be particularly stressful for image compression algorithms. For that sequence, the quality loss was 0.75 grade. In the 720P mode, twenty-one of the twenty-six sequences were statistically indistinguishable from the reference. For the five sequences that were statistically significant, the average quality loss was 0.5 grade. Sequence M49 showed a quality loss of 1.3 grades.

Figure 1 is a graphical representation of the quality scores for the four original digital systems, and for the Grand Alliance system in the 720P mode and in the 1080I mode. Only the sequences that were common in the two rounds of testing are included in the figure.

Figure 2 shows the quality scores for the Grand Alliance system on all sequences used in the second round of testing. The figure shows that both modes performed close to reference, and that the relative performance of the two modes varied from test sequence to test sequence.

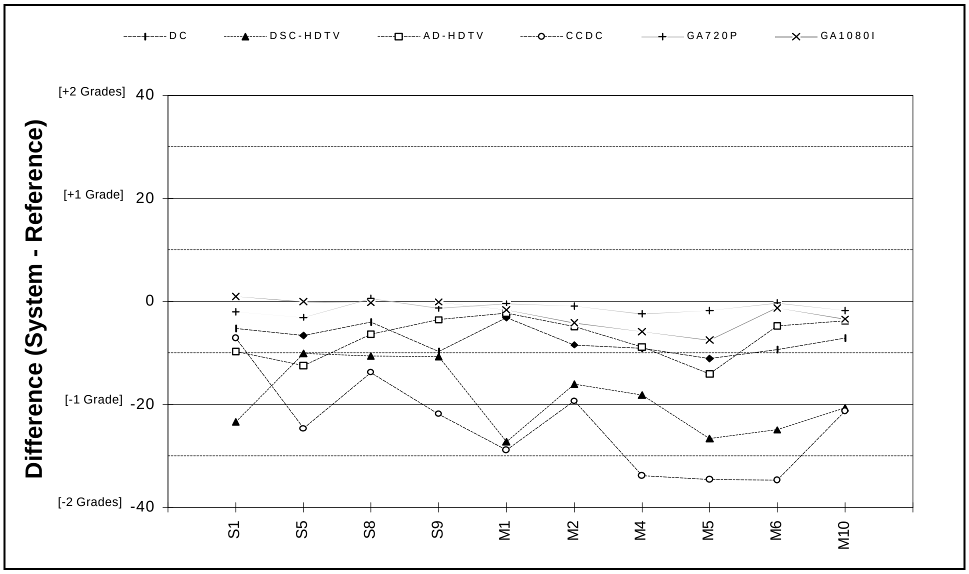

Figure 1. Quality of the Grand Alliance prototype and the four original digital systems compared with the 1125-line studio quality reference.

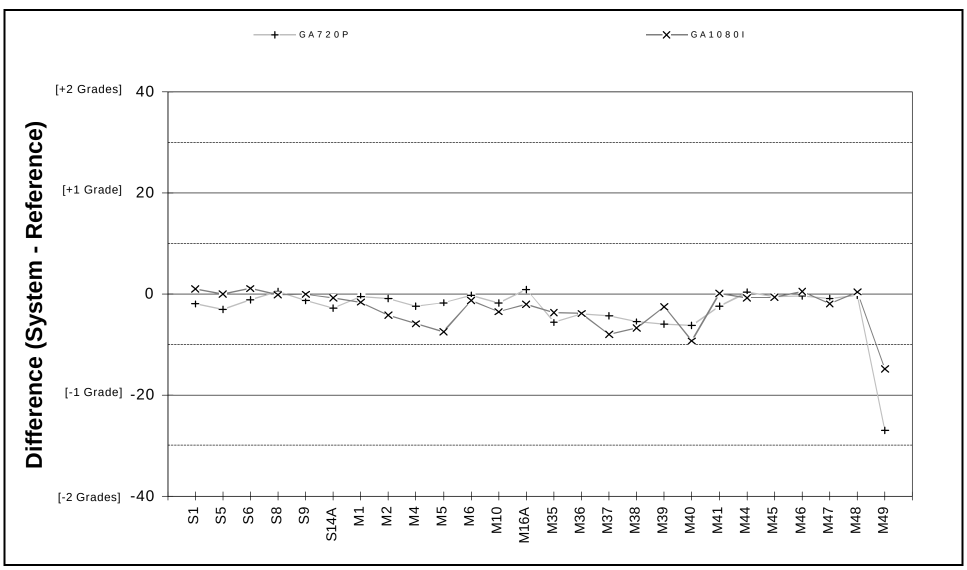

Figure 2. Quality of the Grand Alliance prototype across all sequences compared with the 1125-line studio quality reference.

The 1080I mode shows improvement over the interlaced scanning systems in the first round of testing; the 720P mode shows substantial improvement. The improvement in the 720P mode has been attributed to two factors, 1) good performance of the Grand

Alliance system in the 720P mode and 2) the use of less noisy source material for the six core camera originated motion sequences.

A number of tests were conducted by the expert observers. The expert observers found that the video quality of the Grand Alliance system was clearly superior to that of any of the previous proponent systems, and they said that applies to all types of video tested — still images, motion sequences, computer graphics, and film. They did observe some compression artifacts, but only on the most difficult images. The level of compression artifacts, they said, was significantly lower than for any previous system. The expert observers, like the non-expert viewers, found the quality of the Grand Alliance system, in both modes, to be excellent and superior to any of the previous systems. They noted that scene cut performance was much improved over the previous systems.

When noise was introduced into the 1080I source, no enhancement of the noise was found at low noise levels. At the highest level of added noise, an increase in blockiness was seen, but the image exhibited much better quality than was observed at the point of unusability (POU). When noise was introduced into the 720P source, a slight increase in image artifacts was found. At high levels, there was an increase in the blockiness of the image, but the image exhibited much better quality than was observed at POU.

The expert observers conducted tests to see how image quality deteriorated as channel capacity was reduced by transmitting auxiliary data. They found little or no increase in artifacts as the auxiliary data rate was increased to 3 Mbps. At 4 Mbps, the sequence M40 (Dream Team) showed a clear increase in the visibility of artifacts. The expert observers concluded that care must be exercised in combining an auxiliary channel with a high data rate together with video scenes with high peak complex motion; subjective degradation of the video may increase rapidly as channel capacity is diverted from video to auxiliary data.

When video material was passed through the system twice, somewhat more noise was seen on the second pass in the 1080I mode. For the 720P mode, more blockiness and noise were visible. The effects were worse with 720P than 1080I.

7.4 Audio quality

Subjective tests of an improved Dolby AC-3 audio compression encoder, as incorporated in the Grand Alliance system tested at the ATTC, were conducted at the National Cable Television Association in Washington, DC in May 1995. The audio test sequences were passed through the entire Grand Alliance system, from audio encoder, through system multiplexing, modulation, demodulation, demultiplexing, and audio decoding. The primary goal of these tests was to verify that the audio coder used in the Grand Alliance system was as good as or better than the coder tested in 1993. In summary, it was concluded that:

1. The audio quality of the fully integrated Grand Alliance coder is better than that of the coder tested in 1993.

2. The audio quality of the Grand Alliance coder in the multi-channel mode was indistinguishable from that of the source.

3. The audio quality of the Grand Alliance coder in the 5.1 mode with 2 channel reproduction, while it can be detected by some expert listeners on some audio test material, is very nearly transparent (better than grade 4.5 on the 5 point impairment scale).

4. The audio quality of the Grand Alliance coder in the 2 channel mode is very nearly transparent (better than grade 4.7 on the 5 point impairment scale).

7.5 Transport tests

7.5.1 Switching between compressed data streams

The Grand Alliance conducted a laboratory demonstration indicating the practicality of decoding video from a bit stream created by concatenating various video elementary streams. Within the range of test material prescribed for this demonstration, the test showed the feasibility of switching between compressed data streams.

7.5.2 Header/descriptor robustness

The Grand Alliance demonstrated that the prototype ATV receiver recovers from loss of certain header information with visible artifacts in the reconstructed video, as expected. For this demonstration, slice headers and picture headers for I, P, and B-frames were deliberately delivered in error. It was observed that for errors on I-frame headers, the visible artifacts could affect the entire group of pictures (GOP). For loss of a B-frame header, the subjective impact is limited to that B-frame only. When a P-frame header is lost, the duration of visible artifacts lies between the duration for loss of an I-frame header and a B-frame header.

7.5.3 Syntactic and semantic compliance of the ATV bit stream

A bit stream recorded at the output of the Grand Alliance encoding system was analyzed through the use of software specially developed to check for MPEG-2 and ATSC syntactic and semantic compliance. Note that although a great number of bit stream elements were checked, practical considerations prevented the tests from being absolutely exhaustive. As a result, these tests did not verify that the Grand Alliance encoder would be completely compliant under all coding conditions. For instance, coded bit streams were not tested for video formats other than 720P at 59.94 Hz frame rate, and 1080I at 29.97 Hz frame rate.

Compliance violations were detected in the Program Association Table, the Program Map Table, the Program Paradigm, in Descriptors, in Packetized Elementary Stream Headers, and in Video Syntax Start Codes. All were considered minor syntactic or semantic violations, and correction of these violations should be straightforward. These corrections, however, may be critical to receivers' ability to decode ATV programs correctly. The detected violations do not represent any impairment in picture quality or transmission coverage, and thus did not affect any test results in these areas. Of course, any commercial encoding systems produced for the marketplace must be produced in full compliance with the overall *ATSC Digital Television Standard*.

7.5.4 Interoperability with ATM networks

The goal of this series of tests was to demonstrate that a 19 Mbps ATV transport bit stream can be interfaced to, and transported by, an Asynchronous Transfer Mode (ATM) network. The tests were conducted at the Charlotte, North Carolina field test site utilizing fiber-based ATM transport facilities provided by Bell South.

Using equipment provided by the Grand Alliance, ATV transport data stream packets were split into ATM-sized payloads and then formed into ATM cells with appropriate ATM headers and syntax. These were then transmitted via the ATM network, through a single ATM switch, and returned to the field test site. Here they were converted back into ATV transport packets. The ATM channel was selected for constant bit rate, which provides minimum timing errors, or “jitter.”

The first of the three tests was designed to verify the basic connection to the ATM network. A D-3 VTR provided 19 Mbps source data, in ATV transport stream format, but consisting of pseudo-random data sequences. These were successfully passed through the ATM channel with no bit errors detected.

The second of the tests utilized a D-3 VTR to feed into the ATM network a transport stream consisting of compressed HDTV pictures and sound. The returned ATM signal was reconverted to an ATV transport stream and fed to the Grand Alliance 8 VSB modulator, and then broadcast via the channel 53 transmitter, and also transmitted via cable television plant (in the 16 VSB mode). Error-free reception was achieved at both broadcast and cable receive sites.

The third test involved increasing the length of the ATM path to a total distance of approximately 450 miles, and increasing the number of ATM switches in the circuit to six. While generally successful, at times ATM packet jitter exceeded the buffer capacity of the ATM receiver, resulting in errors in the decoded picture that were different in appearance from those caused by typical over-the-air impairments.

In summary, all three tests proved the feasibility of carrying the ATV transport stream over a public carrier’s fiber-based ATM network, but indicated that commercial equipment will need to be designed to cope with packet jitter that arises in more complex ATM network configurations.

7.5.5 Multiple ancillary data services

In order to demonstrate, in a limited fashion, the ability of the Grand Alliance prototype system to deliver multiple independent programs within a single 6 MHz RF channel, for this test the system was configured to transmit simultaneously four data channels at bit rates as follows: 4.738 Mbps, 5.744 Mbps, 3.747 Mbps, and 4.717 Mbps. The transmission channel was unimpaired, and a strong level signal (-28 dBm) was presented to the receiver. Each of the “sub-channels” was selected, in turn, for output at the decoder, and each was received error-free.

7.6 Spectrum utilization

7.6.1 Introduction

The Advisory Committee considered two criteria for spectrum utilization — accommodation percentage and service area. “Accommodation percentage” specifies the fraction of existing NTSC television stations that could be assigned an ATV channel. “Service area” refers to the interference-limited coverage area of new ATV stations. The methodology for calculating the results of the analyses of these criteria is described in Chapter 8 of references 1 and 2.

7.6.2 Accommodation percentage

Allotment studies were undertaken based on the results of laboratory testing of the Grand Alliance prototype system. For terrestrial broadcasting, an allotment/assignment plan that provides a second channel for each television licensee, construction permit holder, and construction permit applicant was developed. In the plan, an attempt was made to match the new ATV coverage with the existing coverage of the companion NTSC station. Approximate realization of that objective was achieved through reducing ATV coverage of some stations and allowing new interference to the coverage areas of some NTSC stations.

7.6.3 Service area

Table 4 shows the planning factors employed in the devising of the allotment/assignment table and in the analyses of service and interference. The carrier-to-noise, co-channel, and adjacent-channel interference data were derived from laboratory testing of the Grand Alliance prototype. Of particular note is the matter of interference to NTSC from an upper adjacent-channel ATV operation.

In the 1993 testing of the original systems, and in the 1994 comparative testing of the 8 VSB and 32 QAM transmission subsystems (called the bake-off), consideration was given only to video interference. In the 1995 testing of the Grand Alliance prototype, interference from ATV into NTSC stereo audio and the second audio program (SAP) channel were tested also. In a substantial number of the twenty-four NTSC receivers used in the ATTC testing program, audio was found to degrade before video when the interfering signal was ATV in the upper adjacent-channel. The threshold for video performance degradation to CCIR Grade 3 was found to be at a desired-to-undesired (D/U) ratio of -17.00 dB for the median receiver. The threshold for audio performance degradation to CCIR Grade 3 for the median receiver was found to be at a

D/U ratio of -11.95 dB.[‡] Since the D/U ratio for audio is greater than the D/U ratio for video (i.e., audio degraded before video), in the instance of upper adjacent-channel ATV-into-NTSC interference, the audio ratio was used in service and interference determinations. In all other interference considerations, video degraded before audio, therefore video D/U ratios were used.

Interference to NTSC audio from the upper adjacent-channel ATV had to be present during the bake-off testing, but audio effects were not tested; concentration was on video.

Table 4. System-specific planning factors, Grand Alliance prototype (D/U in dB).

	Measured Value
Carrier-To-Noise	+15.19 dB

Co-Channel	**Measured Value**
ATV-into-NTSC	+34.44 dB
NTSC-into-ATV	+1.81 dB
ATV-into-ATV	+15.27 dB

Adjacent-Channel	**Measured Value**
Lower ATV-into-NTSC	-17.43 dB
Upper ATV-into-NTSC	-11.95 dB*
Lower NTSC-into-ATV	-47.73 dB
Upper NTSC-into-ATV	-48.71 dB
Lower ATV-into-ATV	-41.98 dB
Upper ATV-into-ATV	-43.17 dB

* Based on audio interference. Measured value for video interference was -17.00 dB.

7.6.3.1 Comparison with four original digital systems

Figure 3 has been provided to allow comparisons to the 1993 testing of the four original digital systems. The computer input for this analysis is based on the 1993 data base, assumes the VHF/UHF scenario, considers only co-channel and adjacent-channel interfering sources, and uses the upper adjacent-channel ATV-into-NTSC D/U ratio of -17.00 dB, which is the video threshold.

[‡] The threshold for audio performance degradation to CCIR Grade 3 was found to be at a D/U ratio of -7.95 dB for twenty percent of the receivers, and at -10.95 dB for thirty percent of the receivers.

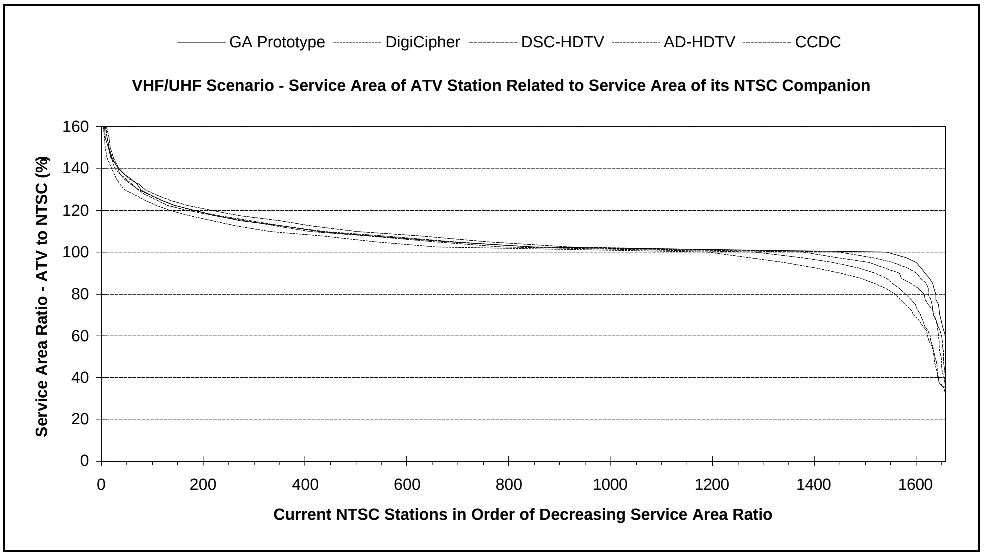

Figure 3. Interference-limited service area of each ATV station relative to the interference-limited service area of its companion NTSC station (VHF/UHF scenario, co-channel and adjacent-channel constraints).

Figure 3 depicts the interference-limited service area of each ATV station, during the transition period, relative to the interference-limited service area of its companion NTSC station under the VHF/UHF scenario, taking into account co-channel and adjacent-channel constraints. The graph shows the Grand Alliance prototype, as a solid line, along with the four original digital systems. In the graph, the 1,657 current NTSC stations are placed in order of decreasing ATV to NTSC service area ratio. Examination of the graph for the Grand Alliance prototype reveals that 11% (183) of the ATV stations under this scenario would have an ATV service area at least 20% larger than their companion NTSC service area, and 98.85% (1,638) would have an ATV service area at least 80% of their companion NTSC service area. The total ATV interference-limited service area for all 1,657 stations is 39.7 million square kilometers. It is clear from this graph that the performance of the Grand Alliance system exceeds that of any of the four original digital systems.

7.7 Transmission robustness

7.7.1 Random RF noise performance

Random noise was added at RF to the desired digital signal. As expected for the Grand Alliance system's modulation and error correction, random RF noise has no effect on the recovered video and audio data until the level of noise is raised to a point very close to a "threshold" value. The value of carrier-to-noise ratio (C/N) where the effects of noise begin to be visible is called the Threshold of Visibility (TOV). For the Grand Alliance system, the C/N at TOV was 15.19 dB. This performance is superior to that of the first round systems.

As expected and designed into the system, the threshold is very sharp. Visible image impairments change from just barely visible to destructive of the picture within ~1 dB of worsening of the C/N. Also as expected, the video and audio fail approximately together, with audio measuring as slightly more robust against RF noise.

7.7.2 Static multipath

Tolerance of single and multiple static echoes was measured. The delay of the echoes tested ranged from -1.8 μs (i.e., a leading echo) to +18 μs (a lagging echo). Multiple echoes were tested in ensembles of 5 echoes at various amplitudes within these ranges. In general, the Grand Alliance system's performance was comparable to the best of the first round systems.

7.7.3 Flutter

Flutter is time-varying or dynamic multipath. This performance attribute was tested with both ensembles of ghosts and with single ghosts at various rates of "motion" from 0.05 Hz to 5 Hz. This testing was more extensive than in the first round. Where comparable data exist, the Grand Alliance system shows improved performance.

7.7.4 Adjacent-channel interference

The Grand Alliance system performed better than the target specifications on all ATV-into-ATV tests, NTSC-into-ATV tests, and on lower adjacent-channel ATV-into-NTSC tests. With regard to upper adjacent-channel video interference ATV-into-NTSC, the tests found a "color stripe" artifact in the NTSC video at all NTSC power levels. Analysis shows that it is caused by the ATV pilot carrier frequency "beating" with the NTSC color subcarrier. Analysis also suggests that another "luminance beat," hidden during the testing by the color beat, would be present, caused by the ATV pilot carrier beating with the NTSC visual carrier. Finally, during these tests, some NTSC receivers showed loss of color and other picture artifacts.

The analysis shows that use of precision carrier offset between the ATV pilot and the NTSC color subcarrier will eliminate visibility of both artifacts. The loss of color and other artifacts, however, would not be affected by carrier offset.

7.7.5 Peak-to-average power

The ratio of peak-to-average power, with 99.9% probability, was measured as 5.9 dB, which was lower (i.e., better) than the target specification.

7.7.6 Cable transmission

A number of cable television tests were performed. A summary of the test results appears in Table 5 and Table 6.

Table 5. Cable television tests.

	Target Specification	**Measured Value**
Composite Second Order Distortion	< 25 dB	27.1 dB
Composite Triple Beat Distortion	< 37 dB	39.1 dB
Phase Noise	< 81 dB	78.3 dB
Residual FM	> 6.5 kHz	9.2 kHz
Fiber Optic Tests	> 4.5 %	7.8 %
Channel Change / Channel Acquisition	< 0.7 s	0.7 s
Threshold Characteristics for Random Noise - Data	< 15.6 dB	15.0 dB
Local Oscillator Instability	> ±89 kHz	> ±100 kHz
Dynamic Multipath - Acquisition Time in the Presence of Multipath and Noise	< 0.75 s	0.9 s
Burst Error Correction	> 169 µs @ 10 Hz	180 µs @ 10 Hz
	> 1.05 kHz @ 20 µs	240 Hz @ 118 µs

Table 6. High data rate cable television tests.

	Target Specification	Measured Value
Composite Second Order Distortion	< 38 dB	35.4 dB
Composite Triple Beat Distortion	< 49 dB	47.2 dB
Phase Noise	< 87 dB	81.8 dB
Residual FM	> 4.0 kHz	7.0 kHz
Fiber Optic Tests	> 4.0 %	7.3 %
Channel Change / Channel Acquisition	< 0.7 s	1.1 s
Threshold Characteristics for Random Noise - Data	< 28.85 dB	29.1 dB
Local Oscillator Instability	> ±89 kHz	> ±100 kHz
Dynamic Multipath - Acquisition Time in the Presence of Multipath and Noise	< 0.75 s	1.2 s
Burst Error Correction	> 129 µs @ 10 Hz	120 µs @ 10 Hz
	> 1.45 kHz @ 20 µs	480 Hz @ 68 µs

7.7.7 Summary of transmission robustness findings

The performance of the Grand Alliance system in laboratory testing met the expectations defined by the target specifications. In the few instances where individual test results did not meet the target values stated for that particular test, the deviations were minor and do not have any significant effect on image quality or spectrum utilization.

7.8 Field test

Field tests were performed under both terrestrial broadcasting and cable conditions.

For terrestrial broadcasting, the complete system was tested at a set of sites selected for their difficult reception conditions, as measured in an earlier field test of the modem subsystem. In those earlier modem-only tests, a bit error rate (BER) of $3x10^{-6}$ was selected as the criterion for the threshold of visibility of video impairments. Full system testing, including subjective observation of pictures and sound, verified the reliability of that value of BER. Because the locations for full system testing were a selected and difficult sub-set of the complete group of test locations, they are not a representative sample. The full system testing, however, verified the utility of the data taken on the full set of locations. The sites for full system testing included 10 sites in homes where tests were performed both within the residence using a set-top antenna, and outdoors, adjacent to the residence, using a mast-mounted antenna.

The field tests were conducted in July and August 1995 using the same facilities near Charlotte, North Carolina that were employed in the modem-only tests. As before, the NTSC transmitted peak visual effective radiated power (ERP) on channels 6 and 53 was one-tenth of the maximum allowed by FCC rules, and the average ATV ERP was approximately one-sixteenth of (12 dB below) the NTSC peak visual ERP.

Tests of the complete system showed, as also indicated by the earlier modem subsystem testing, that satisfactory digital HDTV reception is available more widely than satisfactory analog NTSC reception. Even where objective measurements of BER indicate the probability of momentary impairment of the signal, subjective observation of picture and sound fails to detect impairment.

An objective measurement that should permit reliable prediction of satisfactory HDTV service at UHF is field strength; subjective assessment of video and audio correlated very well with field strength in channel 53 tests. When signal strength was at or below that which laboratory testing had indicated to be the limit of HDTV service, subjectively satisfactory service was observed at only two of seven sites. When signal strength was weak, but above the threshold, subjectively satisfactory HDTV service was observed at fourteen out of fifteen sites. The 28 sites with moderate or strong signal strength all had subjectively satisfactory HDTV service. This correlation did not hold at channel 6 because sample size and impulse interference effects prevented a proper channel 6 analysis.

In brief, terrestrial transmission testing of the complete system supports the conclusion that HDTV service will be available where NTSC service is presently available, and in many instances where NTSC service is unacceptable.

The complete system, with both 8 VSB and 16 VSB modulation, was tested also in cable environments in Charlotte, including existing cable systems and fiber optic links. Tests of 16 VSB were the more stringent. The 16 VSB receiver worked at all locations where the delivered signal met FCC specifications, and at many sites where it did not. Some systems were tested at frequencies beyond their maximum design frequency, resulting in less than FCC-specification conditions. Also, strong in-band beats were observed on some systems that affected both the NTSC and HDTV signals. The 16 VSB receiver continued to operate in these situations until the carrier-to-noise threshold was reached.

7.9 Conclusions of testing program

Based on the testing, the Technical Subgroup found:

1. The Grand Alliance system met the Committee's performance objectives and is better than any of the four original digital ATV systems;

2. The Grand Alliance system is superior to any known alternative system; and

3. The *ATSC Digital Television Standard*, based on the Advisory Committee design specifications and Grand Alliance system, fulfills the requirements for the U.S. ATV broadcasting standard.

In its "Final Technical Report," approved on October 31, 1995, the Technical Subgroup recommended that the *ATSC Digital Television Standard* be adopted as the U.S. ATV broadcasting standard. This recommendation will be presented to the Advisory Committee in November 1995.

8. OTHER ISSUES

While the Grand Alliance was fine-tuning the specifications of their proposal and constructing the prototype, new questions began to surface. With this fantastic technology, is it possible to send data in addition to, or even in place of television programs? Is it preferable to send multiple SDTV programs in place of one HDTV program?

The Technical Subgroup and Grand Alliance discussed many of these issues. It was pointed out that the FCC had made it clear, earlier, that HDTV was the target. The Technical Subgroup did make sure, however, that data transmission and SDTV were possible within the framework of the system. Eventually, as was noted earlier, it was agreed that SDTV should not only be possible, but be included specifically in the standard.

The United States, Europe, and Japan still seem to be going in different directions. While the Americans and Europeans agree on MPEG-2 for video compression, the U.S. insists that the High Level must be supported and Europeans will use only the Main Level. The U.S. will use AC-3 for audio compression, Europe will use MPEG-2 audio. Both plan to use MPEG-2 transport. The U.S. will use VSB, Europe plans to use coded orthogonal frequency division multiplex (COFDM). In Japan, digital techniques are being investigated, but the analog MUSE system is being broadcast by satellite. For more information regarding current studies in Europe, see reference 14; for more information regarding current studies in Japan, see reference 15.

What about different standards among Europe and America and Japan? As TV becomes digital, and processing power increases, it will be easier to convert from one standard to another and maintain quality. Does that mean standards are not needed? Not at all. Common standards are preferable, but we seem to have great difficulty getting to that point. And, we are individually making sure our own standard fits our way of doing things.

What will be the long-term effect of the often discussed convergence of television, telephone, and computers? The author continues to believe that users of different applications will support different equipment “tuned” to the specific applications. There will be equipment which works for multiple applications, but either it will cost more, or it will sacrifice quality in some or all modes. Thus there will continue to be specialized equipment.

9. FCC ACTION

It is expected that the recommendation of the Technical Subgroup will be adopted by the Advisory Committee and proposed to the FCC in November 1995.

There are several issues the FCC must address. Who gets which channels, when, and how? Do broadcasters have to pay for the ATV channel? When do broadcasters have to return the NTSC channel? Do broadcasters have to broadcast some minimum amount of HDTV programming? Do receivers have to be able to display all digital formats, including HDTV? What are the rules regarding the technical standard? And, when will all FCC decisions be made final?

The ATV process has been remarkable. Ten years ago, it could not have been foreseen that private sector organizations in the United States would be the world-leaders in establishing digital HDTV broadcasting standards. The private sector has completed its work. The system has been specified and documented. The future of digital television is now in the hands of the FCC.

10. ACKNOWLEDGMENTS

The work described in this paper represents significant contributions from many dedicated people. Some portions were extracted from Advisory Committee and ATSC reports. The author of this paper was privileged to serve as the chair of various groups involved in the work.

11. REFERENCES

1. “ATV System Recommendation,” *IEEE Transactions on Broadcasting*, Vol. 39, No. 1, pp. 2-245, March 1993.

2. “ATV System Recommendation,” *1993 NAB HDTV World Conference Proceedings*, pp. 237-493, 1993.

3. Robert Hopkins, “Progress on HDTV broadcasting standards in the United States,” *Image Communication*, Vol. 5, Nos. 5-6, pp. 355-378, December 1993.

4. Robert Hopkins, “Choosing an American Digital HDTV Terrestrial Broadcasting System,” *Proceedings of the IEEE*, Vol. 82, No. 4, pp. 554-563, April 1994.

5. R. Hopkins, “Digital Terrestrial HDTV for North America — The Grand Alliance HDTV System,” *EBU Review*, No. 260, pp. 36-50, Summer 1994.

6. Robert Hopkins, “Digital Terrestrial HDTV for North America: The Grand Alliance HDTV System,” *IEEE Transactions on Consumer Electronics*, Vol. 40, No. 3, pp. 185-198, August 1994.

7. C. Basile, A.P. Cavallerano, M.S. Deiss, R. Keeler, J.S. Lim, W. Luplow, W.H. Paik, E. Petajan, R. Rast, G. Reitmeier, T.R. Smith, and C. Todd, “The U.S. HDTV Standard,” *IEEE Spectrum*, Vol. 32, No. 4, pp. 36-45, April 1995.

8. ISO/IEC IS 13818-2, International Standard (1994), MPEG-2 Video.

9. ISO/IEC IS 13818-1, International Standard (1994), MPEG-2 Systems.

10. *ATSC Digital Television Standard*, ATSC Standard A/53, 1995.

11. *ATSC Digital Audio Compression Standard (AC-3)*, ATSC Standard A/52, 1995.

12. *Guide to the Use of the ATSC Digital Television Standard*, ATSC Document A/54, 1995.

13. “Final Technical Report,” Advisory Committee on Advanced Television Service, available from International Transcription Services, 2100 M Street NW, Suite 140, Washington, DC 20037, telephone 202-857-3800, fax 202-857-3805, October 31, 1995.

14. Barry Fox, “Dawn of Digital TV in Europe,” *IEEE Spectrum*, Vol. 32, No. 4, pp. 50-53, April 1995.

15. Yuichi Ninomiya, “The Japanese scene,” *IEEE Spectrum*, Vol. 32, No. 4, pp. 54-57, April 1995.