Application of the Advanced Communications Technology Satellite to Teleradiology and Real-Time Compressed Ultrasound Video Telemedicine

Brent K. Stewart, Stephen J. Carter, Jay N. Cook, Brian S. Abbe, Deborah Pinck, and Alan H. Rowberg

The authors have investigated the application of the NASA Advanced Communications Technology Satellite (ACTS) to teleradiology and telemedicine using the Jet Propulsion Laboratory (JPL)–developed ACTS Mobile Terminal (AMT) uplink. In this experiment, bidirectional 128, 256, and 384 kbps satellite links were established between the ACTS/AMT, the ACTS in geosynchronous orbit, and the downlink terrestrial terminal at JPL. A terrestrial Integrated Digital Services Network (ISDN) link was established from JPL to the University of Washington Department of Radiology to complete the bidirectional connection. Ultrasound video imagery was compressed in real-time using video codecs adhering to the International Telecommunication Union—Telecommunication Standardization Sector (ITU-T) Recommendation H.261. A 16 kbps in-band audio channel was used throughout. A five-point Likert scale was used to evaluate the quality of the compressed ultrasound imagery at the three transmission bandwidths (128, 256, and 384 kbps). The central question involved determination of the bandwidth requirements to provide sufficient spatial and contrast resolution for the remote visualization of fine- and low-contrast objects. The 384 kbps bandwidth resulted in only slight tiling artifact and fuzziness owing to the quantizer step size; however, these motion artifacts were rapidly resolved in time at this bandwidth. These experiments have demonstrated that real-time compressed ultrasound video imagery can be transmitted over multiple ISDN line bandwidth links with sufficient temporal, contrast, and spatial resolution for clinical diagnosis of multiple disease and pathology states to provide subspecialty consultation and education at a distance.

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KEY WORDS: image compression, medical images, satellite, telemedicine, teleradiology, ultrasonography, video compression.

THE ADVANCED Communications Technology Satellite (ACTS) was successfully launched in September 1993 by the space shuttle Discovery (STS-51). The satellite is presently deployed and operating (Fig 1). The ACTS is in geosynchronous orbit about 19,000 miles above the equator at 100°W longitude—just west of the Galapagos Islands (Fig 2).

The stated goal of the ACTS satellite program is to bring together US industry, government, and academia to test and prove pioneering concepts and technologies that advance on-demand, flexible communication services to strengthen the US economy in the 21st century. ACTS technologies will provide a much higher rate of communications between users—20 times that offered by conventional satellites, greater networking flexibility, and on-demand digital services. Many technical details of the ACTS (eg, the multibeam antenna, broadband processor, microwave switch matrix and control algorithms, and spot beam coverage) have been described in an earlier publication of ours.[2]

Servicing remote regions with state-of-the-art medical diagnostic techniques often is difficult, if not impossible, largely because of the absence of sophisticated telecommunication infrastructure and technical expertise in these areas. If clinical images or video streams were digitized and accurately transmitted from remote areas to urban, teaching medical centers, this could significantly improve medical care to rural and remote populations. Herein we present an investigation of the application of the ACTS to teleradiology and telemedicine using the Jet Propulsion Laboratory (JPL)–developed ACTS Mobile Terminal (AMT) uplink.

The Ka-band. The flexible capability of the ACTS satellite with on-demand usage, steerable spot beam, wide bandwidth, and on-board digital switching should allow both ease of use and greatly reduced costs. The sizes of the sending and receiving units also are significantly reduced because of the Ka-band frequencies used (uplink allocation 27.5-30.0 GHz, downlink allocation 17.7-20.2 GHz, Fig 3).

The Ka-band (2.5-GHz bandwidth) is being explored in view of the inevitable congestion of the limited bandwidth available at the L-band, and the

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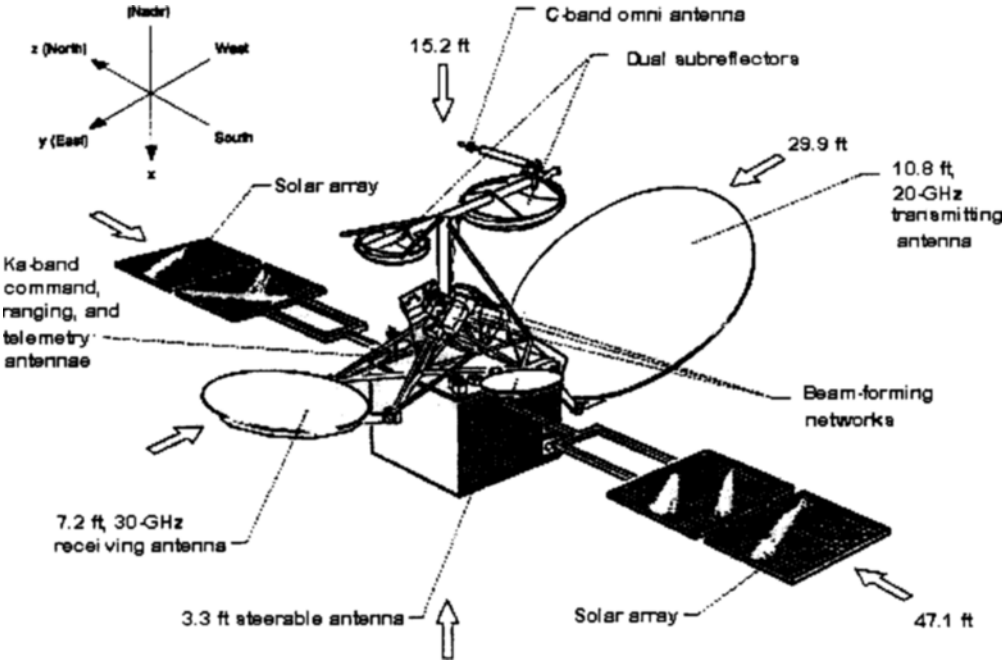


Fig 1. The Advanced Communications Technology Satellite (ACTS) deployed flight configuration. Reprinted with permission.[1]

existing congested allocations at the C- and Ku-bands (0.5-GHz bandwidth each, Fig 3). Moreover, the Ka-band has the potential for supporting user equipment that is significantly smaller and simpler. Therefore, the Ka-band is a good candidate in the pursuit of the high capacities, service diversities, and user convenience sought by current and future satellite users (eg, the Teledesic[3] and Iridium[4] proposals). However, operation in the Ka-band poses significant challenges. Key among these challenges are immature technology, lossy RF components, significant rain attenuation (Fig 3), and large Doppler shifts for mobile applications.

This experiment exploits these capabilities further, using a reduced-size Ka-band antenna to allow portability (mobile van) to rural and remote areas, and the steerable beam of the ACTS satellite (Figs 1 and 2). The AMT mobile van (Fig 4) developed by the JPL uses a 23-cm-diameter antenna that tracks the satellite while the vehicle is moving.

ACTS MOBILE TERMINAL

The baseline modulation format of the AMT developed by the JPL is differential phase-shift keying. At its top end, the modem handles up to 384 kbps and is capable of demonstrating compressed video (15 fps) on the uplink. Fade control is implemented through data rate change at the mobile terminal and uplink power control at the fixed link evaluation terminal (LET).

The AMT is a proof-of-concept experiment designed to overcome the challenges of Ka-band mobile operation and the validation of several key technologies. Two major technical challenges were (1) to maintain the satellite link in a demanding propagation environment (rain fade, Doppler compensation, and antenna pointing algorithms), and (2) the development of enabling Ka-band technologies (eg, low-cost, small-size antenna utilizing Ka-band monolithic microwave integrated circuit components [MMIC] and packaging).

Detailed information regarding the AMT data acquisition system (DAS), Ka-band RF electronics, and maintaining the mobile satellite link can be found in a previous communication of ours.[2]

AMT antenna. Two antennae have been developed for the AMT (Fig 5): a passive elliptical reflector antenna and an active phased-array antenna consisting of a multilayered microstrip, an EM-coupled slot, and a dipole MMIC. Both antennae have extremely compact form factors to enable mobile operation. The elliptical reflector antenna is 10-cm high with a 23-cm diameter. The dimensions of the MMIC are 16 cm (L) × 13 cm (W) × 2 cm (H).

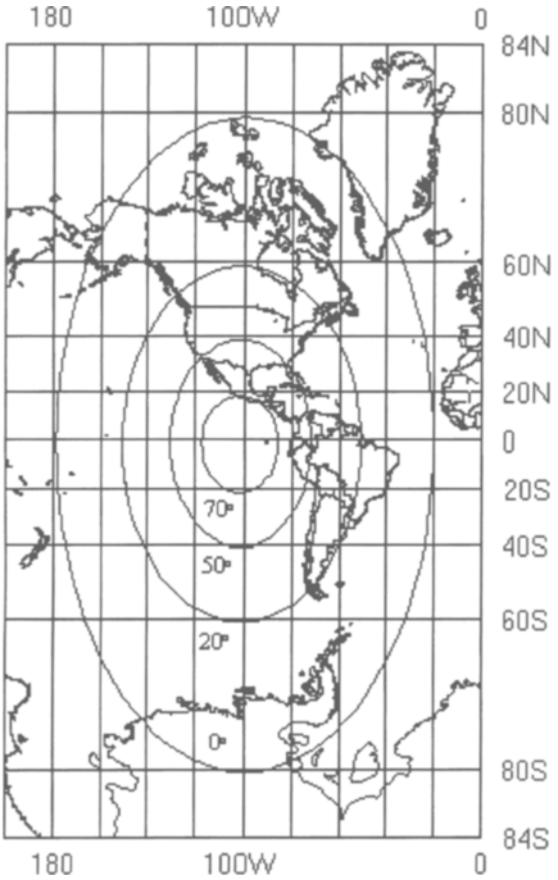


Fig 2. Steerable antenna coverage as a function of the AMT antenna elevation angle.

The 30-GHz MMIC was developed by Texas Instruments. The effective isotropic radiated power (EIRP) is 18.8 dBW for a 4 × 4 array of aperture-coupled microstrip patch radiating elements. This array is fully modular in the sense that multiples of the 4 × 4 units can be placed side-by-side to create larger arrays.

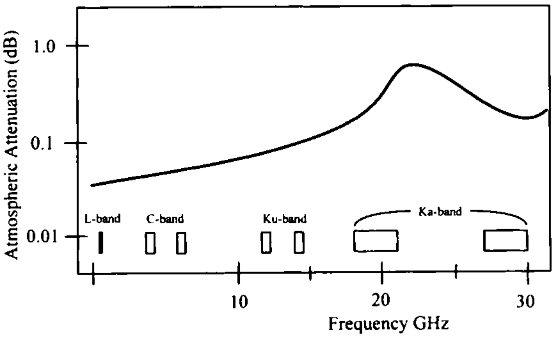


Fig 3. Satellite frequency band allocations and atmospheric attenuation as a function of frequency.

Fig 4. ACTS mobile terminal van. The Ka-band antenna is mounted on the left-rear corner of the roof. Reprinted with permission.[1]

The design specification for each of the elements is 5-dB gain, and the subarray transmitting power is 1.5 W. The 20-GHz downlink antenna also is an MMIC array.

The antenna controller tracks the satellite as the AMT vehicle is in motion. Tracking the satellite requires only azimuthal steering, because the antenna elevation coverage is wide enough to accommodate typical vehicle pitch and roll variations within any single geographic region of operation restricted to paved roads. The antenna controller steers the antenna azimuth angle in response to an inertial vehicle yaw-rate sensor and an estimate of antenna pointing error obtained by "mechanical dithering" of the antenna. The antenna is smoothly rocked (dithered) side-to-side, through a small angle, while the signal strength of the pilot tone received through the antenna is monitored.

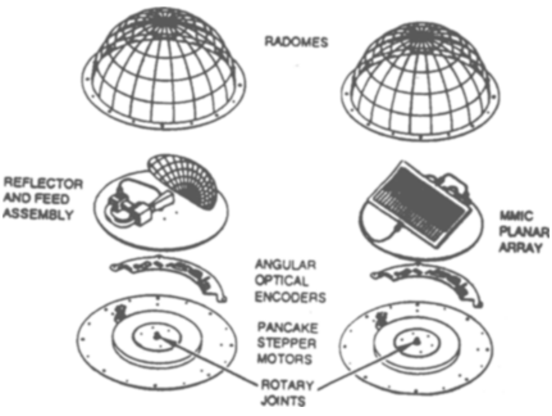


Fig 5. ACTS mobile terminal reflector (left) and active array antennae (right). Reprinted with permission.[1]

ACTS/AMT EXPERIMENTS

The experiment involved the transmission of digital medical images (computed tomography [CT], magnetic resonance [MR], ultrasonography, computed radiography, and digitized radiographs—including a mammogram) between the field-deployed ACTS/AMT and the Department of Radiology at the University of Washington (UW) in Seattle. This task was accomplished by locating the AMT mobile terminal experiment van in various locations throughout Washington state, Idaho, Montana, and Hawaii. A generic configuration of the test is given in Fig 6.

Data transmission was bidirectional. Digital medical image data files were uplinked to the ACTS and immediately transmitted by the ACTS, thus acting in a "bent pipe" configuration. Medical images were transmitted from the AMT back to the fixed station (consisting of AMT equipment and the high burst rate-link evaluation terminal [HBR-LET]) at the JPL in Pasadena, California. These images were then routed via the Internet or Integrated Digital Services Network (ISDN) from the JPL to the UW Medical Center in Seattle. Once the images arrived in the UW Radiology Department, they were stored on a PC computer disk, were available for softcopy review, and also were printed using a high-quality laser film printer.

The ACTS/AMT experiment involved three phases: (1) initial field testing at 128 kbps, (2) extended field testing of a new high-gain antenna at 384 kbps, and (3) field testing of the high-gain antenna in Hawaii.

Images and compression. Several categories of static images were transmitted across the ACTS/AMT satellite link: CT, MR, computed radiographs, and digitized projection radiography films.

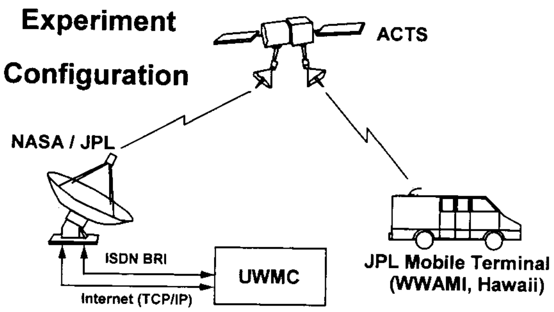


Fig 6. Generic ACTS/AMT "bent pipe" configuration for the University of Washington experiments. WWAMI, Washington, Wyoming, Alaska, Montana, and Idaho.

The smaller image sets (CT and MR) were losslessly compressed using a modified Lempel-Ziv-Welch (LZW) algorithm[5] before transmission, providing an approximate 2.5:1 compression ratio. The JPEG algorithm[6] was used for lossy compression of the larger image sets. The lossy JPEG quality factor was set to provide a 10:1 compression ratio for the larger radiographs so that the compression artifacts were minimal and visually imperceptible. However, the main goal of the experiment was the evaluation of transmitted real-time ultrasound compressed video imagery.

The compression of a video signal digitized to CCIR-601 specifications (approximately 160 Mbps) to a bandwidth capable of being transmitted over satellite connections or low-bandwidth terrestrial links (56 kbps to 1.5 Mbps) requires compressing the signal by approximately 3000:1 to 100:1, respectively. Digitized video data, even after compression at ratios of roughly 400:1 (384 kbps), can be decompressed with close-to-analog VHS videotape quality. There are many means for a video coder-decoder (codec) to achieve these high degrees of compression: (1) reducing the effective luminance and chromanance sampling structure matrix dimensions, (2) reducing the frame rate, (3) a hybrid of interframe prediction to utilize temporal redundancy and transform coding of the remaining signal to reduce spatial redundancy, and (4) various combinations of these three. For the ACTS/AMT experiment, the International Telecommunication Union—Telecommunication Standardization Sector (ITU-T) Recommendation H.320 suite of videoconferencing standards[7] were used, specifically the H.261 Codec for Audiovisual Services at p × 64 kbit/s,[8] intended for use at video bit rates between approximately 40 kbps and 2 Mbps. A 16-kbps in-band audio channel was used throughout. Both video and audio communications were bidirectional.

Images transmitted over the satellite link were evaluated for artifacts through subjective visual comparison with the originals. The original and transmitted images also were compared using quantitative image processing measurements (eg, normalized mean square error [NMSE] and peak signal to noise ratio [PSNR]). The effect of image and video compression was analyzed by examining the dropout rate versus the bit error rate. In the case of video compression analysis of the H.261 algorithm, the video image quality has been subjectively critiqued and videotapes of the compressed video transmitted by satellite have been digitized and are being analyzed.

Initial field testing. The initial testing was to begin using the Seattle-Portland Fixed Hopping Beam[2]; however, the HBR antenna for the AMT was moved from the NASA Lewis Research Center (LeRC) in Cleveland, Ohio, to the JPL in Pasadena, California. This move meant that both the AMT and the JPL HBR would be using East polarity hopping beams, which is not allowed in the bent-pipe configuration. Therefore, the steerable antenna was used to cover transmissions from the AMT in the Puget Sound basin area, including the UW School of Medicine (Seattle, WA), Madigan Army Medical Center (south of Tacoma, WA), Advanced Technology Laboratories (Bothell, WA), and an ultrasound clinic on Whidbey Island (near Columbia Beach, WA).

The purposes of these experiments were to test the basic functionality of the ACTS/AMT equipment and to perform teleradiology image file transfers (Fig 7) and the more challenging transmission of real-time ultrasound video at 128 kbps between an NEC VisuaLinks TC5000 video codec in the AMT and a PictureTel 3000 video codec in the UW Department of Radiology (Fig 8).

Extended field testing. The UW School of Medicine (UWSoM), established in 1946, is the only medical school directly serving the five states of Washington, Wyoming, Alaska, Montana, and Idaho (WWAMI). The UWSoM operates a decentralized program of medical education via a network of teaching affiliates throughout the WWAMI region. The WWAMI area comprises approximately 30% of the US landmass (spread over three time zones), but less than 3% of the US population. This region is noted for its rugged terrain and diverse climactic conditions, which vary from mild temperatures along the Pacific Coast to extremes of heat and cold in portions of Alaska and on the Great Plains of eastern Montana. The nation's highest mountain chains (the Rocky Mountains, the Cascade Mountain Range, and the Alaska and Brooks Ranges) form natural subregions. As such, UWSoM-WWAMI provides an ideal testbed for rural and remote teleradiology and telemedicine.

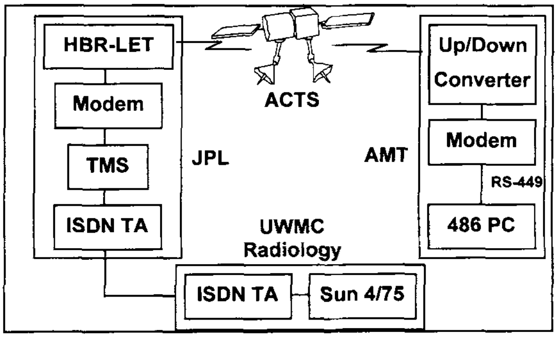


Fig 7. Initial field testing configuration for image file transfer. TA, terminal adapter.

Field trials in the WWAMI area were conducted in various types of weather and terrain to test the rain fade compensation and propagation error correction functions of the AMT. In addition, during the extended field testing, real-time compressed video telemedicine links were established (Fig 8) at 128, 256, and 384 kbps using the NEC VisuaLinks TC5000 H.261 codecs at both the AMT and UW Department of Radiology ends. In addition, a link-up of the AMT with a medical mobile MR scanner trailer was effected at the Covington Medical Clinic (Kent, WA) for the teleradiology transmission over the ACTS of MR images (Fig 9) from an MR scanner in a mobile trailer.

The UW has been awarded a telemedicine grant from the Office of Rural Health at the Department of Health and Human Services. The purpose of this grant is to provide expert consultation to rural primary care physicians. As part of this grant, desktop PCs were outfitted with video compression boards that operate using the H.320 standard.[7] Four of these systems have been deployed in the following rural sites: Colville, WA; Petersburg, AK; Ronan, MT; and Driggs, ID. An additional four systems have been deployed in the emergency departments of the following Seattle sites: UW Medical Center, Harborview Medical Center (Seattle's level 1 trauma center), Children's Hospital Medical Center, and the Roosevelt Outpatient Center.

It was possible to dial-up any of these telemedicine PCs using the ISDN lines from Pasadena and display the remote video from the AMT on these systems (Fig 8). This demonstrates the utility of mobile remote consultation for emergency triage and disaster relief, and the value of the ubiquity of the H.320 standard to telemedicine.

A simulated MASH environment was arranged at Madigan Army Medical Center. A dozen soldiers were imaged with an ATL HDI-3000 ultrasound machine in a MASH triage tent at Fort Lewis, WA.

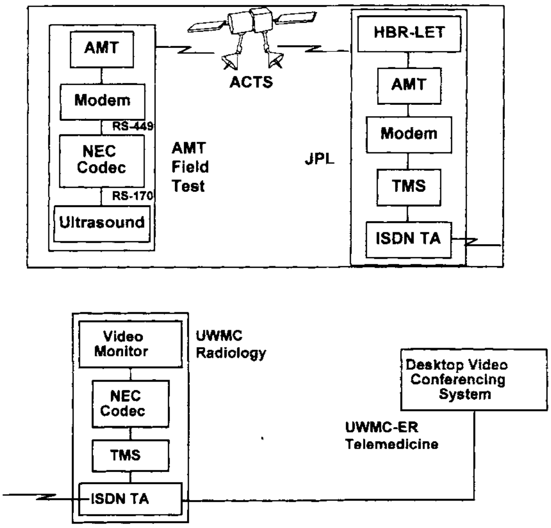


Fig 8. **Extended field testing configuration for compressed ultrasound video and teleconferencing.**

Video lines were run from that tent to the AMT and the compressed video images viewed at the UW Department of Radiology in real-time. A 384-kbps data rate was used throughout the simulation. From the 12 presumed-normal Special Forces volunteers arose one liver lesion and one gallstone.

Hawaii field testing. The Hawaii portion of the ACTS/AMT experiments demonstrated: mobile at-sea transmission with the Navy at Pearl Harbor, relay transmission between a ground station in Micronesia and the ACTS/AMT at Tripler Army Medical Center, and disaster simulation with PacSpace and the Hawaii Civil Defense. Again, the static and real-time video imagery was downlinked from the ACTS to the JPL and transmitted to the UW Radiology Department as described above.

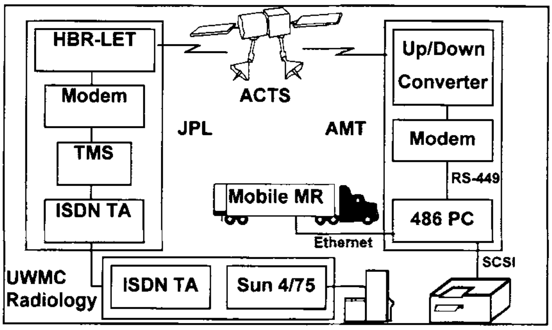


Fig 9. **Initial field testing configuration with external modalities, ie, a mobile MR trailer.**

METHODS AND RESULTS

Teleradiology transmission rates. To transmit static image data files over the ACTS/AMT link, an independent segment of the Internet was implemented between a Xyplex router in the AMT and an equivalent router at the UW. The TCP/IP (Transport Control Protocol/Internet Protocol) File Transfer Protocol (FTP) was used to transmit files between two 486 PCs utilizing Microsoft Windows 3.1 and connected to the routers through a 10BaseT Ethernet connection. The observed effective data transfer rate was 12,800 (1,440) bits per second (bps) and 23,800 (370) bps when the AMT transmission rate was operated at 128 and 256 kbps, respectively.

These low utilization rates (9.8% and 9.1%, respectively) can be attributed to the relatively long time it takes for data to travel to and from the satellite in geosynchronous orbit and the TCP acknowledgment policy used. The ACTS is in geosynchronous orbit about 19,000 miles above the equator at 100°W longitude. The roundtrip from the AMT to the JPL takes approximately one-half second (0.58 seconds). This is contrasted by the terrestrial telecommunications round trip from Pasadena to Seattle of approximately one-thirtieth of a second.

The TCP/IP sliding window acknowledgement protocol policy[9] for in-order data being accepted by a receiving TCP node has two options concerning the timing of an acknowledgment: (1) when data is accepted, immediately transmit an empty (no-data) segment containing current acknowledgment information, and (2) when data is accepted, record the need for acknowledgment, but wait for an outbound segment with data on which to piggyback the acknowledgment. Because the transmission of image data for this link was unidirectional FTP transfers, the former TCP/IP acknowledged protocol policy was used, causing low utilization primarily from the large next packet transmission delay, in large part due to the one-half second geosynchronous orbit round trip.

Compressed ultrasound video evaluation. Through one of the author's (B.K.S.) previous experiments with compressed ultrasound video transmission,[10] it was determined that the visual quality of real-time compressed ultrasound video is highly dependent on the transmission rate selected for bandwidths below 1.5 Mbps. Thus, a primary objective of the ACTS/AMT experiments was to gather data on the diagnostic quality of the compressed video stream versus transmission data rate (the compression rate is approximately inversely proportional to the transmission rate).

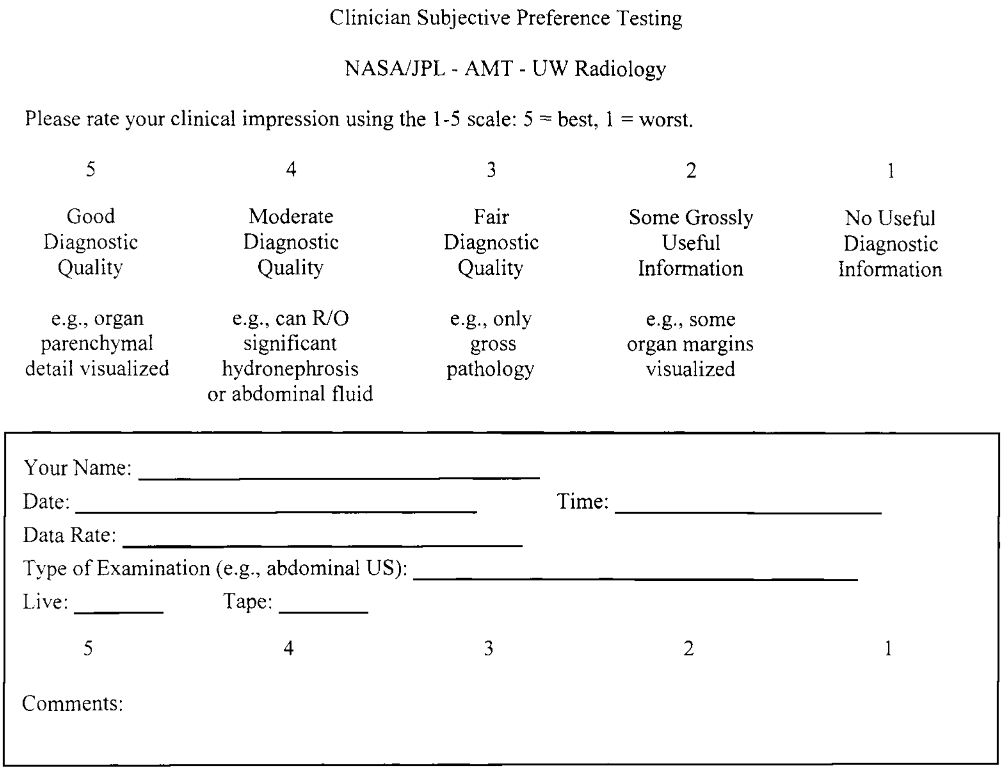
The goal of this radiologist preference testing is to determine the level of compression at which diagnostic signs are no longer interpretable. For each live case, radiologists and sonography technologists were asked to complete the form shown in Fig 10. This form consists of fields for the type of examination (eg, abdominal ultrasonography) and the data rate for compressed video transmission. A five-point Likert scale[11,12] was used to gauge the viewer's impression of the diagnostic quality: 1–no useful diagnostic information, 2–little useful information, 3–some useful information, 4–moderate diagnostic quality, and 5–good diagnostic quality. The results of the questionnaire were analyzed using a combination of descriptive and summation statistics (Table 1).

Based on the analysis of the sampling provided in Table 1, it can be seen that at 128 kbps, the real-time compressed ultrasound video image quality for the abdomen, kidney, and liver provided, at best, some grossly useful information. At 256 kbps, the image quality for the abdomen, carotid artery, fetal survey, and thyroid provided fair to moderate diagnostic quality, with a wide spread among viewers. At 384 kbps, all imaging categories provided predominantly good image quality with a fairly small degree of variance amongs the viewers.

All compressed ultrasound video sessions transmitted at the various bandwidths (40 hours' worth) were videotaped using high-quality S-VHS recorders and media at the transmit and receive ends. S-VHS produces a minimal degradation in image quality compared with video compression effects. This will allow for further evaluation of compressed ultrasound video image quality as a function of bandwidth with a larger number of reviewers.

DISCUSSION

Overall, the transmission of static images and compressed ultrasound video operated better than anticipated. Although there were no problems establishing a TCP/IP network using the ACTS, the TCP acknowledgment protocol used caused problems due to the long propagation delays of the ACTS geosynchronous orbit. As the video codecs impose a compression stream delay of about one-half second per side, the extra-geosynchronous delay



Clinician Subjective Preference Testing

NASA/JPL - AMT - UW Radiology

Please rate your clinical impression using the 1-5 scale: 5 = best, 1 = worst.

5	4	3	2	1
Good Diagnostic Quality	Moderate Diagnostic Quality	Fair Diagnostic Quality	Some Grossly Useful Information	No Useful Diagnostic Information
e.g., organ parenchymal detail visualized	e.g., can R/O significant hydronephrosis or abdominal fluid	e.g., only gross pathology	e.g., some organ margins visualized	

Your Name: ____________________
Date: ____________________ Time: ____________
Data Rate: ____________________
Type of Examination (e.g., abdominal US): ____________________
Live: ______ Tape: ______
5 4 3 2 1
Comments:

Fig 10. Likert scoring forms used to assess diagnostic quality for various anatomic regions at different transmission bandwidths.

Table 1. Ultrasound Radiologist and Ultrasonographer Likert Scoring for Compressed Ultrasound Video at Receiving End for Various Anatomic Locations

Anatomy	Data Rate (kbps)	Likert Score Mean (SD)
Abdomen	128	1 (0)
	256	3.13 (0.85)
	384	4.45 (0.71)
Carotid artery	256	3.7 (n/a)
	384	4.70 (0.36)
Fetal	256	3.80 (0.28)
Kidney	128	2 (0)
	256	3.50 (0.71)
	384	5.0 (0)
Liver	128	2 (0)
	384	4.67 (0.58)
Pancreas	384	5 (0)
Spleen	384	5 (0)
Thyroid	256	3.10 (1.98)
	384	4.03 (0.74)

did not in itself cause a large impediment to the video component of the telemedicine consultations. However, the delay time did cause some problems when two people started talking within one or two seconds of each other. In that case, just as with the Ethernet carrier-sense multiple access with collision detection (CSMA/CD) protocol, a verbal collision detection algorithm must be employed to produce a meaningful two-way dialog. This meant that upon collision, both parties backed off for a few seconds and then began speaking again. However, this could lead to further collisions. The preferred method was a token ring network–type protocol with expression of the verbal token "over" relinquishing control of the audio link.

We see this study as a platform for the application and implementation of real-time compressed ultrasound video for clinical application within the UW Academic Medical Center. As part of our work under an ultrasound telemedicine contract with the Defense Advanced Research Projects Agency (DARPA), we have developed an infrastructure to transmit real-time compressed ultrasound video over local area networks consisting of FDDI and switched 10BaseT Ethernet. This is being used to connect the radiology departments at the UW Medical Center, the Harborview Medical Center (Seattle's level 1 trauma center), and the Roosevelt Outpatient Clinic, somewhat compensating for limited staffing of the ultrasound sections as well as facilitating physician-to-physician consultation.

We also view this study as a platform for the investigation of providing remote real-time ultrasound imaging at the point-of-need. If highly portable ultrasound units with video codecs and telecommunication links were available to health care providers in the nursing home, or to nurses in the obstetrics ward, or even to paramedics in an ambulance (we have demonstrated that the AMT can transmit images and video while in motion)—and they were all trained to acquire the images for review by an ultrasound expert via telemedicine—the ultrasound examination could be taken to the patient. This not only would allow examinations in situations such as remote and emergency scenarios but also would keep the patient from being transported to the examination site (hospital or clinic), eliminating both transportation costs and inconvenience to the patient. This ultrasound instrument portability also might allow patients to spend more time at home and less time in care facilities such as nursing homes. The use of highly portable ultrasound devices with telemedicine capabilities has the potential for increased diagnostic ultrasound utilization and reduced health care costs, while also providing an extended range of quality health care.

The authors are currently participating with Advanced Technology Laboratories in a funded DARPA TRP (Technology Reinvestment Program) to develop a lightweight (less than 3 lb), fully functional (including color Doppler and power Doppler capabilities) ultrasound device. This is a joint collaboration between the UW Department of Radiology, the UW Applied Physics Laboratory and Advanced Technology Laboratories (Bothell, WA), Harris Semiconductor (Palm Bay, FL), and VLSI Technology, Inc (San Jose, CA). The goal of the telemedicine component of this ARPA TRP is the design, analysis, and testing of wavelet video compression algorithms specifically tailored for diagnostic ultrasound imaging over civilian and military communication infrastructures.

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