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PRELIMINARY EVALUATION OF SYNTHETIC SPEECH

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16. Abstract

This report briefly discusses the methods for storing and generating synthetic speech and a preliminary evaluation of the intelligibility of a speech synthesizer having a 75-word vacabulary selected for air traffic control messages. A program is suggested for additional testing based upon a vocabulary expanded to 128 words.

17. Key Words
Synthetic Speech, Air Traffic Control, Digital Data Link

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PREFACE

The synthetic speech preliminary evaluation described in this report was performed as a joint effort by the Transportation Systems Center STOL Avionics Program Branch and Human Factors Branch. The work was sponsored by the Federal Aviation Administration, Systems Research and Development Service.

This work is a part of a continuing effort to test and evaluate cockpit man/machine interface devices for air-ground data link systems for the continental United States (CONUS) and oceanic areas.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

1.0 INTRODUCTION

Digital Data Link with its capability for efficient transmission of information provides an attractive solution to the present problem of overcrowding of communication links for Air Traffic Control (ATC). A variety of visual display technologies are available which can present such digitally transmitted information in highly readable and reliable form; all that is required is minor repackaging of the displays to fit the space constraints of the cockpits of specific aircraft and the routine development of interfaces to handle the specific signal characteristics of the digital transmission system being used.

The use of such visual displays does, however, force a change in the pilot's present habit patterns. Communication by analog voice signals, while inefficient by digital standards, offers the advantage that it can be noted by the pilot regardless of the direction of his gaze; that is, he can listen without interrupting his scanning pattern. The use of voice either by itself or as a supplement to visual displays of air traffic commands or advisories should not be discounted.

One way to relieve the overcrowding of communication channels and still allow the pilot listen to, rather than look at, ATC information is to transmit digital signals that control the selection of words generated synthetically in the cockpit. Rather than use the signal to cause a dial to move or a number to light up, use it to cause a box to speak. This report discusses preliminary evaluation of such equipment for air traffic control messages.

2.0 METHODS OF SPEECH SYNTHESIS

Analysis of speech to permit its storage and later synthesis consists essentially of measuring, storing and retrieving of signals which represent the relative energy at various frequencies in the speech spectrum. The quality of any speech reconstructed from such signals is, of course, a function of the number of discrete frequency bands which are used, but a reasonably small number of bands can represent speech with acceptable quality and intelligibility.

Since the relative energy in the various frequency bands is changing rapidly during speech, the signal must also reflect these changes. This can be accomplished by sampling the speech at regular intervals, or alternatively, a signal may be generated which indicates the duration of a particular combination of frequencies. This latter method makes for more efficient storage of the characteristics of speech, particularly when the speech involves a high proportion of long vowel sounds.

At the speech generating end of the system, these various equivalents of the speech must be stored, such that an incoming signal triggers the selection of a desired word or phoneme. Here there is a choice between technologies. Normal English is made up of approximately 40 different speech sounds or phonemes (the precise number is a function of the skill and dedication of the transcriber). Completely recognizable speech may be synthesized by sequential selection of such stored phonemes, but if naturalness is to be achieved, a number of intra-phoneme transitions must also be stored. A southern accent consistently involves the interpolation of extra long-vowel sounds not present in the spelled word. In the so-called universal American dialect largely attributable to radio communications, these additional vowel sounds are almost but not quite completely unvoiced, and these rapid intra-phoneme transitions provide smoothness and naturalness to the speech.

With digital storage of words, transitions are not a problem providing that the speech has been sampled with rapidity such that these transitions are represented. However, there is a requirement that these transitions be stored in the generating equipment.

Once all phonemes and all of the intra-phoneme transitions deemed necessary are stored, it is possible to generate all possible English words by appropriate selection of speech components. Storage of complete words thus appears more efficient for applications requiring a limited vocabulary, while phoneme storage becomes increasingly attractive as the size of the required vocabulary increases.

Multiple techniques also are available for storing information. Drums with multiple tracks and readout heads employing either magnetics or electro-optics might be employed. However, the reliability of such mechanical movements in an airborne environment might be questionable, and more importantly, the use of such equipment results in awkward pauses, since at the completion of a word it is not possible to start the generation of the next word until the drum has rotated to the proper position. For these reasons, the TSC study was confined to devices in which the vocabulary was stored in digital solid-state form with no moving mechanical parts.

In early FY'72, TSC requested proposals from industry for a speech synthesizer with a 75-word vocabulary to permit preliminary evaluation of the applicability of synthetic speech to ATC applications. On the basis of demonstrated capability as evidenced by an audio tape submitted with their proposal, a contract was awarded to Advanced Communications, Inc., a part of Actron Industries. As a result of corporate mergers during and after contract negotiations, the device contracted for was eventually fabricated in the plant of the parent organization, McDonnell Douglas Electronics, using the designs of the personnel who originally submitted the proposal.

In the device as delivered, (pictured in Figure D-2) information is stored digitally as complete words, and any of the 75-words may be selected by the use of a 7-bit digital code. When the device has completed the synthesis of any of these words, it returns a signal indicating that it is ready to accept the next word.

Digital storage permits independent control of the speed and pitch of the synthesized words. Switches on the McDonnell Douglas synthesizer permit words to be generated at slow, normal or fast speeds, and in either a baritone or tenor register. A photograph of the synthesizer is appended.

3.0 INTELLIGIBILITY TESTING

Intelligibility testing of the vocabulary of the voice synthesizer was performed at Regis College using twenty female subjects, all of whom had previously been screened for any possible hearing defects. Outputs from the synthesizer were recorded on magnetic tape using a professional tape deck. Normal speed and baritone register sellings were employed with the synthesizer. The tape was presented to the subjects via earphones as they sat in individual cubicles in a language laboratory.

In making an evaluation of this sort, it would have been possible to have the subjects memorize the existing 75-word vocabulary and later to attempt to differentiate the words as they were presented in random order. However, an attempt was made during the testing to obtain information not only as to the intelligibility of the existing vocabulary but also concerning confused sounds within words as an aid toward programming future vocabulary additions more reliably.

With these purposes in mind, the 20 subjects were scheduled for approximately one hour on each of three successive evenings. On evening one, the words were first presented in random order and the subjects were asked to write down their best guess as to what they thought they heard. They had no previous knowledge as to what to expect other than that the words were all used in air traffic control. The subjects were then given a copy of the vocabulary to follow as the words were sequenced three times. The session concluded with the presentation of the words in random order five times. During each of these presentations, the subjects checked off the words which they thought they heard using sheets containing 128 possibilities; these possibilities varied from sheet to sheet to prevent the subjects from learning a fixed pattern for checkoff. Appendix C contains the list used for one of these presentations and actually contains additional words which were on order at the time the test was run.

Session two followed the same pattern of five presentations with word checkoff on the answer sheets, at the end of which time the words were presented once more and the subjects were again asked to write down what they thought they heard. Session three again provided five presentations for word checkoff, and concluded with a request that subjects provided comments as to the quality of reproduction of individual words.

The vocabulary used consisted of the phonetic alphabet, the digits zero thru nine and the following additional words: affirmative, altimeter, altitude, approach, ascend, at, ceiling, center, cleared, contact, descend, eleven, heading, hold, knots, left, located, maintain, marker, miles, negative, o'clock, on, radar, report, right, runway, slow, speed, squawk, ten, thousand, tower, traffic, turn, twelve, use, visibility, wind.

As might be anticipated, the initial run in which the subjects heard the words only once and with no precise knowledge of the vocabulary produced somewhat erratic answers. In particular, the unfamiliarity of the subjects with the words of the phonetic alphabet caused many errors, since they obviously could not be expected to relate such words as "Romeo", "Juliet", "Hotel", "Wiskey" and "Tango" to the context of air traffic control. The total errors per word for the 20 subjects were as follows:

Errors	Words
0	Left, Yankee, eleven, five, Alfa, negative, seven, zero, X-ray, ascend
1	Altitude, speed, cleared, on, affirmative, runway
2	Radar, November, report
3	Contact, one, turn, Victor
4	Delta, traffic, descend, two, wind, at, nine, India, center
5	Sierra, six, approach, use, Uniform, three, twelve
6	Four, located
7	Slow, Kilo, ceiling
8	Right, eight
9	Golf, Whiskey
10	Altimeter, tower, o'clock

Errors	Words
11	Miles, Charlie
12	Visibility, Zulu
13	Lima, Foxtrot, thousand, Oscar
14	Papa
15	Hotel, hold, Romeo
16	Knots
17	Maintain, heading
18	Marker
19	Ten, Quebec, Mike
20	Echo, Tango, Squawk, Juliet, Bravo

As an aid in the programming of future words, the subjects' incorrect guesses are tabulated in Appendix A.

By the end of the second day, after the subjects had heard the words a total of eleven times as they attempted to match them with the possibilities appearing on their checkoff sheets, and were again asked to write down the possibilities, performance was greatly improved. Correct responses were recorded by all twenty subjects on 58 of the 75 words presented, and 15 or more subjects gave correct responses on the balance. In descending order of accuracy, scores were as follows:

Correct	Words
19	Ten, two, Victor, ascend
18	Hold, center, Golf, eight, miles
17	Descend, knots, Echo, Bravo, Tango
16	Heading
15	Tower, Mike

These data indicate the improvement in accuracy of recognition which occurred as the subjects became more familiar with the vocabulary. On this basis, any requirement imposed on the manufacturer for reprogramming of words should be based upon scores obtained on the last series of trials. Appendix B lists the errors for the series of five trials on each of the three sessions. On the third day (trials 11-15) only two words (Mike and Tango) had recognition accuracy below 95%.

Acceptance of the remainder of the original vocabulary has, however, been delayed until the new vocabulary words which have recently arrived can also be evaluated. In particular, we are concerned about possible sound-alikes in the original and expanded vocabulary. Total vocabulary including new vocabulary words is listed in Appendix C. Examples of this are:

Mike, right, light
Heading, heavy
Slow, snow
Ascend, descend

When data have been obtained concerning these possible confusions and the acceptability of the other new vocabulary words, a decision as to the precise requirements for word reprogramming will be made. At that time, the manufacturer will also be given the opportunity to reprogram certain other words which are somewhat difficult to understand (Bravo, Tango, knots). Reprogramming of these words is, however, less critical since they are not likely to be confused with any other words in the total 128-word vocabulary.

4.0 SIMULATOR TRIALS

Even though an interface with an entry device to permit the generation of air traffic control messages in anything approaching real time from the output of the speech synthesizer is not presently available, it was decided that a preliminary test might provide something in the way of useful information as to the acceptability of synthetic speech in the cockpit. A scenerio containing a series of commands for directing a light aircraft from the vicinity of the Whitman VOR approximately 15 miles south of Boston's Logan Airport to an eventual backcourse landing on Runway 22L at Logan was prepared with appropriate intervals between commands and advisories. A program based upon this series of commands was generated in the TSC/Honeywell DDP-516 laboratory. The speech synthesizer was used to generate the commands, and an audio tape of its output was recorded using normal speed and baritone register settings on the synthesizer. The scenerio used and the flight path which it directed are reproduced in Appendix D.

Subject performance comparing this tape with an identically-timed tape generated by a real voice and containing the same series of commands overlaid on a background of typical air traffic control commands to other aircraft was obtained in a Link GAT-1 simulator. Four subjects, all familiar with the operation of the simulator, were employed. Three had actual flying experience of varying amounts; the experience of the fourth was limited to approximately 40 hours of simulator operation. Each subject made two runs, once using the tape containing a real voice and once using the synthetic voice, and the order of these presentations was counterbalanced to minimize practice effects.

Each tape contained 16 commands or advisories, such that 128 data points total were obtained from the four subjects. Repeats were requested on only five commands, all with the synthetic speech. However, four of these occured at the start of runs and can be attributed to incorrect audio volume settings. With the tape containing real voice, this was not a problem since volume settings could be adjusted while listening to commands to other aircraft prior to the first command directed to the GAT trainer.

All subjects found the synthetic speech understandable and acceptable. However, there was consensus that the synthetic speech should be faster. Subjects complained about a lack of realism when air traffic control commands were presented at a normal rate of speech. They missed the urgency with which such commands are normally issued.

For this reason, a third tape was prepared with the synthetic speech recorded at a faster rate.* This was played to the subjects outside the simulator and all agreed that it provided a much more acceptable presentation.

This new tape was then compared against the tape with real voice using two more subjects in the simulator. During these runs, one subject missed two commands on the tape containing the real voice, while the other subject missed one command from the taped synthetic voice.

One new comment emerged from these runs. One subject stated that he missed the chatter normally present during air traffic control communications, not because it provided him with anything in the way of specific information, but because it constantly assured him that his radio was working. Means for overcoming this deficiency will be evaluated during the forthcoming tests on the GAT-1 simulator so that appropriate corrective action is incorporated in the Data Link flight tests.

*On this tape, the commands were issued at approximately 155 words per minute as compared with a normal rate of approximately 90 words per min.

5.0 DISCUSSION, CONCLUSIONS, AND FUTURE PLANS

This preliminary evaluation of synthetic speech has demonstrated that it is desirable to incorporate it as part of the Data Link system to be flight-tested. While some reprogramming of certain words in the existing vocabulary is required to make them less likely to be confused with other words, the majority of the vocabulary is completely intelligible and the quality of generated message is acceptable within the limits of the conditions tested. Unlike the case with analog voice transmission, there is no saving in message transmission time if the synthesizer is asked to put out messages at a faster than normal rate of speech; despite this, subjects felt that rapid speech was more acceptable by reflecting the urgency of air traffic control messages.

Thus far no evaluation has been made of other uses of the synthesizer in the cockpit. Logical candidates are the automatic callout of out-of-tolerance conditions and of altitudes during landing.

As part of its future program for eventual evaluation of synthetic speech in the Data Link Flight Test Program now in its planning stage, TSC expects:

1. To evaluate the intelligibility of the total synthesizer vocabulary after the words now on order have arrived.
2. To specify reprogramming requirements for words which are confused or of poor intelligibility.
3. To run further tests on the GAT-1 simulator using a keyboard interface now being fabricated which will permit the generation of control commands in approximately real time.
4. To maintain an awareness of the state-of-the-art of voice synthesizers from various manufacturers.

WORD	# of OK RESPONSES	NO GUESS	WRONG GUESSES
Zero	20	0	
Turn	17	0	earn (2), burr
Wind	16	0	livid, width, with, siz
Juliet	0	15	Julia (2), nuyen, New Year, Looyer
Marker	2	4	Martyr (5), barter (3), latter, partner, archer, harder, charter, mail
Whiskey	11	3	misty (2), risky, listening, listing, western
Mike	1	0	light (13), like (4), might, vice
At	16	0	act (4)
Zulu	8	4	lulu (6) zero (2)
Affirmative	19	0	vicinity
Bravo	0	2	goggle (14), follow (2), gargle, dawdle
Charlie	9	4	plowway, clearly, curly, sorry, plowing, trolly, cloudy
Runway	19	1	
Nine	16	1	knive, night, dive
Eight	12	0	egg (2), ache (2), age (2), did, H
Victor	17	1	Richard, drifter
India	16	3	icthia
X-ray	20	0	
Center	16	0	sitter (2), thicker, bitter
Twelve	15	0	dwell (4), well
Ascend	20	0	
Ceiling	13	1	seaweed (4), silly, sealy
Located	14	3	broken, vote, rotated

APPENDIX A

Preliminary Test of Voice Synthesizer Intelligibility. Each word presented once in random order to 20 subjects who had no previous knowledge of the vocabulary other than that it was words in air traffic control.

WORD	# of OK RESPONSES	NO GUESS	WRONG GUESSES
Lima	7	12	Rima
Foxtrot	7	9	All Stop, Hofstra, oxcart, cough drop
Echo	0	5	Ghetto (9), depot, detour, bakan, preto, toe, picto
Sierra	15	4	Sylup
Altitude	19	1	
Speed	19	0	Stayed
Left	20	0	
Six	15	0	certs (2), search, cuts, since
Hotel	5	7	odell (5), opel, propel, goddle
Yankee	20	0	
Contact	17	1	doctor, gandet
Knots	4	3	thus (7), nuts (4), not, socks
Approach	15	4	across
Ten	1	3	end (6), air (3), hen (3), head, hand, can, air
Visibility	8	1	inability (7), ability, livability, liability, lindibility
Hold	5	0	old (7), code (3), cold (2), oda (2), load
Altimeter	10	5	altitude, almeter, alchemiter, alemitude, out
Eleven	20	0	
Use	15	1	fuse, airs, ears, ills
Romeo	5	1	Mobile (13), rodeo
Maintain	3	15	Vacate, lay
Cleared	19	1	

WORD	# of OK RESPONSES	NO GUESS	WRONG GUESSES
Uniform	15	1	utifirm, air defirm, interfere, unit one
Papa	6	9	pompom (2), cough drop, pop off, author
Five	20	0	
Tower	10	0	Hour (6), our, sour, (2), power
Delta	16	2	yalta, shelter
Traffic	16	2	placid, trappa
Right	12	0	ride (7), light
Thousand	7	8	houses, housing, oven, house, lob
Tango	0	13	agnew (2), hug, signal, thale, thank you, shadow
Golf	11	0	gulf (8), know
Miles	9	2	aisles (4), isle (4), pile
Slow	13	0	flow (6), low
Kilo	13	2	Hilo, halo, gullo, heilo, vile
Radar	18	0	graveyard, regard
For (four)	14	0	ford (3), ore (2), forge
Descend	16	3	ascend
Alfa	20	0	
November	18	0	
One	17	2	was (2), what
Squawk	0	2	Swapped (3), swamped (2), squat, swabbed, stopped, squaw, stop, (2) stwap, squat, struck, strat, swap, swap, slot
O'Clock	10	4	apart (4), opark, ocompt
Two	16	0	new (2), do (2)
Oscar	7	2	oster (7), roster (2), auster, aster
Heading	3	0	heavy (16), hippie
On	19	1	
Report	18	2	
Quebec	1	10	rebet (4), regret, wingback, bebet, be back, right
Three	15	0	lead, read, greed, re, we
Negative	20	0	
Seven	20	0	

APPENDIX B

Errors of omission for groups of five trials for 20 subjects: the numbers are thus directly equivalent to % errors in recognition.

WORD	TRIALS 1-5	6-10	11-15	WORD	TRIALS 1-5	6-10	11-15
Affirmative	1	0	0	November	1	5	0
Alfa	0	0	0	O'clock	0	0	0
Altimeter	0	0	0	On	4	1	0
Altitude	0	2	0	One	2	1	0
Approach	0	0	0	Oscar	0	3	0
Ascend	0	0	0	Papa	0	0	0
At	1	0	0	Quebec	5	13	0
Bravo	35	22	5	Radar	0	0	1
Ceiling	0	0	0	Report	0	1	0
Center	4	13	3	Right	4	2	4
Charlie	5	6	0	Romeo	7	2	1
Cleared	1	0	0	Runway	0	0	0
Contact	0	0	1	Seven	0	0	0
Delta	3	0	0	Sierra	0	0	0
Descend	0	1	1	Six	0	1	0
Echo	11	14	1	Slow	4	5	4
Eight	8	18	3	Speed	1	3	0
Eleven	0	1	1	Squawk	1	3	1
Five	1	1	1	Tango	30	22	9
Four	1	6	1	Thousand	4	5	0
Foxtrot	0	0	0	Ten	4	9	4
Golf	1	0	0	Three	4	4	0
Heading	23	13	3	Two	0	0	1
Hold	13	10	1	Tower	5	5	1
Hotel	5	6	0	Traffic	0	1	0
India	2	0	1	Turn	0	0	1
Juliet	5	1	0	Twelve	0	0	0
Kilo	0	1	0	Uniform	0	3	0
Knots	7	19	9	Use	4	3	1
Left	0	2	1	Victor	3	2	0
Lima	1	3	1	Visibility	0	2	0
Located	2	0	0	Whiskey	4	3	1
Maintain	5	1	0	Wind	0	0	0
Marker	3	0	2	X-ray	1	0	1
Mike	26	28	17	Yankee	0	0	0
Miles	5	5	3	Zero	2	1	0
Negative	0	2	0	Zulu	0	1	0
Nine	3	1	0				

APPENDIX C

MASTER VOCABULARY LIST FOR SPEECH SYNTHESIZER

Above	Center	Emergency	If Able	Marker	Question	Slow	Turbulence
Acknowledge	Charlie	Feet	IFR	Mike	Radar	Snow	Turn
Affirmative	Cleared	Five	Increase	Miles	Rain	South	Twelve
Ahead	Contact	Fog	India	Minimum	Reach	Speed	Uniform
Alfa	Continue	Follow	-ing	Minutes	Repeat	Squawk	Use
Altimeter	Control	Four (For)	Intermittent	Negative	Report	Stop	VFR
Altitude	Degrees	Foxtrot	Juliett	Nine	Request	Takeoff	Victor
And	Delay	Frequency	Kilo	North	Restriction	Tango	Visibility
Approach	Delta	Golf	Knots	November	Right	Taxi	Weather
Ascend	Departure	Ground	Leave	O'clock	Romeo	Ten	West
At	Descend	Gusty	Left	On	Runway	Thanks	Whiskey
Below	Don't	Heading	Light	One	RVR	Thousand	Wind
Bound	East	Heavy	Lima	Oscar	Seven	Three	X-ray
Bravo	Echo	Hold	Located	Outer	Sierra	To (Two)	Yankee
Cancel	Eight	Hotel	Lowest	Papa	Six	Tower	Zero
Ceiling	Eleven	Hundred	Maintain	Quebec	Slippery	Traffic	Zulu

Total: 128 Words

APPENDIX D

APPENDIX D

Scenario of commands to fictitious aircraft Seven Eight Bravo to direct a landing on Runway 22 Left at Logan International.

MESSAGE #	MESSAGE
1.	Seven eight Bravo. Squawk 1300. Maintain heading zero four zero.
2.	Seven eight Bravo. Turn right, heading zero five six.
3.	Seven eight Bravo. Descend to four thousand. Maintain one three zero knots.
4.	Seven eight Bravo. Report at five thousand.
5.	Seven eight Bravo. Descend to four thousand.
6.	Seven eight Bravo. Maintain heading zero five six. Use runway two two left. Wind two three zero at six knots. Ceiling three thousand.
7.	Seven eight Bravo. Turn left, heading three six zero.
8.	Seven eight Bravo. Descend to three thousand. Report at three thousand.
9.	Seven eight Bravo. Turn left, heading three two zero.
10.	Seven eight Bravo. Descend to two thousand.
11.	Seven eight Bravo. Report altitude.
12.	Seven eight Bravo. Turn left, heading two seven zero.
13.	Seven eight Bravo. Turn left, heading two three zero. Contact tower on one one nine one.
14.	Seven eight Bravo. Slow to one two zero knots.
15.	Seven eight Bravo. Cleared to use runway two two left.
16.	Seven eight Bravo. Report on runway.

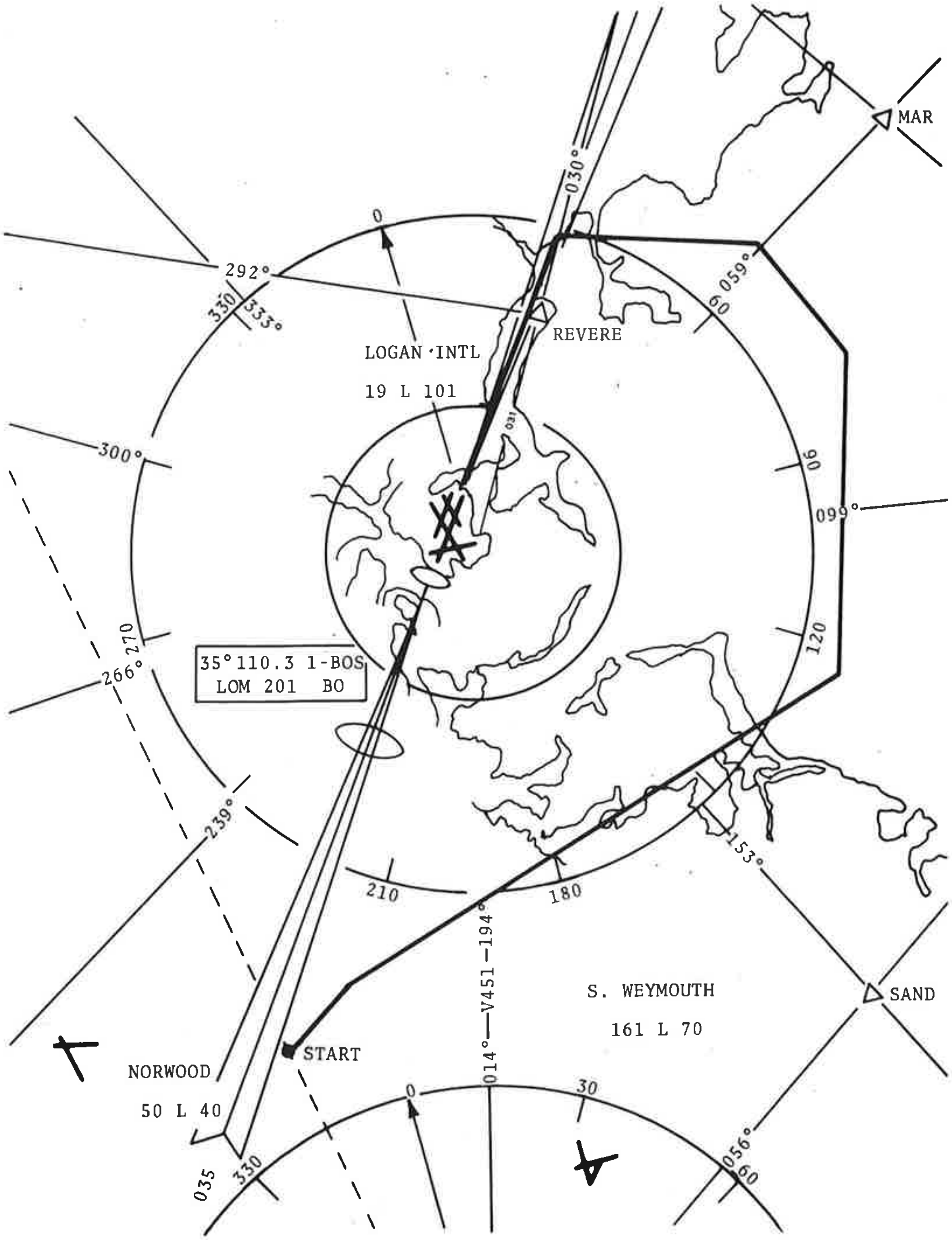

Figure D-1. Idealized Flight Path Directed by Synthetic Speech in GAT-1 Simulator

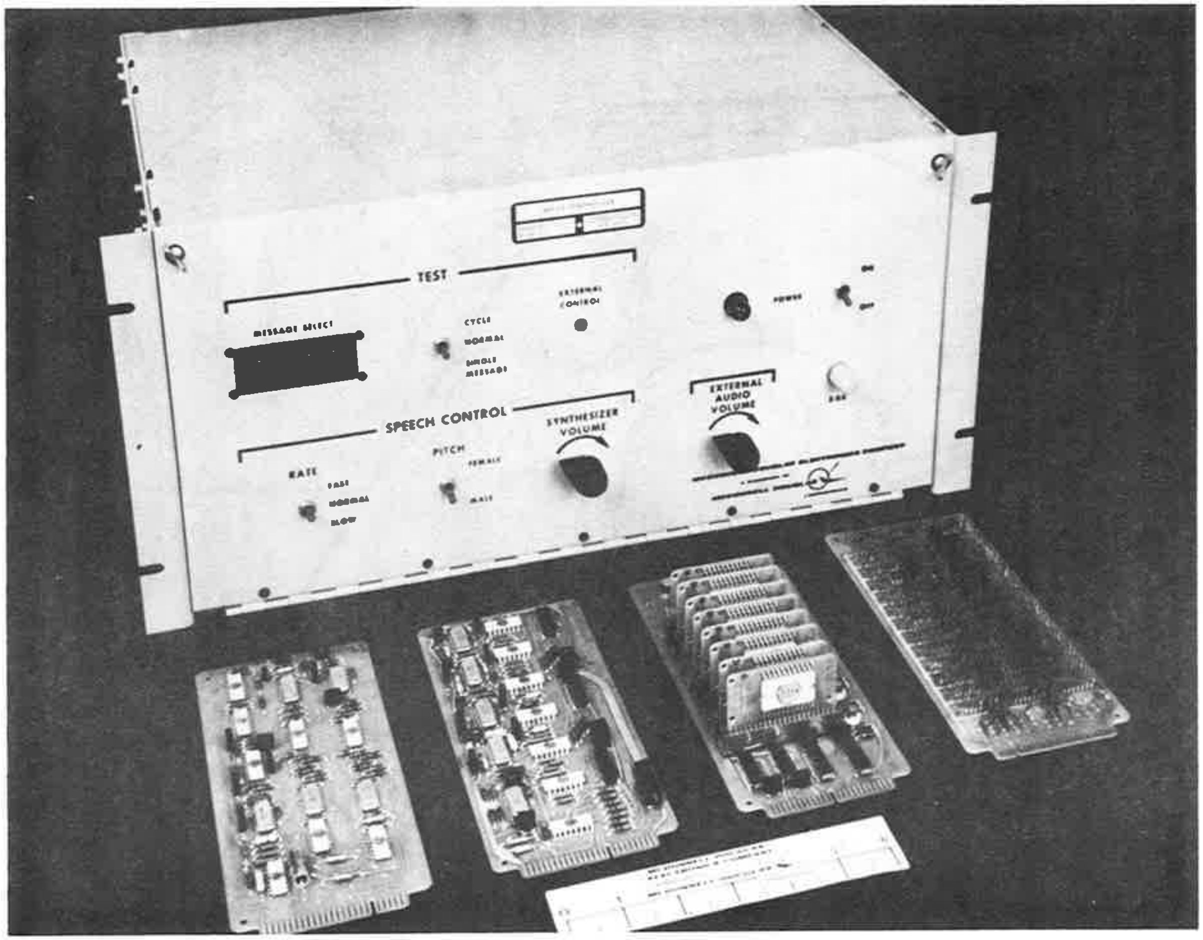

Figure D-2. Photograph of McDonnell Douglas Synthesizer