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FAA TECHNICAL CENTER LETTER REPORT

Aircraft Tracking and Data System (ATADS)

Enroute Accuracy

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PURPOSE

This letter report documents a technical evaluation of the enroute accuracy of the multi-DME position reference subsystem of ATADS.

BACKGROUND

A multiyear contract was awarded by SRDS in October 1978 to Amex Systems, Inc. to develop an airborne data acquisition and position reference system for evaluation of LORAN-C system performance. The Remote Area Precision Positioning System (RAPPS) was developed during phase 1 of the contract by Sierra Nevada Corporation (SNC). The RAPPS 1, delivered to the Technical Center in August 1979, was evaluated and used for field testing of LORAN-C in Vermont during the winter of 1979. The ATADS is the second generation airborne position reference and data collection system developed by SNC to provide improved accuracy and capability for evaluation of LORAN-C and other navigation systems.

An effort is presently in progress by DOT and DOD to evaluate existing and future radionavigation systems to provide inputs to the Federal Radionavigation Plan (FRP). The FRP will present an integrated policy for Federal, military, and civil navigation systems through the year 2000 to achieve maximum operational and technical utility to all users. LORAN-C is being evaluated by the FAA as a candidate radionavigation system to supplement or replace present navigation systems.

The evaluation of the ATADS at the Center will proceed with the complete testing of the system as planned, but an immediate evaluation of the position reference subsystem in the enroute mode was undertaken to respond to requirements for LORAN-C testing.

RELATED DOCUMENTS

1. Project No. 047-310-520 Test and Evaluation of RAPPS, Phase 1. FAA Report No. NA-80-32-LR, "Data Reduction and Analysis Techniques used in Determining the Accuracy of RAPPS 1", February 1980. FAA Report No. FAA-CT-80-52, "Test and Evaluation of RAPPS, Phase 1", March 1981.

2. Project No. 048-312-510. Investigate LORAN-C in Mountainous Areas. FAA Report No. FAA-RD-80-28, "West Coast LORAN-C Flight Test", March 1980. FAA Report No. FAA-CT-81-22, "LORAN-C in Mountainous Areas, Phase 1 - Vermont Tests", June 1981. TSC Report No. DOT-TSC-RSPA-80-21, November 1980.

3. Contract No. DOT-FA78WAI-955, "Develop aircraft positioning and data collection system". SNC Final Report, "Remote Area Precision Positioning System", December 1979.

4. Project No. 047-310-200, Report No. DOT/FAA/CT/81/193, "Test and Evaluation of the Aircraft Tracking and Data System", Test Plan, March 1982.

SYSTEM DESCRIPTION

The ATADS is an airborne data collection package with an integral position reference capability. The three subsystems that comprise the system are the multi-DME position reference system, the data collection system, and the data analysis system. Figure 1 is a block diagram of the ATADS.

The position reference system provides aircraft position in space by multilateration of range information from DME ground stations. The position reference system,located on the ATADS airborne rack, consists of a modified airborne DME interrogator unit and a microprocessor unit. The station channeling, station acquisition, and range tracking are controlled by the microprocessor. The normal sequencing rate of this cycler/tracker is ten stations per second. The DME interrogator was modified to process both the normal (ICAO) pulse and fast rise (precision) pulse return. Supplied with the system are portable DME ground stations specially designed for higher accuracy (precision pulse) for use in areas without adequate signal coverage and for non-precision approaches.

The ATADS functions in 2 Modes:

1. A preprogrammed mode controlled by a user specified programmable read only memory (PROM). The PROM allows selection of ten predetermined stations. The ten stations can be all normal pulse, all precision pulse, or a mix of both.

2. A free scan mode whereby the stations are selected by signal strength and scanned sequentially.

The data collection system contains a SESCO 8080 microprocessor as the central processing unit (CPU) and appropriate interfaces in a ruggedized airborne package. The system accepts inputs from various data sources which include the system clock, altimeter, cycler/tracker, LORAN-C, INS, and a keyboard terminal. The CPU time tags each data source and formats the data for the system digital tape recorder. Capability is provided to monitor system operation during the flight by optional printout of selected parameters.

Data reduction and analysis is accomplished by post flight processing the data on either a ground base minicomputer or a portable microcomputer. A PDP-11 computer at the Center is the processor for the home facility data analysis and an HP-85 portable computer is supplied for "quick look" of the raw flight data. The software algorithm for the position solution is the same for each computer, but different languages are used for the programs. The HP-85, although slower for data processing, provides a capability to produce post flight plots and statistics in the field to indicate the quality of the data.

FLIGHT TEST DESCRIPTION

The ATADS flight tests reported in this document were conducted as per Test Plan (item #4 under Related Documents) section 5.2 and 5.2.1 pertaining to enroute flight testing.

The enroute accuracy of the ATADS position reference system was measured using the Technical Center Nike instrumentation radar. After a brief period of laboratory system checkout and operation, the airborne rack was installed in the CV-580 test bed aircraft, N-49, for a series of local test flights. The ATADS rack was mounted in the forward section of the aircraft cabin and connected to the ship's AC and DC power. A DME blade antenna located on the bottom of the aircraft was used for signal reception. Digital altitude information from the pilot's encoding altimeter was input to the ATADS rack. A time code generator provided the external clock input to the system for reference time. Although ATADS provides the capability to record other navigation systems, i.e., INS (LTN-51) and LORAN-C (TDL-424 and TDL-711), these were not included in this test. The primary objective of this test was to evaluate only the ATADS position reference system.

The patterns were flown at altitudes between 4500 and 6500 feet MSL. These altitudes insured the constant reception of a minimum of 6 DME stations throughout each flight pattern. The flight patterns are shown superimposed on a low-altitude air navigation chart in Figure 2. The flight profiles for these tests included orbits of 10 nm radius centered around the ACY VORTAC and radial routes between the local VORTAC stations. Table 1 is a list of the ground facilities utilized for the flight tests.

Four flights as listed below provided over four hours of data:

Flight	Date	Duration	Description
1	1/22/82	1.5 hr.	4500' Altitude Orbit, 4500' Altitude Pattern, Checkout, No data
2	3/2/82	1.0 hr.	6500' Altitude Orbit, 6500' Altitude Pattern; Free Scan
3	3/3/82	1.5 hr.	6500' Altitude Orbit, 6500' Altitude Pattern; Preselected Scan
4	3/4/82	1.75 hr.	5000' Altitude Orbit, 6500' Altitude Pattern; Preselected Scan

DATA PROCESSING AND ANALYSIS

Data reduction and analysis were conducted as per Test Plan (item #4 under Related Documents) section 6.

The raw flight data recorded at 9600 baud on the system cartridge tape recorder consisted of date, time, altitude, and range information from the cycler/tracker. Also recorded on the tape were any comments input from the terminal during the tests. The information from each individual data source constituted a logical record with an identifier ASCII start character and ASCII "F" terminating character. Physical records were 1024 bytes in length. ASCII "0" fill characters were inserted at the end for any unused bytes. The format for the various data sources are listed in Table 2. Each data source was tagged with time at the instant received by the data collector.

The ATADS as operated on the local flight tests permitted approximately forty minutes of data collection per track. Almost two minutes of data were lost during each track change due to tape rewind.

The flight data was processed by both the portable HP-85 computer and the PDP-11 minicomputer using the same position solution algorithm. It was necessary to convert the contractor supplied BASIC software to FORTRAN for operation on the PDP-11 in order to merge the reference radar data with the ATADS computed positions. The processing of the raw flight data was identical on both computers except for I/O differences. A Qantex cartridge tape unit was interfaced to the PDP-11 to provide input of the raw flight data. The HP-85 used the airborne Tandberg cartridge recorder for flight data processing. A description of the data processing analysis executed on the PDP-11 minicomputer is detailed in Appendix A. A description of the position determination software translated for use on the PDP-11 minicomputer is in Appendix B. The position solution iteration interval which is software selectable, was updated every five seconds. The validation of the FAA software is presented in Appendix C. The three BASIC language programs supplied by the contractor for the HP-85 "quick look" data processing capability are outlined in Appendix D.

Appendixes E and F were furnished by SNC as part of the hardware/software documentation package required by the ATADS development contract. These appendixes describe the algorithms implemented within the ATADS for DME range filtering and least squares position solution.

RESULTS

Data from the initial test flight of the ATADS on January 22, 1982, revealed a deficiency in the airborne cycler/tracker. Too many replies (fruit) from adjacent channels were processed due to the lack of selectivity of the modified airborne DME which allowed undesirable replies to contaminate the position solution. An attempted quick fix by the subcontractor to improve selectivity resulted in degradation of ranging information.

The hardware problem was not resolved. The contractor improved system performance by modifying the tracker software and by adding pre and post filter routines in the position computation. In addition, problems were experienced while exercising the HP-85 software. Users unfamiliar with the system were prone to induce nonrecoverable errors. The software was revised by the contractor for easier operation. These modifications required one month after which the test flights resumed with flights #2 through #4.

The results of flight #2, operated in the free scanning mode, showed the the initial range solution deficiencies previously described were improved. The ATADS mean and one sigma east, north and circular errors (see Appendix A) are presented in Tables 3, 4 and 5 for test flights two through four. The circular error distributions (percent of the errors inside of a circle of specified radius) are presented in Tables 6, 7 and 8 for flights two through four. The circular error mean and one sigma, circular error probable (CEP), ATADS design specification and AC 90-45A accuracy requirements are summarized in Table 9. The CEP is defined as the 50% circular errors. Flight 4 circular mean error and CEP were approximately half the values for flights 2 and 3. Further investigation revealed the following information (see Figure 9).

Elimination of the high bias range error stations (0.1 nm) reduced flight 3 mean circular errors and CEP's, but did not reduce similar errors for flight 2.

The tracking radar time reference had slewed 30 seconds during flight 2. The time slew had been compensated for in post flight processing. Compensating for additional undetected time skews did not reduce flight 2 errors.

The high range bias errors and the high measured errors for flight 2 are unresolved and remain under investigation.

The tracking radar will not be available for enroute navigation system tests to validate range bias errors. Hence, high range bias error stations may unintentionally be included in position solutions for enroute navigation system tests. Position errors including high range bias stations will be more representative of enroute field test data. The combined 50% circular errors were 324 feet and 218 feet respectively for stations with and without high range bias errors (0.1 nm) in the position solution. The 200 ft. CEP specification was not met, based on the combined results from three quite similar flight profiles. However, as shown in Table 9 enroute system accuracy is more than adequate to allow comparison of navigation systems against the accuracy requirement of Advisory Circular 90-45A.

The ATADS accuracy was evaluated as delivered by the contractor and no experimentation was conducted to change software constants to optimize accuracy performance.

CONCLUSIONS

1. The ATADS system contains a position reference system of sufficient accuracy to allow measurement of enroute navigation system performance with respect to AC 90-45A.

2. The ATADS system did not meet the 200 foot CEP error design specification when data from flights were combined.

3. The airborne DME hardware remains susceptible to undesired replies (fruit) that degrade the position solution.

4. The HP-85 "quick-look" software remains awkward to use.

RECOMMENDATIONS

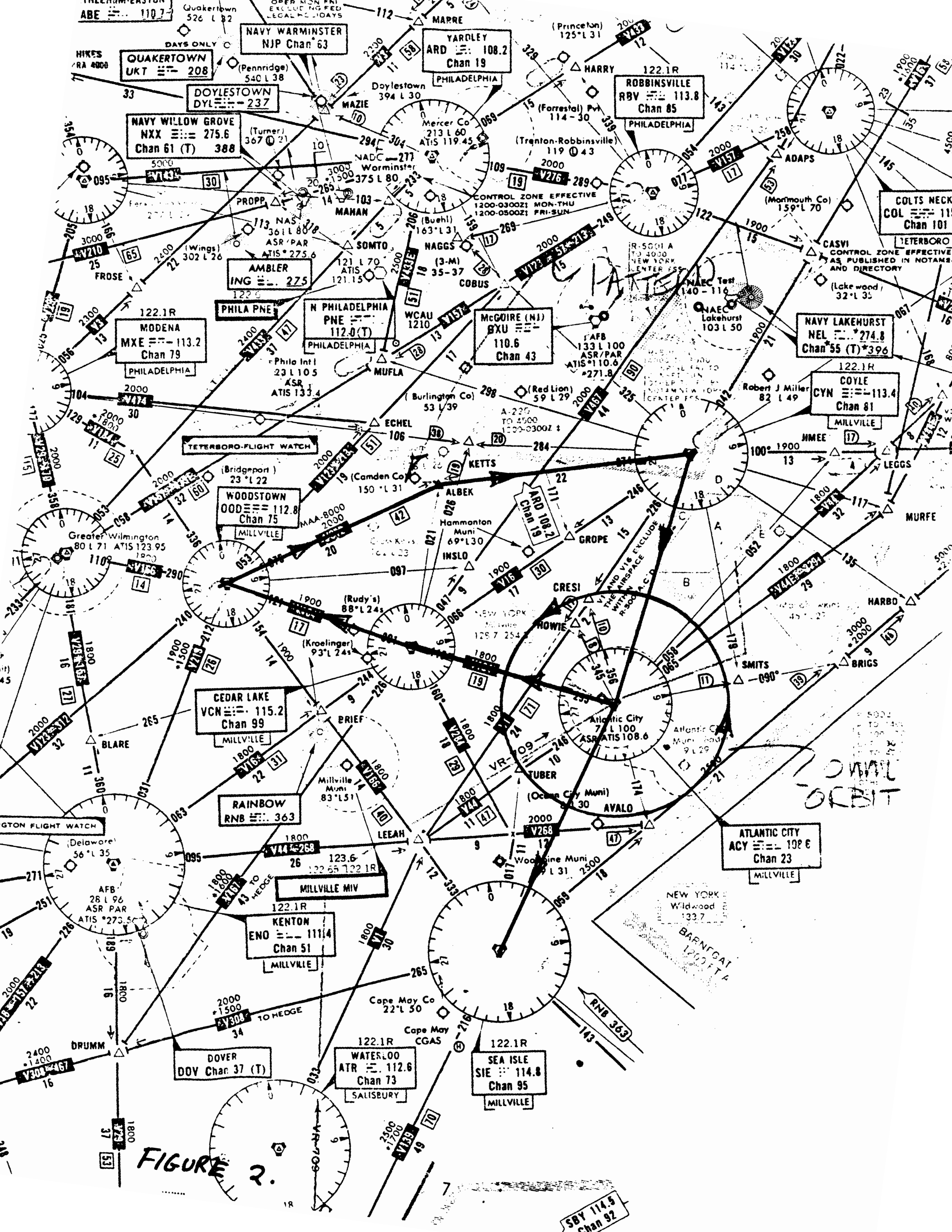
1. Follow-on testing should be conducted to allow determination of ATADS positioning accuracy in the non-precision approach mode using the contractor supplied portable ground stations designed for high accuracy. Further testing should also establish the capability of the ATADS as a navigation data collection system.

2. The airborne DME hardware should be modified to eliminate undesired replies.

3. The HP-85 software should be restructured for improved user operation.

4. An examination of software constants should be conducted to determine if optimization will improve system performance.

5. An additional flight test should be conducted in the free scan mode if the position errors observed in flight 2 cannot be resolved.



NAVY WARMINSTER
NJP Chan 63
YARDLEY
ARD 108.2
Chan 19
PHILADELPHIA
QUAKERTOWN
UKT 208
DOYLESTOWN
DYL 237
NAVY WILLOW GROVE
NXX 275.6
Chan 61 (T) 388
ROBBINSVILLE
RBV 113.8
Chan 85
PHILADELPHIA
COLTS NECK
COL
Chan 101
TETERBORO
AMBLER
ING 275
PHILA PNE
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McGUIRE (NJ)
BXU
110.6
Chan 43
MODENA
MXE 113.2
Chan 79
PHILADELPHIA
NAVY LAKEHURST
NEL 274.8
Chan 55 (T) 396
COYLE
CYN 113.4
Chan 81
MILLVILLE
TETERBORO FLIGHT WATCH
WOODSTOWN
OOD 112.8
Chan 75
MILLVILLE
CEDAR LAKE
VCN 115.2
Chan 99
MILLVILLE
RAINBOW
RNB 363
MILLVILLE MIV
KENTON
ENO 111.4
Chan 51
MILLVILLE
ATLANTIC CITY
ACY 108.6
Chan 23
MILLVILLE
DOVER
DOV Chan 37 (T)
WATERLOO
ATR 112.6
Chan 73
SALISBURY
SEA ISLE
SIE 114.8
Chan 95
MILLVILLE
SBY 114.5
Chan 92
MARRE
HARRY
MAZIE
PROPP
MAHAN
SOMTO
NAGGS
COBUS
FROSE
MUFLA
ECHEL
KETTS
ALBEK
INSLO
GROPE
CRESI
HOWIE
BRIEF
BLARE
LEEAH
TUBER
AVALO
SMITS
BRIGS
HARBO
MURFE
LEGGS
JIMEE
ADAPS
CASVI
DRUMM
CONTROL ZONE EFFECTIVE
1200-0300Z MON-THU
1200-0500Z FRI-SUN
Greater Wilmington
80 L 71 ATIS 123.95
Atlantic City
71 L 100
ASR ATIS 108.6
Hammonton Muni
69 L30
Cape May Co
22 L 50
Cape May CGAS
NEW YORK Wildwood 133.7
BARNEGAT

FIGURE 2.

TABLE 1 - TACAN STATIONS USED FOR FLIGHT TESTS

	CHAN	IDENT	LAT	LON	ELEV(ft)	LOCATION
1	019X	ARD	40.25324	74.90796	310	Yardley, PA
2	023X	ACY	39.45574	74.57672	10	Atlantic City, N.J.
3	051X	ENO	39.23153	75.51626	10	Kenton, Delaware
4	055X	NEL	40.03583	74.35500	100	Lakehurst, N.J.
5	075X	OOD	39.63590	75.30338	140	Woodstown, N.J.
6	081X	CYN	39.81718	74.43201	210	Coyle, N.J.
7	085X	RBV	40.20226	74.49541	250	Robinsville, N.J.
8	087X	FYT	39.67266	75.62199	80	Fatima, Delaware
9	095X	SIE	39.09538	74.80071	10	Sea Isle, N.J.
10	099X	VCN	39.53754	74.96751	120	Cedar Lake, N.J.

TABLE 2 - ATADS CARTRIDGE TAPE FORMAT

DATA SOURCE	TOTAL BYTES	IDENT. CHAR	TIME TAG	DATA	TERM CHAR	EXAMPLE OF DATA
Date Time	8	ASC117	-	6 Bytes	ASCIIF	TYMDHMSF
Altitude	14	ASCIIA	2 Bytes	2 Bytes	ASCIIF	
Comment	42	ASCIIC	-	40 Bytes	ASCIIF	
INS	8	ASCIII	2 Bytes	4 Bytes	ASCIIF	
Range Tracker	20	ASCIIR	2 Bytes	16 Bytes	ASCIIF	CCCX-RRR.RRR-TTT
TDL-424	8	ASCII4	2 Bytes	4 Bytes	ASCIIF	
TDL-711	163	ASCII7	2 Bytes	157 Bytes	ASCIIF	

TABLE 3 FLIGHT 2 ATADS POSITION ERROR SUMMARY (IN FEET)

# Stations in Solution	Samples	North Error Mean	North Error Sigma	East Error Mean	East Error Sigma	Circular Error Mean	Circular Error Sigma
3	1	-	-	-	-	-	-
4	30	199	86	23	260	393	119
5	112	185	99	268	198	371	129
6	121	202	76	283	119	363	93
7	92	215	62	296	106	374	93
8	0	*	*	*	*	*	*
9	0	*	*	*	*	*	*
10	0	*	*	*	*	*	*
6 or More	213	208	71	288	113	368	93
Summary	356	200	83	276	161	371	108

TABLE 4 FLIGHT 3 ATADS POSITION ERROR SUMMARY (IN FEET)

(3/3/82)

# Stations in Solution	Samples	North Error Mean	North Error Sigma	East Error Mean	East Error Sigma	Circular Error Mean	Circular Error Sigma
3	2	309	.05	-23	38	311	2.8
4	6	288	281	-96	180	396	182
5	20	265	207	-25	266	387	174
6	61	294	116	107	205	369	129
7	114	289	105	236	182	411	117
8	162	268	92	300	145	421	117
9	138	266	85	321	113	431	92
10	41	237	61	309	100	401	66
6 or More	516	273	95	269	165	414	110
Summary	544	273	104	255	180	412	114

TABLE 5 FLIGHT 4 ATADS POSITION ERROR SUMMARY (IN FEET)

Stations in Solution	Samples	North Error Mean	North Error Sigma	East Error Mean	East Error Sigma	Circular Error Mean	Circular Error Sigma
3	1	X	X	X	X	X	X
4	1	X	X	X	X	X	X
5	11	27	114	-71	267	272	97
6	40	-24	136	-23	218	236	101
7	72	-54	96	-41	177	191	92
8	143	-49	72	-95	155	178	94
9	170	-52	69	197	126	226	107
10	119	-26	57	249	93	257	89
6 or More	544	-44	79	144	167	216	100
Summary	557	-42	80	140	172	217	101

TABLE 6 FLIGHT 2 ATADS CIRCULAR ERROR PROBABILITY DISTRIBUTION - For Solutions Including 6 or More Stations

(3/2/82)

Circular Error (feet)	Points Inside	Total Points	Percent Total
0	0	213	. 0
50	0	213	. 0
100	0	213	. 0
150	50	213	. 0
200	5	213	2.35
250	19	213	8.92
300	46	213	45.54
350	97	213	64.32
400	137	213	64.32
450	177	213	83.10
500	193	213	90.61
550	205	213	96.24
600	211	213	99.06
650	212	213	99.53
700	212	213	99.53
750	213	213	100.00

TABLE 7 FLIGHT 3 ATADS CIRCULAR ERROR PROBABILITY DISTRIBUTIONS - For Solutions Including 6 or More Stations

Circular Error (feet)	Points Inside	Total Points	Percent Total
0	0	516	.0
50	0	516	.0
100	0	516	.0
150	0	516	.0
200	3	516	.58
250	13	516	2.52
300	63	516	12.21
350	158	516	30.62
400	269	516	52.13
450	341	516	66.09
500	409	516	79.26
550	463	516	89.73
600	492	516	95.32
650	504	516	97.67
700	506	516	98.06
750	508	516	98.45
800	511	516	99.03
850	512	516	99.22
900	515	516	99.81
950	516	516	100.00

TABLE 8 FLIGHT 4 ATADS CIRCULAR ERROR PROBABILITY DISTRIBUTIONS - For Solutions Including 6 or More Stations

Circular Error (feet)	Points Inside	Total Points	Percent Total
0	0	544	.0
50	13	544	2.39
100	73	544	13.42
150	151	544	27.76
200	252	544	46.32
250	349	544	64.15
300	432	544	79.41
350	483	544	88.79
400	524	544	96.32
450	538	544	98.90
500	543	544	99.82
550	543	544	99.82
600	543	544	99.82
650	544	544	100.00

TABLE 9 SUMMARIZED REQUIREMENTS AND RESULTS OF ATADS ENROUTE ACCURACY FLIGHT TEST

	Includes High Bias Stations			High Bias Stations (≥0.1NM) deleted			
Flight No.	Circular Error Mean Ft.	Circular Error 1 Sigma Ft.	CEP	Circular Error Mean Ft.	Circular Error 1 Sigma Ft.	CEP	No. of Stations in Solution
2	368	93	362	386	84	397	>6
3	414	110	395	242	99	223	≥6
4	216	100	209	202	93	194	≥6
Combined			324			218	≥6
ATADS Specification			200				
AC 90-45A			*5156				

*Positioning System Accuracy should be an order of magnitude (X10) more accurate than the specification requirement.

APPENDIX A - DATA PROCESSING AND ANALYSIS

DATA PROCESSING

The airborne data is processed on a PDP 11/34 computer with RAPFIL and RAPPRO (See Appendix B) to produce a file containing time tagged aircraft position estimates. The position estimates are latitude, longitude and altitude and are spaced 5 seconds apart in time.

Nike Hercules tracking data is processed into latitude, longitude and altitude on the Honeywell 66/60 computer. The data is time tagged and stored on a magnetic tape. The data tape contains tracking position spaced .1 seconds apart. Two radar tracking data tapes (one from each Nike radar) are time merged and position averaged on a PDP 11/34 to generate a processed tracking tape. Data for which the difference between the radars positions exceeds 50 feet in either axis are rejected, to insure against outliers in radar data. The processed tracking data and the processed airborne data are time merged (skew tolerance of 10 milliseconds) and stored in merged data files for access by data analysis programs.

DATA ANALYSIS

The merged data are processed on a PDP 11/34 computer to compute differences in latitude and longitude between the ATADS and the NIKE HERCULES. The north and east errors are computed in feet by the following two flat earth approximations:

$$\text{North Error}_i = (\text{LAT}_{\text{ATADS}} - \text{LAT}_{\text{NIKE}}) * 60 * 6076.115$$

$$\text{East Error}_i = (\text{LONG}_{\text{ATADS}} - \text{LONG}_{\text{NIKE}}) * \text{COS}(\text{LAT}_{\text{NIKE}}) * 60 * 6076.115$$

where all lat/long values are in degrees.

The sums of errors and sums of squares of errors are accumulated and means and sigma values of the errors are estimated by the following two equations:

$$\text{MEAN ERROR} = \frac{1}{N} \sum_{i=1}^{N} \text{ERROR}_i$$

$$\text{ONE SIGMA ERROR} = \left\{ \frac{1}{N-1} \left[\sum_{i=1}^{N} (\text{ERROR}_i)^2 - \frac{1}{N} \left(\sum_{i=1}^{N} \text{ERROR}_i \right)^2 \right] \right\}^{1/2}$$

where N = Number of samples.

The circular error is also computed as:

$$\text{CIRCULAR ERROR}_i = \text{CE}_i = \left[(\text{North Error}_i)^2 + (\text{East Error}_i)^2 \right]^{\frac{1}{2}}$$

$$\text{MEAN CIRCULAR ERROR} = \frac{1}{N} \sum_{i=1}^{N} \text{CE}_i$$

$$\text{ONE SIGMA CIRCULAR ERROR} = \left\{ \frac{1}{N-1} \left[\sum_{i=1}^{N} (\text{CE}_i)^2 - \frac{1}{N} \left(\sum_{i=1}^{N} \text{CE}_i \right)^2 \right] \right\}^{1/2}$$

The cumulative distribution of circular errors in steps of 50 ft. up to 100% of data inclusion is determined for solutions including 6 or more stations.

APPENDIX B

ATADS POST FLIGHT POSITION DETERMINATION SOFTWARE

The post flight processing of the ATADS data takes place in two stages. In the first stage, the data is read from the magnetic tape cartridge via a Quantex recorder into a PDP 11/34 minicomputer. There the ranges and altitude and time are processed into floating point and integer representations in a data file for future use. This program is named RAPFIL.

In the second stage, these data files are processed to determine position from the multiple range information contained therein. The program which does this is named RAPPRO.

The purpose of this appendix is to discuss the position determination software and the techniques employed therein.

RAPPRO solves for aircraft position by means of an algorithm supplied by the contractor in the form of a program written in BASIC,

The heart of this algorithm is a range data filtering algorithm (see Appendix E) and a linear least squares solution algorithm (see Appendix F). The filtering algorithm fits a straight line to range/time data from the ATADS which occurs in a contractor specified data window (12 seconds wide) for each station with 2 or more returns in the window. Then the filtering algorithm computes the ranges at the center of the window. In this way, the range measurements from various stations, occuring at different times are extrapolated/interpolated to a common specified time. This is necessary to employ the least squares solution, which assumes simultaneous measurement data.

The solution algorithm solves a set of simultaneous distance equations at the center of the data window using the "filtered" ranges. The solution algorithm requires a minimum of 3 filtered ranges to compute position in a local East-North-Up (ENU) coordinate system.

Altitude (Z) is assumed to be the measured barometric altitude corrected for pressure and for earth curvature. The solution algorithm iterates from an initial guess to a final solution, and stops iterating when the sum of the changes in X and Y is less than .001 nautical miles.

The local ENU coordinates are transformed into latitude, longitude, and altitude using Clarke's spheroid of 1866.

RAPPRO was developed by translating the program supplied by the contractor from the BASIC into FORTRAN. Features have been added to RAPPRO which are not in the original BASIC program. RAPPRO performs all computations in double precision DEC Fortran. The inputs to RAPPRO are in single precision, but the accuracy of the ATADS is preserved (.001 nautical miles in range and 10 milliseconds in time) by RAPFIL, which stores two values for each parameter. Range is read into RAPPRO as two integer parameters, miles and millimiles; time is read into RAPPRO as one single precision parameter and one integer parameter, total seconds and milliseconds. Range and time input parameters are reassembled into double precision floating point parameters by RAPPRO, thus preserving the precision of the ATADS.

RAPPRO is initialized by specifying a flight data file which contains the station identifiers of ground stations to be included in the solution, the latitude, longitude and altitude of the origin of the local coordinate system which is an ENU system. The flight data file also contains the barometric altimeter setting for correcting barometric altitude. RAPPRO then searches a specified station library file for the identified stations and reads in their latitude, longitude and altitude. These coordinates are first converted to Earth Centered Earth Fixed Coordinates (ECEF) as an intermediate step, and then the ECEF coordinates are converted into local ENU coordinates.

RAPPRO then reads a start time and a stop time (programmer option at run time). A sync time is read, which synchronizes the RAPPRO processing with the contractor's processing results for comparison purposes. This was necessary due to the differences between time and handling logic in two programs. Next RAPPRO begins to process the file created by RAPFIL in the following sequence:

Step 1 - A range data record is read from the data file and converted to double precision.

Step 2 - Time is tested and if not synchronized, RAPPRO, returns to Step 1. Otherwise RAPPRO tests time to see if stop time limit is exceeded. If so, RAPPRO continues at Step 18. If not, RAPPRO tests time to see if current data window upper time limit is exceeded. If so, RAPPRO continues at Step 7; otherwise, continue at Step 3.

Step 3 - The range measurement is indexed via the station ident code, to correlate it to the correct storage areas associated with the received station.

Step 4 - Range multipath rejection is accomplished by examining time code from the cycler tracker and rejecting later range records with current time codes. The assumption is that the later recorded range is a longer path measurement. This feature is removed from the latest contractor version, but retained in RAPPRO.

Step 5 - A prefilter algorithm checks to see if a return from the received station occurred within a specified time gap. If not, a range change rejection level is modified up from 1.5 to 40 nautical miles. Next the prefilter algorithm compares the previous filtered range to the current measurement. If the magnitude difference is greater than the rejection level, RAPPRO returns to Step 1. Otherwise, RAPPRO tests whether or not sufficient recent updates have occurred, if not, RAPPRO continues on to Step 6. Otherwise, RAPPRO compares current measured range with previous measured range. If the magnitude difference exceeds .7 nautical miles, RAPPRO rejects the new value and returns to step 1. Otherwise RAPPRO continues on to Step 6.

Step 6 - RAPPRO updates the current station return counter. RAPPRO stores the measured range, the time of measurement and time since data window lower time limit in the appropriate arrays. All are indexed by station ident and the return counter. RAPPRO returns to Step 1.

Step 7 - RAPPRO continues here from Step 2. At this point all range/time data pairs in the current data window have been indexed and stored.

Step 7A - RAPPRO indexes through the station data base, and tests for those with at least 2 returns in the current data window. If there are none, RAPPRO continues at Step 17. For each station with 2 or more returns, RAPPRO continues on to Step 8.

Step 8 - RAPPRO initializes summation variables to zero and accumulates sums, sums of squares and sums of cross products of ranges, and times for the received station data pairs, and performs least square straight line curve fit to the data in the window and continues to Step 9.

Step 9 - RAPPRO tests for any range/time data pair which is more than .03 nautical miles from the current least squares line, and indexes the largest for later removal. RAPPRO continues to Step 10.

Step 10 - If any range/time data pairs are indexed for removal, RAPPRO revises the data arrays and continues to Step 7A. Otherwise RAPPRO uses the final straight line solution to inerpolate and create a range/time data pair for the received station at the center of the current data window. In this way, RAPPRO synchronizes all received stations measurements to a common time. If all received stations have veen synchronized, RAPPRO continues on to Step 11. Otherwise RAPPRO returns to Step 7A.

Step 11 - If less than 3 stations have been time synchronized, RAPPRO continues at Step 17.

Step 11A - RAPPRO initializes summation variables, continues on to Step 12.

Step 12 - RAPPRO checks for gross outliers in the current position and if the situation occurs (1000 nautical mile errors). RAPPRO reinitializes position to zero and continues on to Step 17. (This outlier feature is not in the contractor's program.) Otherwise, RAPPRO continues and computes an earth curvature altitude correction factor from the current position estimate. RAPPRO rejects flagged (Step 15) stations and tests to see if less than 3 stations remain in the solution, if so continue to Step 17, otherwise continue to Step 13.

Step 13 - RAPPRO computes factors for the least squares solution. If division by zero would occur, RAPPRO reinitializes position to zero, and continues on to Step 17. Otherwise, RAPPRO computes correction factors for X, Y position estimates and up dates current position estimates. Continue to Step 14.

Step 14 - RAPPRO tests the iteration count for the convergent least squares solution, and if iterations exceed specified level (a run time option, this feature not in contractor's software), current position is initialized to zero and processing continues at Step 18. Otherwise RAPPRO continues at Step 15.

Step 15 - RAPPRO tests the sum of magnitudes of the X and Y correction factors. If this sum exceeds .001 nautical miles, RAPPRO returns to Step 11A. Otherwise RAPPRO flags stations for rejection from current solution if current range bias residuals exceed .04 nautical miles and returns to Step 11. If no more stations are flagged at this iteration, RAPPRO accumulates bias residuals and computes new estimates of station range biases. In the case of flagged stations, RAPPRO substitutes estimated ranges based on estimated position for interpolated (straight line) ranges. RAPPRO does not accumulate computed bias residuals greater than 1.0 nautical miles. Continue at Step 16.

Step 16 - RAPPRO transforms the estimated local ENU position coordinates into ECEF coordinates, and then computes latitude and longitude from the ECEF coordinates. RAPPRO then stores the time (center of data window) latitude and longitude, and the local coordinates in the output file in double precision format. Continue to Step 17.

Step 17 - RAPPRO slides the data window forward a specified number of seconds, removes old data from the new data window and returns to Step 2.

Step 19 - RAPPRO closes all files and halts.

APPENDIX C - RAPPRO VALIDATION

Prior to computation of position errors, the program RAPPRO was validated to insure that it processed the ATADS data in the manner prescribed by the contractor. This was accomplished by comparing printouts of estimated positions produced on the HP 85 computer with contractor software to printouts of estimated positions produced on a PDP 11/34 computer with RAPPRO.

RAPPRO was "synchronized" to the identical start time and window times used to process the data with the contractor's program. This insured identical input data, and if the outputs matched, the software would be validated.

The results of a typical sequence of data is shown in Tables C.1 and C.2. Looking at tables C.1 and C.2, it is easy to see that RAPPRO is a satisfactory replacement for the contractor's program. The computational differences amount to a position error of about 6 feet between the two programs, which is the terminal tolerance specified in the iterative solutions employed in both programs.

TABLE C.1 - LATITUDE COMPARISON

TIME	RAPPRO	CONTRACTOR	D LAT (feet)
102501	39.717587	39.717596	-3.3
102506	39.720409	39.720421	-4.4
102511	39.723012	39.723023	-4.0
102516	39.725357	39.725371	-5.1
102521	39.727712	39.727725	-4.7
102526	39.730434	39.730446	-4.4
102531	39.732978	39.732990	-4.4
102536	39.735506	39.735517	-4.0
102541	39.738224	39.738235	-4.0
102546	39.740670	39.740681	-4.0
102551	39.742987	39.742998	-4.0
102556	39.745489	39.745500	-4.0
102601	39.748767	39.748778	-4.0
102651	39.773968	39.773978	-3.6

TABLE C.2 LONGITUDE COMPARISON

TIME	RAPPRO	CONTRACTOR	(feet)
102501	75.105094	75.105097	- .8
102506	75.097977	75.097974	.8
102511	75.090639	75.090638	.3
102516	75.083233	75.083236	- .8
102521	75.075680	75.075682	- .6
102526	75.068337	75.068338	- .3
102531	75.060395	75.060396	- .3
102536	75.052980	75.052981	- .3
102541	75.045963	75.045964	- .3
102546	75.038450	75.038451	- .3
102551	75.030724	75.030726	- .6
102556	75.023089	75.023091	- .6
102601	75.016515	75.016515	0.0
102651	74.942821	74.942821	0.0

APPENDIX D

HP 85 HP-85 BASIC SOFTWARE

The software is comprised of three main programs:

1. Data base
2. Data processing
3. Data analysis

I. Data Base. Two programs

a. "BEACON" - Data entry and storage program. It stores ground station information in a known format that can be accessed by "THE SET-UP" program.

b. "SET-UP" - Allows selection of beacons to be used in the local test area. Computes and stores the user defined local coordinate system for access by the processing program.

II. Data Processing. One program. "PROCESS"

a. Computes and stores position as a function of time for the ATADS, LORAN 711, and LORAN 424.

b. Recovers and formats flight data.

c. Produces printout of intermediate results.

d. Produces CRT plot or hard copy plot of aircraft track.

e. Produces magnetic cassette tape of computed position.

III. Data Analysis. Six programs.

These six programs access the data stored on the HP-85 cassette tape to produce various plots on the HP-7225 plotter.

a. "DLTVST" - delta latitude vs time

b. "DLNVST" - delta longitude vs time

c. "NORTH" - northing error vs time

d. "EAST" - easting error vs time

e. "RADIAL" - radial error vs time

f. "XYP85" - track plots

In a similar way,

$$\frac{\partial E}{\partial b} = 0 \rightarrow a \sum_{i=1}^{N} t_i + bN = \sum_{i=1}^{N} R_{mi}$$

or

$$a_{21}a + a_{22}b = C2 \qquad (2)$$

Equations (1) and (2) are solved simultaneously,

$$\boxed{\begin{aligned} a &= (a_{22}C1 - a_{12}C2)/DET \\ b &= (a_{11}C2 - a_{12}C1)/DET \end{aligned}}$$

$$(a_{12} = a_{21})$$

where

$$DET = a_{11}a_{22} - a_{12}^2$$

Computed (estimated) range for i^{th} point is,

$$R_{ci} = at_i + b$$

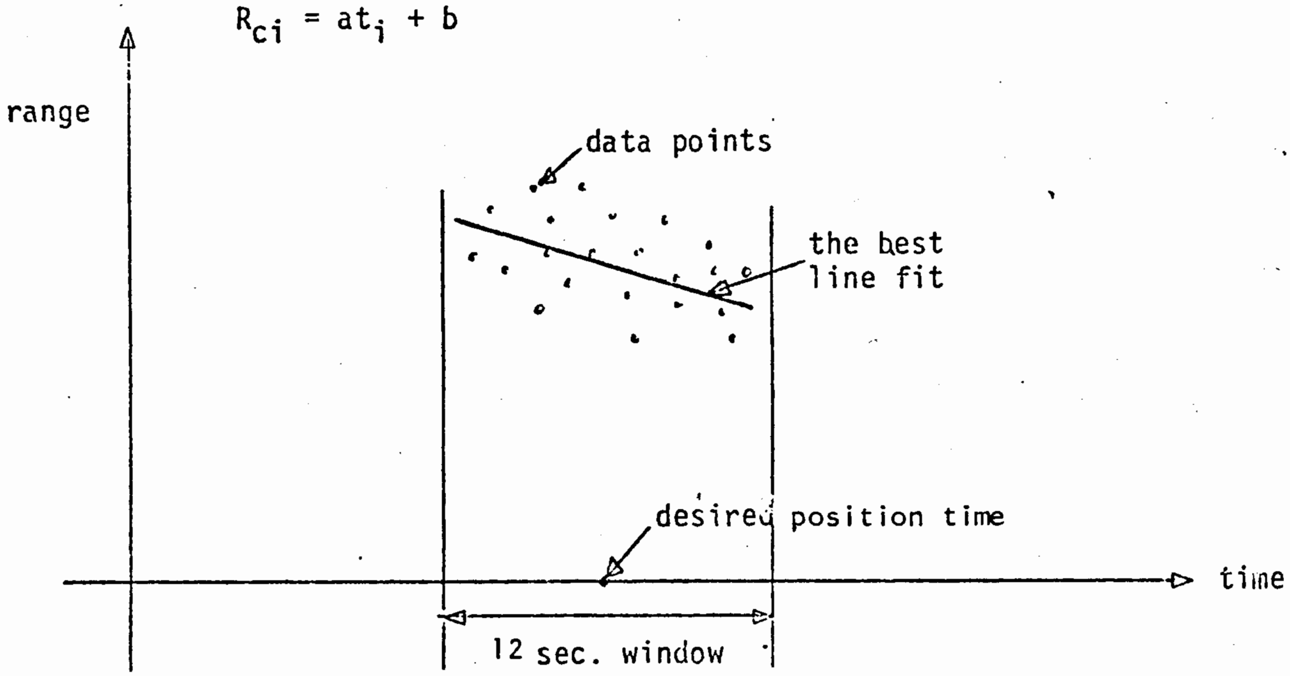


Figure 1

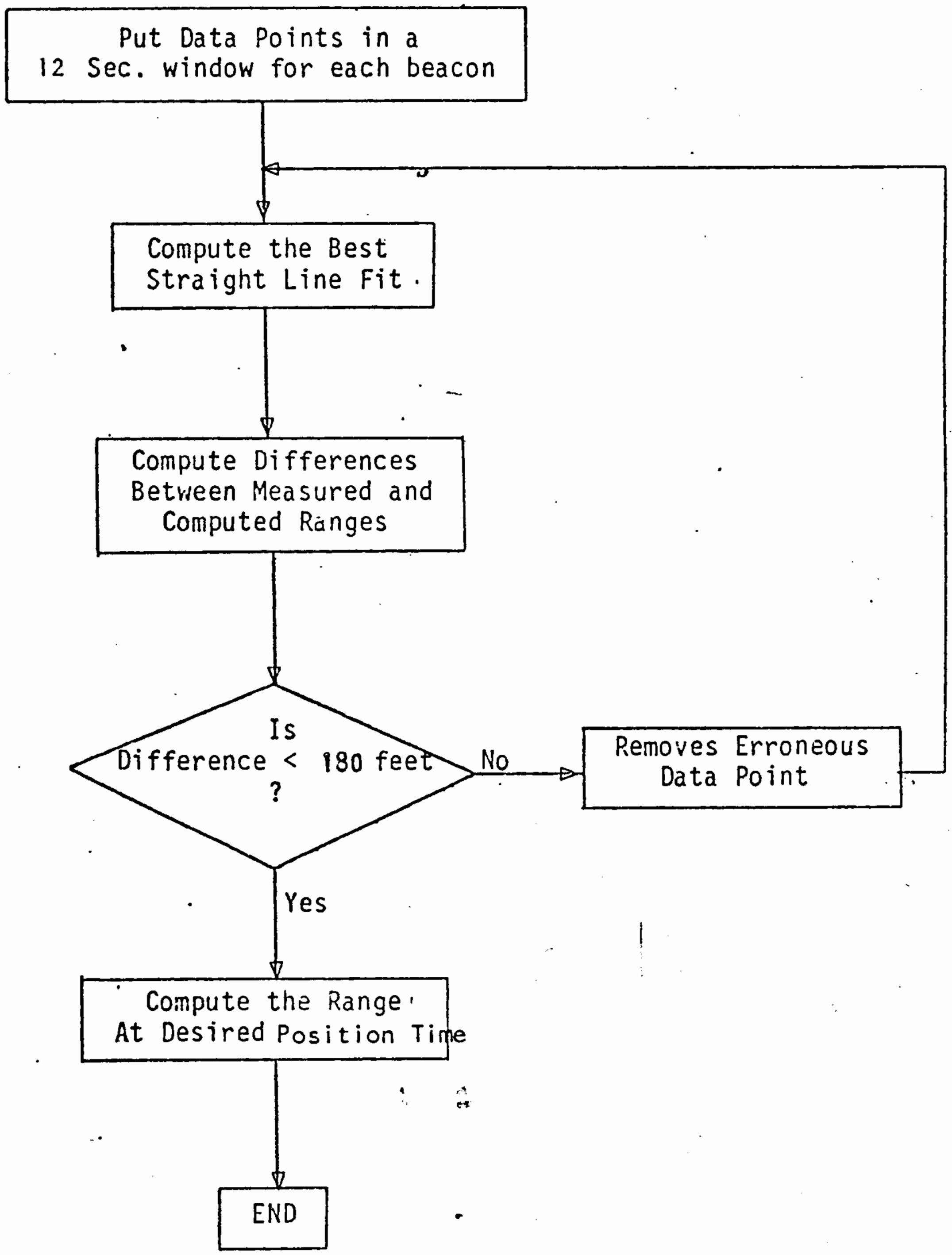
B. Filtering

In second step, differences between measured (R_{mi}) and computed (R_{ci}) ranges are computed. The data point which has the greatest difference among the differences greater than 180 feet is found and thrown out. Then, the best line fit is recalculated. The same procedure is iterated for each beacon until the differences are less than 180 feet.

After fitting the best straight line to the data points left, the range is computed from it at the desired position time.

At the next position time (5 seconds later), the window is slid 5 seconds forward and new data points are put in the window. The same computations are then made in order to find the best estimated range at the desired position time.

C. Flow Diagram



APPENDIX F

LINEAR LEAST SQUARES SOLUTION ALGORITHM

A. Derivation

The criterion for the best estimate of position is to minimize the the sum of squares of differences between "measured" and the "estimated" ranges for all stations.

R_i = measured range from i^{th} station to the aircraft location.

S_i = estimated range from i^{th} station to the aircraft location.

$$\hat{S}_i = \sqrt{(\hat{X}-X_i)^2 + (\hat{Y}-Y_i)^2 + (Z-Z_i)^2}$$

$$\hat{X} = \hat{X}(-) + \delta$$

$$\hat{Y} = \hat{Y}(-) + \varepsilon$$

(-) denotes previous estimation.

where: $(\hat{X},\hat{Y},Z)$ is estimated aircraft location.

(Z is known)

(X_i,Y_i,Z_i) is i^{th} station location

δ,ε are increments used to update our estimates.

$R_i-\hat{S}_i = \eta$ is range error to be minimized.

η is a function of ε and δ

Taylor series expansion of range equation,

$$S_i = \hat{S}_i(-) + \Delta\hat{S}_i(-) + \Delta^2\hat{S}_i(-) + \ldots$$

After a few manipulations and throwing out terms of order higher that the first:

$$\hat{S}_i = \hat{S}_i(-) + P_i\delta + q_i\varepsilon$$

where: $P_i = [\hat{X}(-)-X_i]/\ \hat{S}_i(-)$

$q_i = [\hat{Y}(-)-Y_i]/\ \hat{S}_i(-)$

Now we can use the least squares technique.

$$\eta(\delta,\varepsilon) = \sum_{i=1}^{N} (R_i - \hat{S}_i)^2 \qquad \text{(N is the number of ground stations)}$$

Minimizing η with respect to δ and ε yields:

$$\frac{\partial \eta}{\partial \delta} = 2 \sum_{i=1}^{N} \{[\hat{S}_i(-) - Z_i]\, P_i + P_i^2 \delta + P_i q_i \varepsilon\} = 0 \qquad (1)$$

or

$$-C1 + a_{11}\delta + a_{12}\varepsilon = 0$$

Similarly setting $\frac{\partial \eta}{\partial \varepsilon} = 0$ yields:

$$\frac{\partial \eta}{\partial \varepsilon} = 2 \sum_{i=1}^{N} \{[\hat{S}_i(-) - Z_i]\, q_i + P_i q_i \delta + q_i^2 \varepsilon\} = 0 \qquad (2)$$

or

$$-C2 + a_{21}\delta + a_{22}\varepsilon = 0$$

Equations (1) and (2) are then solved simultaneously for ε and δ,

$a_{12} = a_{21}$ and

$$\delta = (a_{22}C1 - a_{12}C2)/DET$$

$$\varepsilon = (a_{11}C2 - a_{12}C1)/DET$$

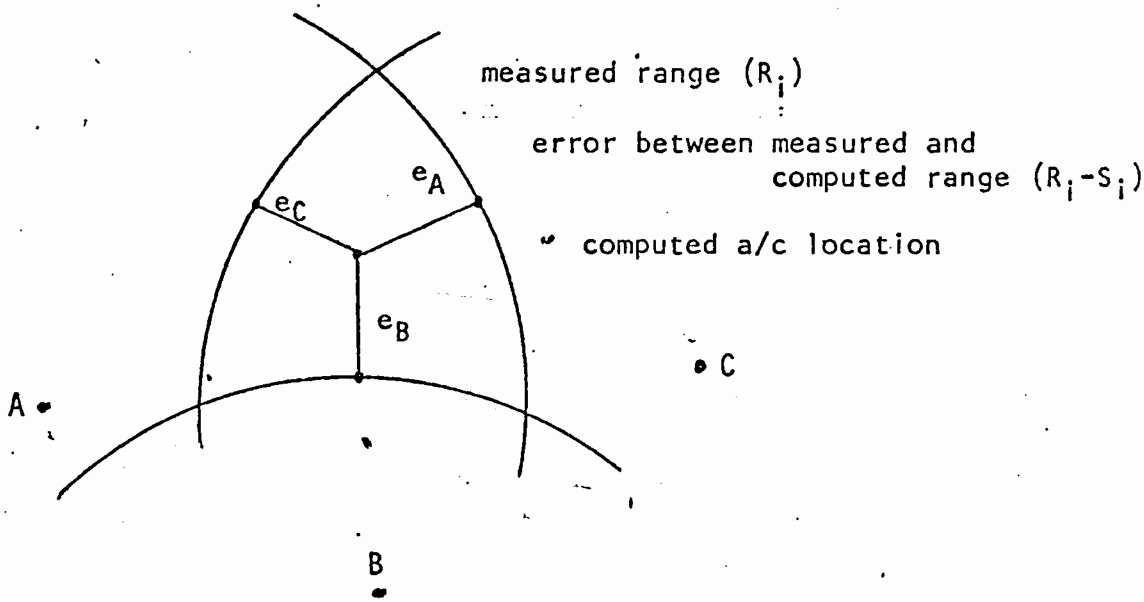
$$DET = (a_{11}a_{22}) - (a_{12})^2$$

The increments δ and ε are added to $\hat{X}(-)$ and $\hat{Y}(-)$ and unless the increments have converged, the procedure is reiterated.

In the algorithm used for position computation, if the sum of increments in X and Y axes are greater than .001 nm. the computation is reiterated.

The following illustrative example explains the least squares technique;

For stations A, B and C the measured and computed ranges and errors are,



$E = [(e_A)^2 + (e_B)^2 + (e_C)^2]$ is minimum at the computed a/c location.

$$\hat{X} = X(-) + \Delta X$$

$$\hat{Y} = Y(-) + \Delta Y$$

$$\hat{Z} = Z(-) + \Delta Z$$

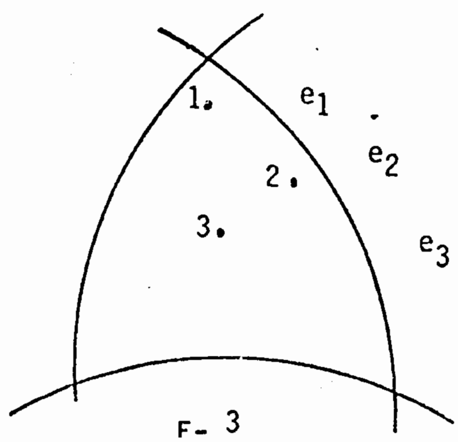
where:

ΔX, ΔY, ΔZ are increments

$(\hat{X}, \hat{Y}, \hat{Z})$ is aircraft location

$[\hat{X}(-), \hat{Y}(-), \hat{Z}(-)]$ is previous aircraft location

Iterative Procedure:



where:

e_1, e_2, e_3 is the sum of the squares of errors.

$(e_i = e_{Ai}^2 + e_{Bi}^2 + e_{Ci}^2)$

Location 1:

a/c coordinates $\longrightarrow$ X_1, Y_1, Z_1 (first guess)

$|\Delta X_1| + |\Delta Y_1| > .001$ nm.

Location 2:

a/c coordinates $\longrightarrow$ X_2, Y_2, Z_2 (first position computation)

where:

$$X_2 = X_1 + \Delta X_1$$

$$Y_2 = Y_1 + \Delta Y_1$$

$$Z_2 = Z_1 + \Delta Z_1$$

and

$|\Delta X_2| + |\Delta Y_2| > .001$ nm.

Location 3:

a/c coordinates $\longrightarrow$ X_3, Y_3, Z_3 (first iteration)

where:

$$X_3 = X_2 + \Delta X_2$$

$$Y_3 = Y_2 + \Delta Y_2$$

$$Z_3 = Z_2 + \Delta Z_2$$

and

$|\Delta X_2| + |\Delta Y_2| < .001$ nm. (the best estimate of position)

B. Flow Diagram