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BEACON COLLISION AVOIDANCE SYSTEM (BCAS) - ACTIVE MODE.(U)
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BEACON COLLISION AVOIDANCE SYSTEM (BCAS) - ACTIVE MODE

Maurice Cohen
Charles Richardson

DEPARTMENT OF TRANSPORTATION
UNITED STATES OF AMERICA

OCTOBER 1977

INTERIM REPORT

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NOTICE

METRIC CONVERSION FACTORS

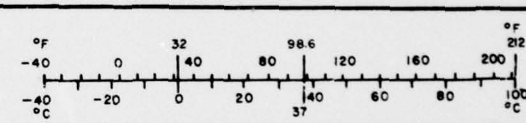
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, *Units of Weights and Measures*, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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16. Abstract

This document describes the FAA/MITRE Active Mode of the Beacon Collision Avoidance System (BCAS) through its initial phase. The hardware, its procurement and modification are described; the theory of operation is presented; and the system performance and accuracy during the feasibility flight tests in the NAFEC and Washington, D.C. airspace were discussed. This is a ground-independent, air-to-air system activated by airborne omnidirectional ATCRBS mode C interrogations occurring at a rate of 2 per second. Range and altitude are obtained for each aircraft replying within a 32-nmi radius. Range and altitude rates are computed, and approaching aircraft are tracked. The cockpit CAS display warns the pilot of aircraft crossing with adequate altitude separation and gives a command to climb or dive if the intruding aircraft is at or near the same altitude. Warnings and/or commands are provided 30 seconds before range minimum. System performance was evaluated during test encounters with 400 ft altitude separation. Performance and accuracy analysis is derived from BCAS and ARTS III magnetic tape, and from the tracking phototheodolites over the NAFEC measurement range. Data analysis was performed by the MITRE Corporation. The system in its initial form was not expected to function in high-density areas; however, the system met the initial design goals. Design ideas to distribute the reply population by using multilevel power interrogations have been incorporated in the system for the next phase. This will, hopefully, allow the system to function in the higher density areas. In a later phase, the compatibility of BCAS with DABS will be evaluated.

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INTRODUCTION

PURPOSE.

This report describes one of the modes of operation of an airborne Beacon Collision Avoidance System (BCAS) based on mode C replies obtained from Air Traffic Control Radar Beacon System (ATCRBS) transponders. Since it is based on the beacon system, it has been termed BCAS.

BACKGROUND.

In this particular application, BCAS is independent of the ground system, but it utilizes the very widely deployed ATCRBS avionics to sense the range and altitude of nearby aircraft. It is designed for aircraft who wish to have a CAS capability in airspace where the air traffic control (ATC) system does not provide surveillance-based separation services. In addition, the system will provide some backup to the ground system in airspace within surveillance coverage.

The active mode of BCAS operation described in this report, and hereafter called BCAS, is an active system consisting of an airborne interrogator, interrogating omnidirectionally with ATCRBS mode C (altitude). Replies are received from all aircraft within a range of roughly 32 nautical miles (nmi) which are equipped with an ATCRBS transponder and a reporting altimeter. The replies are then sorted to obtain range and altitude, and then tracked to determine whether or not they are a threat. When the BCAS threat detection and resolution logic projects a time to "range zero" of 30 seconds, evasive action is displayed to the pilot.

The system thus assumes widespread deployment of altitude-reporting ATCRBS, which the BCAS-equipped aircraft can sense and avoid. The ATCRBS-only aircraft, which does not have the BCAS equipment, would not receive collision avoidance warnings; it is assumed that this aircraft continues on its present course. This class of aircraft is said to be a remitter. BCAS also provides protection for two BCAS-equipped aircraft, ensuring complementary maneuvers.

The BCAS hardware was first assembled as two complete systems and bench checked at the National Aviation Facilities Experimental Center (NAFEC). The two BCAS systems were then installed on two Gulfstream aircraft and flight tests were conducted. Tests continued until December 1975, when one Gulfstream had to be refurbished. The system was then transferred to a DC6, and flight tests continued through April 1976.

The attractiveness of BCAS is that the cost is only to the equipped user desiring an independent collision avoidance capability, which protects him from all aircraft which are transponder-equipped with a mode C (altitude reporting) capability. However, the cosharing of the channel with ATCRBS imposes two requirements on the design which had to be met if this concept was to be feasible.

The first requirement was that BCAS should not significantly impact the ATCRBS performance. It was shown during the flight tests that there was no evidence of interference to the ATCRBS system performance. The second requirement stated that BCAS would have to work in spite of the fact that replies from any interrogated aircraft might be received simultaneously. This is known as synchronous garble. To minimize the impact on ATCRBS, the rate of interrogations has to be kept low. The design calls for a rate of only two interrogations per second. Preliminary analysis of flight data indicated the system is capable of tracking successfully through garbled situations where as many as five overlapped replies occurred.

SYSTEM DESCRIPTION

OVERVIEW.

The BCAS functional block diagram is given in figure 1. Mode C interrogations are transmitted sequentially via top and bottom antennas, and received replies are demodulated in the receiver and then passed to the detector/tracker. The detector/tracker determines if the received replies are from new targets, established target tracks, or simply fruit. Tracks are formed and maintained in range and altitude. An altitude reference is provided by the aircraft's own encoding altimeter, which enables the tracker to estimate the relative altitude of targets.

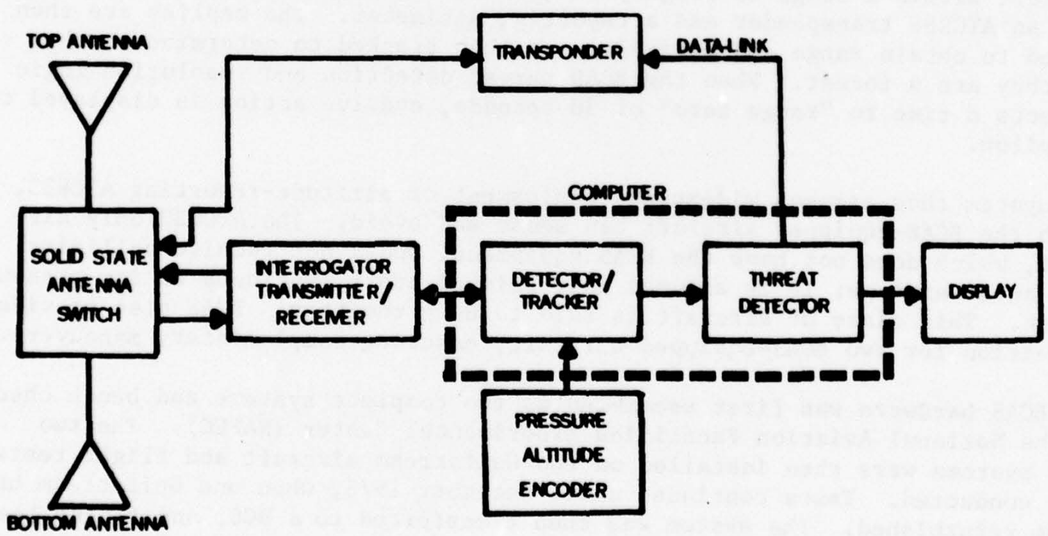

FIGURE 1. ACTIVE MODE BCAS SYSTEM BLOCK DIAGRAM

Newly formed tracks within a 10-nmi range and established tracks whose range difference becomes 10-nmi or less are flagged by the tracker and a determination of whether this target is BCAS equipped or not is made. To make this determination, a mode D interrogation is sent. If the target replies (and it appears at the expected range and altitude), the tracker labels the target as BCAS equipped; otherwise, it is labeled as unequipped since all equipped aircraft have a mode D reply capability.

Established tracks (tracks are declared established after being tracked for at least 30 seconds or after four successive ungarbled reports) are passed on to the threat detector to determine if a target is a threat. Separate algorithms are used for equipped and unequipped targets. When an unequipped target is determined to be a threat, a command is displayed to the pilot for him to maneuver his aircraft away from danger. If, on the other hand, an equipped target is determined to be a threat, a mode D interrogation is made to the target to assess the maneuver intent of the target. On the basis of the reply received, a command is displayed to the pilot which makes him aware of the situation and which may direct him to either maneuver or not to maneuver his aircraft. When interrogated on mode D, the aircraft replies with a code that describes the command message sent to the display. This elementary data link provides the means for ensuring that the aircraft make complementary maneuvers.

TRANSMITTER/RECEIVER.

The transmitter/receiver used by BCAS is a standard Air Force Identification, Friend or Foe (IFF) transmitter/receiver. The transmitter/receiver is coupled both to the bottom and to the top antennas, with interrrogations transmitted alternately via each antenna at a combined rate of one every 1/2 second. Thus, in areas where a null exists in either the top or bottom antennas, aircraft will receive mode C requests at a 1-second update rate. The receiver takes the ATCRBS replies from the several aircraft in the vicinity, demodulates them, and looks for pulse pairs separated 20.3 microseconds (μs) apart. The window size for this bracket pair detection is made sufficiently wide to account for pulse position uncertainty, due to such things as pulse jitter and pulse tolerance. All bracket detected pulse pairs and their associated formed binary sequences are sent to the detector/tracker.

DETECTOR/TRACKER.

There are three major functions of the detector/tracker. These functions, discussed in this section, are: track acquisition, track extension, and track elimination.

TRACK ACQUISITION. To acquire or form new tracks, all replies (bracket detected pulse pairs) on four successive interrogations are used. Each second reply received is connected by a straight line to all replies received on the third interrogation, which could possibly relate to a given track, and for which the range rate would be negative (aircraft closing on interrogator). This would mean the slope of the straight line should be negative. However, due to transponder jitter, some straight lines will be formed with slightly positive slopes. The maximum negative slope allowed is limited by the anticipated maximum closing rate of aircraft.

Once all reasonable pairs have been connected by straight lines, each line is extended backwards and projected forward in time by a one-time interval. At each end of the straight line corresponding to the first and fourth interrogation replies, a range window is placed. This window accounts both for aircraft motion and for expected transponder jitter. Any replies falling into the window are considered part of a track. If more than one point falls within a window, there will be more than one track formed. If no reply falls at either end point, no track acquisition is declared.

After a new track is formed, an altitude is associated with this track by taking the altitude reports from each of the four replies associated with the track and passing them through an "AND" logic. Thus, if at least one of the reports is garble free, the correct altitude will be associated with the target. It must be mentioned, that "1's" are resistant to interference and "0's appear when the interference disappears.

THREAT DETECTOR.

The threat detector receives as its input the relative range, relative range rate, altitude, and altitude rate of established aircraft tracks. It determines whether a command is necessary, and if so, issues it until the conflict is resolved.

The threat detector is capable of solving conflicts with another BCAS-equipped aircraft, or with an ATCRBS mode C aircraft. In some cases multiple aircraft conflicts can also be resolved.

Two different detection and resolution logics are used depending on the equipage of the intruder aircraft. If it is BCAS-equipped, the logic specified in the Air Navigation/Traffic Control (ANTC) Report No. 117 (issued by the Air Transportation Association of America, June 1967) is employed; otherwise, a remitter logic is utilized which makes use of either a modified range-tau test and a vertical-tau test, if the relative range rate is negative, or an immediate range and altitude test, if it is positive. In both logics, a maneuver command is not displayed until it appears as a result of two consecutive interrogations.

When the ANTC-117 logic determines that a command should be displayed, it interrogates (mode D) to determine the maneuver intent issued by the ANTC-117 logic of the intruder aircraft. Based on the mode D reply, a compatible collision avoidance command is displayed to the pilot.

DISPLAY.

The display is shown in figure 2. It is a standard CAS display which indicates to the pilot the following positive and negative commands:

Positive

Level off
Climb
Descend

Negative

Don't climb
Don't descend
Don't climb more than 500 ft/min
Don't climb more than 1,000 ft/min
Don't climb more than 2,000 ft/min
Don't descend more than 500 ft/min
Don't descend more than 1,000 ft/min
Don't descend more than 2,000 ft/min

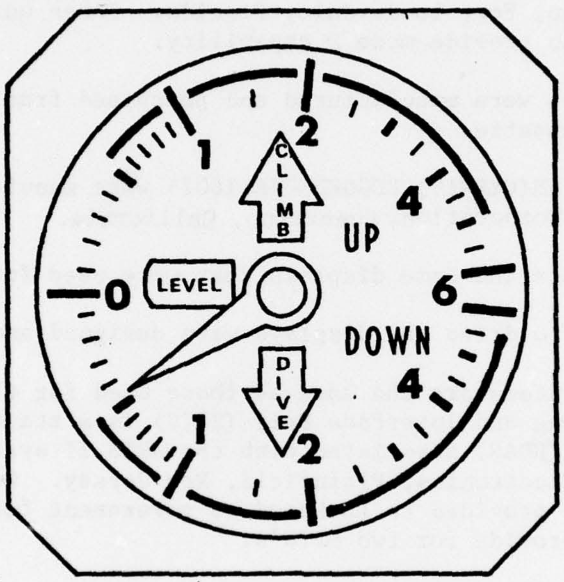

FIGURE 2. BCAS DISPLAY

DATA LINK.

As indicated in preceding sections, communication between equipped aircraft is required to coordinate maneuvers. The mode D transponder reply is used in BCAS. This was chosen because, for feasibility tests, it was easily implemented and relatively garble free. For the final system configuration the DABS signal format will be utilized as the data link. In addition, the identity of the target aircraft is not needed to effect the communication.

There are a total of four different mode D messages (level off, climb, descend, or no positive command). Therefore, four mode D code words are needed. The code words are chosen so that the message is decodable when up to 3 pulse positions are garbled. Further error protection against fruit is obtained by repeated interrogation and periodic interrogation once a threat is detected.

The code word for the mode D response is supplied to the transponder immediately upon determination of the maneuver, so that any aircraft making a mode D interrogation after that instant will be informed of the aircraft's intent.

HARDWARE PROCUREMENT.

The interrogator receiver/transmitter (RT 868A), part of APX-76, is manufactured by Hazeltine Corporation, Little Neck, New York. Three of these units were borrowed from the United States Air Force (USAF).

The transponder receiver/transmitter (TRA-63A) is manufactured by Bendix Avionics Corporation, Fort Lauderdale, Florida. Three units were procured and modified by NAFEC to provide mode D capability.

The antenna switches were manufactured and purchased from Microwave Associates, Burlington, Massachusetts.

The minicomputers (AN(UYK-19) RUGGEDNOVA 1602) were manufactured and purchased from Rolm Computer Corporation, Cupertino, California.

The BCAS displays are the same displays that were used for the ACAS evaluation.

The interface used to drive the displays were designed and built at NAFEC.

The time code generators are the same as those used for the ACAS evaluation. The Signal Processing and Interface Unit (SPIU) is a standard Beacon Data Acquisition System (BDAS) associated with the ARTS II system. It was manufactured by Lockheed Electronics, Plainfield, New Jersey. One BDAS and one set of spare cards were provided to Lockheed as government furnished equipment (GFE) to be modified to provide for two SPIU's.

HARDWARE FUNCTIONAL DESCRIPTION

OVERVIEW.

The computer software controls all hardware components of BCAS through the SPIU. The computer provides the master control signals to the SPIU defining the mode and the sequence of each of the hardware functions. The SPIU contains the interface receiver, driver amplifiers, pulse shapers, memory, and logic components required to control and communicate with each of the hardware components (figure 3).

SPIU CONTROL AND MONITOR FUNCTIONS.

The SPIU, upon command from the computer, controls the very critical timing sequence, generates the interrogate pulse pairs for the specified interrogation mode, and controls the duration of the reply period. The SPIU monitors the command signals from the computer, and will not permit an invalid combination of commands (as might result from a programming error) to initiate an

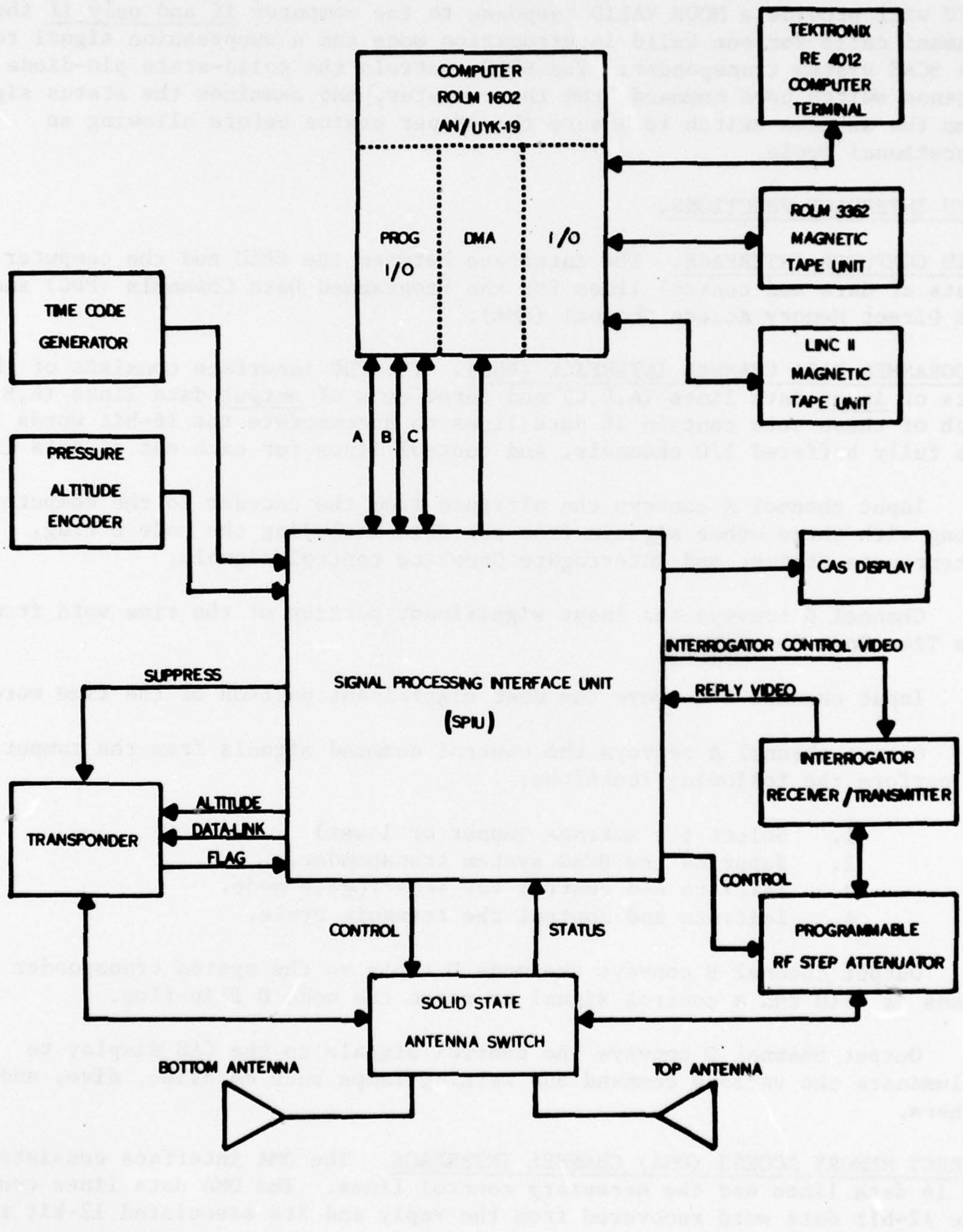

FIGURE 3. ACTIVE MODE BCAS TEST BED BLOCK DIAGRAM

operational cycle. For example, the SPIU will reject the simultaneous issuance of a mode C and a mode D interrogation. It also will reject any combination such as a mode C and P1-P2 suppress or a mode D and a P1-P2 suppress. The SPIU will provide a MODE VALID response to the computer if and only if the command calls for one valid interrogation mode and a suppression signal to its own BCAS system transponder. The SPIU controls the solid-state pin-diode antenna switch upon command from the computer, and examines the status signal from the antenna switch to insure the proper status before allowing an operational cycle.

SPIU INTERFACE FUNCTIONS.

SPIU COMPUTER INTERFACE. The interface between the SPIU and the computer consists of data and control lines for the Programmed Data Channels (PDC) and from the Direct Memory Access Channel (DMA).

PROGRAMMED DATA CHANNEL INTERFACE (PDC). The PDC interface consists of three sets of input data lines (A,B,C) and three sets of output data lines (A,B,C). Each of these sets contain 16 data lines to accommodate the 16-bit words from the fully buffered I/O channels, and control lines for each set of data lines.

Input channel A conveys the altitude from the encoder to the computer, along with three other signals from the SPIU including the mode D flag, Interrogate Status, and Interrogate Complete control signals.

Channel B conveys the least significant portion of the time word from the Time Code Generator.

Input channel C conveys the most significant portion of the time word.

Output channel A conveys the control command signals from the computer to perform the following functions:

1. Select the antenna (upper or lower)
2. Suppress the BCAS system transponder.
3. Initiate and control the interrogate mode.
4. Initiate and control the transmit cycle.

Output channel B conveys the mode D reply to the system transponder by means of SPIU and a control signal to reset the mode D flip-flop.

Output channel C conveys the control signals to the CAS display to illuminate the various command and warning lamps such as climb, dive, and others.

DIRECT MEMORY ACCESS (DMA) CHANNEL INTERFACE. The DMA interface consists of 16 data lines and the necessary control lines. The DMA data lines convey the 12-bit data word recovered from the reply and its associated 12-bit range words.

SPIU-TRANSPONDER INTERFACE. The SPIU-Transponder Interface consists of:

1. A suppress line to provide a 25-volt (V) pulse to suppress the transponder during the interrogation cycle.

2. A mode D flag line to inform the computer of a mode D interrogation detected by the transponder.

3. Twelve data lines to convey the mode D reply from the computer to the transponder.

SPIU-INTERROGATOR INTERFACE. The SPIU-Interrogator Interface consists of two coaxial lines; one to convey the interrogation video pulse pairs from the SPIU to the interrogator, and the second line to convey the serial video pulse of the reply to the SPIU.

SPIU-ALTITUDE ENCODER INTERFACE. The SPIU-Altitude Encoder Interface consists of dual serial inverters in each of the 10 altitude encoder lines,which provides an open-bit line for a "0" and a grounded bit line for a "1". The altitude signals are thus buffered by the inverters. The first inverter provides the correct signal polarity for the programmed data channel, and the second inverter returns the signal to the polarity required by the transponder.

SPIU-TIME CODE GENERATOR INTERFACE. The SPIU-Time Code Generator Interface is made up of a Schmitt trigger followed by an inverter in each of the 24 time-bit lines. The reason for this circuit configuration is to provide reliable operation in view of the fact that the time code generators do not have adequate line drive capability.

SPIU-ANTENNA SWITCH INTERFACE. The SPIU-Antenna Switch Interface consists of two pairs of differential driver lines and two pairs of differential receiver lines. The driver lines control the antenna switch, and the receiver lines report the status of the antenna switch to the computer through the SPIU. The power for the antenna switch (+12V and -12V d.c.) is provided by the SPIU by way of the interface.

SPIU-CAS DISPLAY INTERFACE. The SPIU-CAS Display Interface consists of 12 dual lamp-driver amplifiers. Each CAS display functions, as commanded by the computer, to turn on its dual lamp driver to illuminate the specified warning or command lamps of the two CAS displays. One lamp is in the cockpit, and one is on the BCAS equipment rack.

PERFORMANCE AND HARDWARE MODIFICATION

INTERROGATION RECEIVER PERFORMANCE.

The theoretical considerations regarding the ability of BCAS to track aircraft through garble situations was based on the reply code "1's" being indestructible and reply "0's" being subject to alteration when replies from several aircraft overlap.

Observation of the data contained in the raw radar buffers, as recorded on the BCAS magnetic tape, indicated that information was lost when two or more replies overlapped. The two remote aircraft may be widely separated, but approximately equidistant from the BCAS-equipped aircraft; thus, the replies overlap and distort their data content. As expected, a reply could superimpose its 1's over the other reply's 0's, but something unexpected happened. When the 1's from the two replies were superimposed, the 1's were destroyed.

Analysis of the performance of the interrogator video processor circuit revealed that the pulses did not add, as expected, when the two video signals merged. Instead of adding, as the pulses started to overlap, the pulses would split into two, and finally, into three narrow pulses, which would be rejected by the pulsewidth discriminator in the data acquisition portion of the SPIU resulting in the loss of information and subsequent discontinuities in the tracking of the garbled replies. This problem was observed primarily in the analysis of the data collected on magnetic tapes in the Washington, D.C. area, where there are a considerable number of ground based interrogators and moderate air traffic density.

INTERROGATOR CORRECTIVE MODIFICATIONS.

The circuit correction, to prevent the loss of reply code 1's in a garble environment, was accomplished by simply bypassing the portion of the video processor circuit that caused the pulse splitting. The only portion of the video processor circuit presently used is the two-stage input driver amplifier coupled directly to the output emitter follower amplifier. The receiver video is thus passed onto the SPIU as analog video. The receiver video amplitude, which was previously standardized digital pulse, is now an analog signal with amplitude inversely related to the range.

This modification corrected the data loss problem in the interrogator but the resulting signal amplitude and baseline level changes required some modification of the beacon video quantizer circuit board of the SPIU.

BEACON VIDEO QUANTIZER (BVQ) MODIFICATIONS. Several modifications were made to the BVQ circuit board to achieve compatibility with the interrogator modification and to generally improve the performance of the quantizer.

A multiturn potentiometer, formerly used to adjust the amplitude of test video (presently not required), was reconnected to function as an input signal level threshold control. This control provided the means to properly match the signal level of the receiver video from the interrogator.

A new multiturn potentiometer was added to the input junction of the amplifier preceding the peak detector. The original detector circuit was designed to detect at approximately the 50 percent amplitude level. The addition of the new control pot and several resistor value changes provided the means to adjust the video pulse amplitude detection to approximately 120 millivolts (mV) below peak amplitude. This change was required since the receiver video pulses from the interrogator are no longer standardized 5 V pulses as mentioned in Interrogator Corrective Modifications.

To further insure the stability of the various input threshold, signal peak and threshold detectors, the three potentiometer circuits are now regulated by zener diodes.

The peak detector was originally reset from the output of the voltage comparator. The circuit performance was improved by resetting the peak detector with the output of the signal threshold detector.

Another minor circuit modification was made which has no effect on the circuit performance; its purpose is to allow the ciruit to operate under test without an enable signal from the computer. The input enable gate, which originally controlled the input beacon video, was reconnected to control the output of the beacon video quantizer.

PARALLEL BRACKET DETECTOR MODIFICATIONS. The following paragraphs analyze the problem and relate the corrective action taken to modify the parallel bracket detector.

Overview of the Problem. The analysis of some of the data collected on magnetic tape indicated occasional loss of reply 1 bits in a garble-free environment.

Although this condition occurred very infrequently, it deserved attention. Transponder pulse spacing or pulsewidth maladjustment is suspected as a possible explanation of this loss of information. The bracket detector is a 208-bit shift register from which the 12 bits of the reply are extracted from their respective pulse position taps. This occurs when coincidence is detected at the "F1" and "F2" bracket taps. Observation of the bracket detector in operation indicated that the presently used taps were the optimum design choice for most transponders.

Corrective Modifications of the Parallel Bracket Detector. Each stage of the 208-bit shift register represents approximately 120 nanoseconds; therefore, the 450-nanosecond reply pulse would be contained in three or possibly four stages. The center stage for each pulse was chosen and appears to be optimum for most transponders, as mentioned in Overview of the Problem.

To accommodate the transponders with the "out of tolerance" pulse spacing, the logic was modified to detect the pulse in the stage following, as well as, the original stage. This was accomplished by adding 12 "OR" gates, one for each of the 12 reply code taps, each gate having two inputs, the original tap and the one following (later in time). This modification appeared to correct the rarely encountered data loss due to suspect transponders.

ALTITUDE ENCODER SPIU PROBLEM AND CORRECTIVE MODIFICATIONS. The following paragraphs outline the modifications to the SPIU in order to prevent erroneous altitude reports.

Overview of the Problem. The aircraft pressure altitude encoder signal bus provides input to the SPIU-Altitude Interface as described in SPIU-Altitude Encoder Interface, as well as the normal connection to the aircraft transponders. During a BCAS test flight, the normal aircraft transponder is turned off and the BCAS transponder becomes the aircraft transponder. During other aircraft flights when the BCAS was not in use, although still connected to the altitude encoder bus, erroneous altitude was being reported by the aircraft transponder. This erroneous altitude is caused by the loading effect of the SPIU interface circuits on the altitude encoder bus with the SPIU in POWER OFF status.

Corrective Modification of Altitude Encloder Interface. A simple solution to this problem is to remove the altimeter cable connector from the rear of the SPIU at the conclusion of the BCAS operation.

APPENDIX A

BCAS ATC ADVISORY FLIGHT TESTS

On July 28, 1976, a flight test was [illegible]ed to test the BCAS ATC Advisory Feature. This feature causes the ai[illegible]sponder to reply with a 7500 identity code whenever the BCA[illegible] climb and 7400 whenever the BCAS indicates a dive command. The B[illegible]isory was successfully tested with the use of the Terminal Air Traf[illegible]y (TATF) ARTS III. The ARTS III operational program was modified to interpret a 7500 code as a 7700 code and display emergency (EM), and also interpret a 7400 code as a 7600 code and display radio failure (RF). The following results were observed during this test:

1. At 09 26 14, aircraft N46 was manually sending a 7400 code via a test switch. The TATF was indicating an RF for the full time that N46 was sending the 7400 code.

2. At 09 27 14, aircraft N46 was manually sending a 7500 code via a test switch. The TATF was indicating an EM for the full time that N46 was sending the 7500 code.

3. During head-on flight with 400 feet separation between N46 and N49. N46 indicated a dive arrow at 09 48 20. The TATF observed the RF at 09 48 27.

4. Later during this same flight a dive command was given in N46 at 09 54 29. The TATF observed the RF at 09 54 34.

5. During head-on flight with 400 feet separation between N46 and N49. N46 indicated a climb arrow at 10 07 27. The TATF observed the EM at 10 07 33.

APPENDIX B

BCAS ACCURACY FLIGHT TESTS

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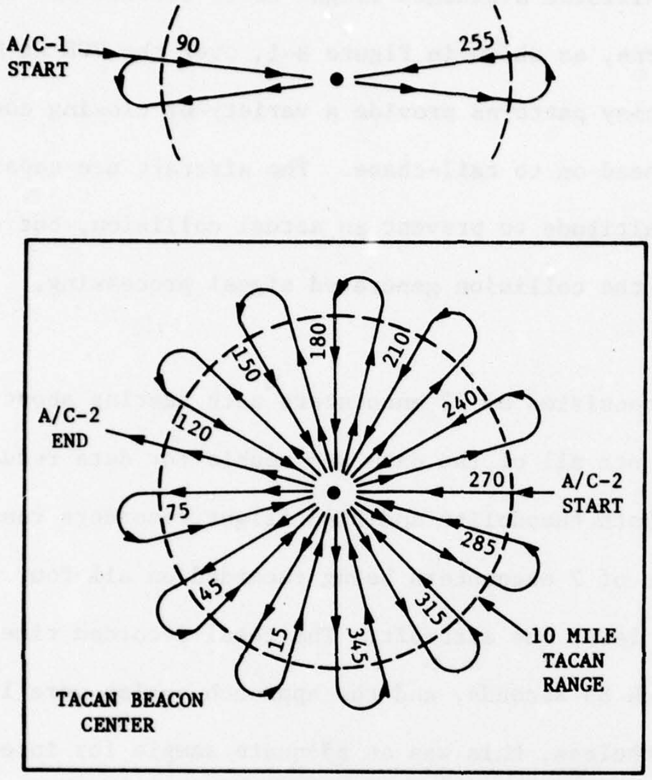
1. DESCRIPTION OF THE FLIGHT

The normal collision avoidance flight tests consist of "double daisy" patterns, as shown in Figure B-1, over the VOR at NAFEC. The double daisy patterns provide a variety of closing configurations from head-on to tail-chase. The aircraft are separated by 400 feet in altitude to prevent an actual collision, but still exercise all the collision generated signal processing.

This flight consisted of 12 encounters each lasting about 3 minutes, but not all of the data was usable for data reduction. Failures of both theodolite and BCAS flight recorders resulted in only parts of 2 encounters being recorded on all four theodolites and at least one aircraft. The total recorded time under track was thus 83 seconds, and the approach angles were 120^{o} and 150^{o}. Nevertheless, this was an adequate sample for interpreting the accuracies of the system.

Approximately 80 minutes of additional data were collected with phototheodolite tracking subsequent to the tests described above. This data is being reduced and analyzed and will appear in the final report.



ENCOUNTER NUMBER	RADIALS FLOW		ANGLE BETWEEN RADIALS (DEG)
	A/C-1 (DEG)	A/C-2 (DEG)	
1	90	270	180
2	255	75	180
3	90	240	150
4	255	45	150
5	90	210	120
6	255	15	120
7	90	180	90
8	255	345	90
9	90	150	60
10	255	315	60
11	90	120	30
12	255	285	30
13	90	90	0

FIGURE B-1
SINGLE DAISY OVER A FIGURE EIGHT

2. TYPE OF DATA RECORDED

The theodolite data was processed at NAFEC to generate x, y, and z of each aircraft ten times per second. The x and y coordinates were relative to an arbitrary coordinate system set up for theodolite tracking, and the z coordinate was height above mean sea level.

Each BCAS aircraft also recorded all returns to its own interrogations, and own altitude, as indicated by its encoding altimeter. These tapes were replayed at METREK and the range, range rate, altitude, and altitude rate of all threats, including the other BCAS aircraft were generated. Because of the branching process in the tracker, many tracks can be generated for one aircraft at any instant in time. In these cases the track with the largest number of returns (highest confidence) was used.

3. DESCRIPTION OF DATA REDUCTION TECHNIQUES

The data was reduced by taking the four target parameters, range, range rate, altitude, and altitude rate and subtracting the corresponding values obtained from the theodolite data. These sets of differences were then processed to obtain the mean error, the mean squared error, and the standard deviation. This was done for each of the 2 recorded encounters separately, and for the combination of both encounters. The same was also done for own ship's altitude and altitude rate.

Range rate and altitude rate do not come directly from the theodolite data, but were obtained by differencing range and altitude. Thus, with a theodolite accuracy of 6 feet or less, one might have as much as an 8.5 ft/sec (1σ) error in range rate or altitude rate.

It was intended to compensate for the barometric pressure, since the encoding part of the altimeters are not set by the pressure correction, but an examination of the data showed that no such correction was needed on that day.

It was noted that the altitude rate accuracy estimates were not complete, since the aircraft were flying level, with no quantization noise other than that introduced into the tracker by fruit and garble. Therefore, as a final presentation, a target of opportunity was selected which had just taken off, and which appeared to have a constant climb rate for almost a minute.

Assuming a constant climb rate, the mean and standard deviation of the BCAS tracked altitude rate was calculated about this assumed value.

4. ACCURACY ESTIMATES

Tables B-1, B-2, and B-3 are the accuracies of the 22 second, the 63 second and the combined 85 second segments.

4.1 Range

As seen in Table B-3, there is a consistent range error of 129 feet which does not vary much from encounter-to-encounter. This is of no practical concern but is probably due to a fast turn around time in the transponder, or else a slight offset in the BCAS and theodolite clocks. The aircraft were closing at about 530 ft/sec.

The standard deviation was 92 feet, which is about 3 times larger than expected. This error, however, would be of consequence only if it affected the range rate.

4.2 Range Rate

The mean error in range rate is negligible, as is expected, because range biases cancel out. Range rate errors are caused primarily by jitter in range measurements. The errors are consistantly measured to be 36 ft/sec. This is very close to the expected value of 33.2 ft/sec (20 knots), accounting for beacon jitter, range quantization, and tracker smoothing.

TABLE B-1

APPROACH NUMBER 4 (22 SECONDS)

Parameter	Mean Error	rms Error	Standard Deviation	Desired Maximum Bias	Desired Precision (1σ)
Range	153.1 ft	169.6 ft	73 ft	350 ft	25 ft
Range Rate	12.8 ft/s	36.5 ft/s	32.2 ft/s	-	33.2 ft/s
Altitude	-36.5 ft	38.3 ft	11.6 ft	106 ft	18 ft
Altitude Rate	-1.44	4.1 ft/s	3.8 ft/s	-	25 ft/s
Own Altitude	-34 ft	42.7 ft	25.8 ft	106 ft	18 ft
Own Altitude Rate	-7.9 ft	8.3 ft/s	2.7 ft/s	-	25 ft/s

TABLE B-2

APPROACH NUMBER 5 (63 SECONDS)

Parameter	Mean Error	rms Error	Standard Deviation	Desired Maximum Bias	Desired Precision (1σ)
Range	120 ft	153 ft	95 ft	350 ft	25 ft
Range Rate	7.6 ft/s	37 ft/s	36 ft/s = 21.4 kt	-	33.2 ft/s
Altitude	.32 ft	24 ft	24 ft	106 ft	18 ft
Altitude Rate	.86 ft/s	6 ft/s	6 ft/s	-	25 ft/s
Own Altitude	-45 ft	57.7 ft	37 ft	106 ft	18 ft
Own Altitude Rate	-4.8 ft/s	6.26 ft/s	57.5 ft/s	-	25 ft/s

TABLE B-3

COMBINED RESULTS (85 SECONDS)

Parameter	Mean Error	rms Error	Standard Deviation	Desired Maximum Bias	Desired Precision (1σ)
Range	128.6 ft	157.5 ft	90.9 ft	350 ft	25 ft
Range Rate	8.9 ft/s	36.9 ft/s	35.8 ft/s	-	33.2 ft/s
Altitude	-9.2 ft	28.4 ft	26.9 ft	106 ft	18 ft
Altitude Rate	-0.26	5.6 ft/s	5.6 ft/s	-	25 ft/s
Own Altitude	-42.2 ft	52.2 ft	34.1 ft	106 ft	18 ft
Own Altitude Rate	-5.6 ft/s	6.8 ft/s	3.9 ft/s	-	25 ft/s

4.3 Altitude

Altitude errors come from many sources, most notably calibration errors, and quantization, or granularity. The measured errors are rather small, 28.4 feet rms, and the target altitude was not measurably worse than own altitude. The same tracker is used on these two altitudes but the own altitude tracker has no garble. Since the garble should only increase the error, apparently all the measured error was due to granularity.

4.4 Altitude Rate

Altitude rate is also presented for both the target aircraft and own aircraft. The errors obtained are well below that expected, and an examination of the input data indicated that most of the error came from the theodolite. However, since the aircraft were usually flying straight and level, a good measurement of altitude rate could not be made.

Therefore, to obtain a closer estimate of the altitude rate error the altitude rate of a climbing target of opportunity was examined. This data is presented in Table B-4, and shows roughly the same accuracy (4.8 ft/sec standard deviation).

TABLE B-4

ALTITUDE RATE FOR CLIMBING TARGET OF OPPORTUNITY

Starting altitude = 94 ft

Final altitude = 1344 ft

Altitude rate for 46 seconds = 27.17 ft/s

BCAS Altitude Rate Estimates

Mean altitude rate = 26.12 ft/s

Maximum deviation = -7 to +14 ft/s

Standard deviation from 27.17 ft/sec = 4.82 ft/s

5. CONCLUSIONS

The measured errors in range rate and altitude were about as expected. It should be noted that the accuracy flight test was not run in a vacuum. There were other aircraft on the ground as well as fixed transponders on buildings, which generated garble. The existence of several BCAS tracks on the target, at slightly different ranges, and many tracks being successfully extended, indicates the presence of garble and phantom bracket detects. This provided a fortuitous chance to measure BCAS accuracy in the presence of some garble.

The altitude rate error was much smaller than expected. Even when a climbing track was analyzed, the same conclusion held. Therefore, it appears that altitude granularity is not a limiting consideration in altitude tracking.

Finally, the range standard deviation was much larger than expected. Fortunately, it did not affect the range rate, and therefore must have been highly correlated from hit-to-hit. The measured range standard deviation has little effect on the ability of BCAS to estimate τ, or predicted time to one mile separation. Since $\tau = \frac{R-d_{min}}{\dot{R}}$, $\frac{\delta\tau}{\delta\dot{R}} \Big/ \frac{\delta\tau}{\delta R} = \tau$

Thus errors in $\dot{R}$ have τ times the effect of errors in R. If the τ threshold is 30 seconds, we can stand 30 times as much error in R as $\dot{R}$, for the same impact on warning timeliness.

APPENDIX C

RAW DATA

THEODOLITE							BCAS						
TIME (SECONDS)	BCAS ALTITUDE Z_1	THREAT ALTITUDE Z_2	$\dot{Z}_1$	$\dot{Z}_2$	RANGE	$\dot{R}$	TRACK AGE (SINCE ESTABLISHMENT)	Z_1	Z_2	$\dot{Z}_1$	$\dot{Z}_2$	RANGE	$\dot{R}$
51788	2597	2869	-0.0901	-3.0999	3.3910	-0.0789	1	2594	2875	5.0659	-1.4160	3.3662	-0.0953
51789	2592	2863	-5.7000	-3.3101	3.3075	-0.0835	2	2594	2881	5.0659	0.0000	3.2764	-0.0932
51790	2592	2860	0.7900	0.3101	3.2265	-0.0810	3	2594	2881	5.0659	0.0000	3.1836	-0.0932
51791	2591	2858	-1.2000	-28.2002	3.1434	-0.0831	4	2594	2881	5.0659	0.0000	3.0908	-0.0932
51792	2590	2857	-1.5901	35.5000	3.0621	-0.0813	5	2594	2881	5.0659	0.0000	2.9980	-0.0932
51793	2588	2859	-2.0000	-6.1099	2.9798	-0.0823	6	2594	2894	5.0659	0.7080	2.9531	-0.0819
51794	2583	2850	-4.4099	0.3101	2.8938	-0.0860	7	2594	2894	5.0659	1.0620	2.8730	-0.0811
51795	2580	2852	-3.0000	5.2998	2.8126	-0.0813	8	2594	2894	5.0659	1.4160	2.7900	-0.0817
51796	2576	2850	-4.3901	-19.2000	2.7297	-0.0828	9	2594	2894	5.0659	1.4160	2.7080	-0.0817
51797	2567	2853	-8.7000	1.7000	2.6467	-0.0830	10	2594	2894	5.0659	1.7700	2.6250	-0.0819
51798	2562	2857	-4.9099	-4.7998	2.5635	-0.0833	11	2594	2894	5.0659	1.7700	2.5430	-0.0819
51799	2557	2861	-5.6899	4.0000	2.4804	-0.0830	12	2594	2894	5.0659	2.1240	2.4609	-0.0819
51800	2550	2862	-6.4001	14.2998	2.3987	-0.0817	13	2594	2894	5.0659	2.4780	2.3770	-0.0827
51801	2547	2861	-3.2100	-3.7998	2.3150	-0.0838	14	2594	2894	5.0659	2.8320	2.2959	-0.0821
51802	2544	2858	-2.8899	-6.5000	2.2325	-0.0824	15	2594	2894	5.0659	3.1860	2.2119	-0.0827
51803	2540	2862	-4.1101	-1.6101	2.1498	-0.0827	16	2594	2900	5.0659	3.1860	2.1309	-0.0819
51804	2534	2859	-5.7000	-4.7900	2.0672	-0.0826	17	2594	2906	5.0659	2.8320	2.0518	-0.0807
51805	2533	2858	-1.3901	-9.5000	1.9842	-0.0830	18	2594	2906	5.0659	2.4780	1.9658	-0.0827
51806	2535	2854	2.0000	-13.0000	1.8999	-0.0843	19	2600	2906	5.0781	2.4780	1.8828	-0.0827
51807	2534	2857	-0.7998	1.2000	1.8174	-0.0825	20	2606	2906	5.0903	2.4780	1.7998	-0.0827
52178	2517	2927	-0.7998	6.0901	5.4589	-0.0784	1	2606	2881	5.0903	0.7080	5.4346	-0.0872
52179	2522	2922	5.1899	-4.8901	5.3724	-0.0865	2	2606	2881	5.0903	0.7080	5.3477	-0.0872
52180	2526	2921	4.7000	-1.7000	5.2883	-0.0841	3	2606	2881	5.0903	0.7080	5.2607	-0.0872
52181	2533	2919	6.5000	-1.8000	5.2081	-0.0802	4	2600	2888	5.0781	1.7700	5.1865	-0.0877
52182	2524	2914	-8.8899	-5.2998	5.1181	-0.0900	5	2594	2894	5.0659	2.4780	5.1006	-0.0872
52183	2530	2906	5.5999	-7.1101	5.0358	-0.0822	6	2594	2894	5.0659	2.8320	5.0146	-0.0868
52184	2531	2902	1.4001	-4.0901	4.9529	-0.0829	7	2594	2894	5.0659	2.8320	4.9277	-0.0868
52185	2529	2899	-2.5000	-3.7998	4.8696	-0.0833	8	2594	2894	5.0659	3.1860	4.8672	-0.0842
52186	2521	2899	-7.3101	0.2998	4.7843	-0.0853	9	2594	2900	5.0659	3.1860	4.7783	-0.0862
52187	2520	2902	-0.8000	3.5000	4.7015	-0.0828	10	2594	2906	5.0659	2.8320	4.6855	-0.0887
52188	2520	2905	-0.7900	3.0000	4.6225	-0.0790	11	2594	2906	5.0659	2.8320	4.5967	-0.0887
52189	2518	2913	-1.9099	8.0901	4.5383	-0.0842	12	2594	2906	5.0659	2.4780	4.5076	-0.0887
52190	2515	2909	-2.5000	-4.0901	4.4535	-0.0848	13	2594	2906	5.0659	2.1240	4.4248	-0.0866
52191	2517	2909	2.0000	-0.5000	4.3672	-0.0863	14	2594	2906	5.0659	1.7700	4.3457	-0.0838
52192	2511	2903	-5.8901	-6.1099	4.2822	-0.0850	15	2594	2906	5.0659	1.7700	4.2617	-0.0838
52193	2512	2899	0.8000	-3.3000	4.1992	-0.0830	16	2594	2906	5.0659	1.7700	4.1777	-0.0838
52194	2515	2889	2.7000	-10.3899	4.1169	-0.0823	17	2594	2931	5.0659	7.0801	4.1318	-0.0698
52195	2516	2878	1.0000	-11.0000	4.0305	-0.0864	18	2594	2925	5.0659	4.9561	4.0410	-0.0776
52196	2518	2875	2.3000	-2.7002	3.9491	-0.0814	19	2594	2925	5.0659	3.1860	3.9492	-0.0829
52198	2518	2875	2.3000	-2.7002	3.7787	0.8022	20	2594	2919	5.0659	0.0000	3.7666	-0.0877
52199	2511	2869	-5.5901	1.2002	3.6948	-0.0839	21	2594	2919	5.0659	0.0000	3.6787	-0.0877
52200	2510	2872	-1.1099	3.5000	3.6116	-0.0832	22	2569	2913	5.0171	-1.0620	3.5967	-0.0856
52201	2509	2873	-1.1899	1.3899	3.5283	-0.0833	23	2550	2906	4.9805	-1.7700	3.5137	-0.0846
52202	2506	2873	-3.0000	0.0000	3.4456	-0.0827	24	2531	2906	4.9438	-2.1240	3.4336	-0.0829
52203	2511	2877	5.2998	3.4099	3.3647	-0.0809	25	2519	2906	4.9194	-2.4780	3.3516	-0.0827
52204	2518	2888	6.5901	11.0901	3.2854	-0.0793	26	2506	2906	4.8950	-2.8320	3.2666	-0.0833
52205	2519	2891	1.2100	3.0000	3.2043	-0.0811	27	2525	2906	4.9316	-3.1860	3.1855	-0.0825
52206	2522	2893	2.7000	2.1101	3.1217	-0.0826	28	2544	2900	4.9683	-3.1860	3.1025	-0.0829
52207	2520	2890	-2.0000	-3.3101	3.0399	-0.0818	29	2563	2894	5.0049	-3.1860	3.0195	-0.0829
52208	2520	2892	0.3901	1.9099	2.9614	-0.0785	30	2575	2894	5.0293	-2.4780	2.9375	-0.0827
52209	2524	2887	3.6099	-4.8000	2.8793	-0.0821	31	2588	2894	5.0537	-2.1240	2.8613	-0.0801
52210	2524	2888	0.3901	1.0901	2.8000	-0.0793	32	2594	2894	5.0659	-1.7700	2.7813	-0.0801
52211	2529	2881	4.5000	-6.7000	2.7203	-0.0798	33	2600	2894	5.0781	-1.4160	2.7021	-0.0797
52212	2533	2878	4.2000	-3.0000	2.6402	-0.0801	34	2606	2894	5.0903	-1.0620	2.6191	-0.0807
52213	2531	2882	-1.5000	4.1099	2.5613	-0.0789	35	2606	2894	5.0903	-0.7080	2.5391	-0.0805
52214	2528	2881	-3.2000	-0.9099	2.4799	-0.0814	36	2606	2894	5.0903	-0.3540	2.4395	-0.0880
52215	2521	2885	-7.0901	3.3000	2.3998	-0.0801	37	2606	2894	5.0903	0.0000	2.3730	-0.0801
52216	2520	2890	-1.5000	5.0000	2.3198	-0.0800	38	2606	2894	5.0903	0.3540	2.2988	-0.0778
52217	2514	2887	-5.9099	-2.3000	2.2393	-0.0805	39	2581	2894	5.0415	0.7080	2.2236	-0.0766
52218	2512	2890	-2.0901	2.9099	2.1577	-0.0816	40	2556	2894	4.9927	1.0620	2.1436	-0.0780
52219	2511	2889	-0.8000	-1.7000	2.0782	-0.0795	41	2538	2894	4.9561	1.4160	2.0635	-0.0786
52220	2507	2890	-3.4099	1.4001	1.9969	-0.0812	42	2519	2894	4.9194	1.7700	1.9805	-0.0804
52221	2505	2899	-2.5000	9.0000	1.9153	-0.0816	43	2506	2894	4.8950	2.1240	1.9033	-0.0792
52222	2512	2901	7.3000	1.5999	1.8363	-0.0791	44	2494	2894	4.8706	2.1240	1.8242	-0.0792
52223	2518	2905	6.2000	4.0000	1.7558	-0.0804	45	2488	2894	4.8584	2.1240	1.7451	-0.0792
52224	2524	2913	5.1101	8.0901	1.6763	-0.0796	46	2513	2894	4.9072	2.1240	1.6660	-0.0792
52225	2525	2917	1.3899	3.9099	1.5946	-0.0817	47	2531	2894	4.9438	2.1240	1.5869	-0.0792
52226	2529	2921	3.6101	4.7000	1.5150	-0.0796	48	2550	2894	4.9805	2.1240	1.5078	-0.0792
52227	2526	2917	-2.3101	-4.7000	1.4297	-0.0852	49	2569	2894	5.0171	2.1240	1.4287	-0.0792
52228	2523	2914	-3.0901	-3.0999	1.3474	-0.0823	50	2581	2925	5.0415	8.1421	1.3418	-0.0819
52229	2517	2920	-5.7100	6.8899	1.2673	-0.0801	51	2594	2925	5.0659	6.3721	1.2588	-0.0823
52230	2513	2918	-4.7000	-2.2000	1.1879	-0.0793	52	2575	2925	5.0293	4.6081	1.1689	-0.0916
52231	2509	2917	-3.3901	-1.1899	1.1070	-0.0809	53	2556	2925	4.9927	2.8320	1.0820	-0.0899
52232	2503	2915	-6.6099	-1.9001	1.0243	-0.0828	54	2538	2919	4.9561	1.4160	1.0010	-0.0868
52233	2502	2922	-0.8901	6.5000	0.9445	-0.0798	55	2525	2919	4.9316	1.4160	0.9141	-0.0868
52234	2504	2923	1.7002	1.4001	0.8636	-0.0809	56	2513	2913	4.9072	0.3540	0.8369	-0.0839
52235	2505	2920	1.5000	-2.6101	0.7840	-0.0796	57	2506	2881	4.8950	-6.0181	0.6805	-0.1079
52236	2507	2921	2.0999	0.9099	0.7051	-0.0789	58	2500	2881	4.8828	-4.6021	0.6330	-0.0882
52237	2511	2930	4.2000	8.2002	0.6266	-0.0785	59	2494	2881	4.8706	-3.1860	0.5762	-0.0771
52238	2511	2929	-0.7000	-0.8101	0.5481	-0.0785	60	2494	2881	4.8706	-1.7700	0.5117	-0.0722
52239	2516	2919	5.2000	-9.8000	0.4641	-0.0840	61	2494	2888	4.8706	-0.7080	0.4424	-0.0710
52240	2519	2913	2.7002	-6.3899	0.3840	-0.0802	62	2494	2894	4.8706	0.0000	0.3691	-0.0718
52241	2524	2910	5.5000	-2.2002	0.3068	-0.0772	63	2494	2894	4.8706	0.3540	0.2930	-0.0734