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LOCKHEED L-1011 AVIONIC FLIGHT CONTROL REDUNDANT SYSTEMS

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SUMMARY

Two of the Lockheed L-1011 automatic flight control systems - yaw stability augmentation and automatic landing - are described in terms of their redundancies. The reliability objectives for these systems are discussed and related to in-service experience. In general, the availability of the stability augmentation system is higher than the original design requirement, but is commensurate with early estimates. The in-service experience with automatic landing is not sufficient to provide verification of Category III automatic landing system estimated availability. Component reliability is, however, generally tracking expectation.

INTRODUCTION

The L-1011 TriStar has been in airline operation since April 1972 as one of the current generation of wide-body jets. In service at present, there are about 80 units of the current model which is a short to medium range airplane that cruises typically at M =.85, H_p = 33,000 feet. Maximum takeoff and landing weights are 430,000 and 360,000 pounds. Figures 1 and 2 show the airplane dimensions and flight control surfaces, respectively.

The Avionic Flight Control System (AFCS) of the L-1011 is highly redundant in comparison to such systems of the previous generation of aircraft. This redundancy to a certain extent is manifest in the so-called "cruise" autopilot portions of the AFCS, but this was more or less a fallout of the need for high redundancy in the Category III Automatic Landing System (ALS). The configuration of the "cruise" portion of the AFCS yaw control channel was also affected by this Category III requirement.

It is intended in the following discussion to provide brief descriptions of the automatic yaw cruise control system and of the automatic landing system, these descriptions to provide the background for judging system redundancy in comparison to other systems familiar to the reader. It is further intended to present in-service derived data describing the reliability of these two systems and to relate this experience to expectation.

AFCS OVERVIEW

The complete AFCS including Category IIIa automatic landing was certificated at the time of initial airplane FAA certification in April 1972. It has been subsequently so certified by Canada (MOT), Great Britain (CAA), Japan (JCAB), and West Germany (LBA). In the total fleet to date, there have been about 160,000 revenue flight hours accumulated for approximately 80,000 flights.

Briefly the AFCS consists of four subsystems:

Stability Augmentation System (SAS)
Autopilot/Flight Director System (APFDS)
Speed Control System (SCS)
Flight Control Electronic System (FCES)

The components which comprise the AFCS are listed by subsystem in Table 1. For total systems function, these components interface with other airplane elements such as sensors-air data, attitude references, radio navigation and altimetry systems, electrohydraulic and electrical flight control servos, flight instruments, control panels, etc.

The SAS functions include yaw damping, turn coordination, runway alignment during automatic landing and automatic steering during the landing rollout.

The APFDS provides for automatic control of the airplane from takeoff to landing. There are the usual modes of

Roll and Pitch Attitude Hold with Control Wheel Steering (CWS) and Turbulence Configuration Control
Altitude Select and Hold
Vertical Speed Select and Hold
Airspeed Hold on Pitch
Mach Hold on Pitch
Heading Select and Hold
VOR and Area Navigation
Localizer Capture and Track

In addition, there are the common axis modes of

Approach
Approach/Land (Autoland)
Go-Around
Takeoff

The pitch commands for Go-Around and Takeoff are derived in the SCS with Takeoff being a flight director mode only.

The SCS autothrottle modes are:

Airspeed Select and Hold
Stall Margin Control

The latter is primarily an approach/land mode which uses angle of attack as the basic reference. And as just mentioned, the SCS also provides for the Go-Around and Takeoff modes using angle of attack as a reference.

The FCES provides a number of functions such as electrical pitch trim, Mach trim, Mach feel, stall warning, altitude alert, primary flight controls monitoring, automatic ground speed brakes and direct lift control. All of these functions operate when either pilot or autopilot is in control.

With these descriptive remarks as background, further discussion is confined to the SAS cruise control system and to the Automatic Landing System. Each of these systems has operational availability/reliability requirements which we shall examine and relate to the reliabilities achieved in service use.

STABILITY AUGMENTATION SYSTEM (SAS)

System Mechanization

Figure 3 depicts the cruise configuration of the SAS. Each of the two yaw computers contains two computation channels that output identical servo commands to an in-line monitored electrohydraulic servo. Four aileron position transducers and three rate gyros service the four computation channels of the total system. The rate gyros provide for Dutch roll damping inputs and the aileron transducers provide for turn coordination.

Figure 4 shows one channel of the SAS cruise computation. It is seen that the gains are scheduled with flap position and the gyro path has the usual low frequency washout filter plus a high frequency cut-off. The aileron input path has a limited washout to remove aileron trim effects and in addition an adjustable dead zone such that turn coordination only comes into play for sufficiently large aileron inputs. The passed signal is subject to gain changing to match the gyro channel and to low pass filtering. The voter output to rudder surface response can be approximated by a two Hz second order servo for small amplitudes. However, the primary control surface servo is severely hinge moment limited in cruise flight.

It is noted that in Figure 4 the output of the computation comprises one input to a voter. The other inputs are derived from the other three computation channels of this dual-dual mechanization. As one would expect, there are two computations and two voters per yaw computer with two voter outputs required to drive one SAS electrohydraulic servo as depicted in

Figure 5. The two voter outputs provide for driving the EHV coils in a push-pull arrangement with two sets of dual monitors acting to shut off the servo loop hydraulics if a fault is detected.

There are also monitors in front of the voters which control the signal configuration of the voter inputs as shown in Figure 6. This figure illustrates the concept whereby the monitors control switching logic that substitutes signal ground or an alternate computation for a faulted channel. Figure 7 shows the voter input crossfeeding for the complete dual-dual system.

In addition to servo and computation monitors, there are rate gyro monitors and electrical power monitors. The latter operate into the servo engage logic while the former monitors operate into the voter switching logic.

Design Objectives and Performance

The function of the cruise mode of the SAS is, of course, to provide improved Dutch roll damping for enhancement of passenger comfort and handling qualities and for reduction of fin loads. This reduction of vertical tail loading, in continuous turbulence, due to the action of the SAS was reflected in the definition of limit design loads.

Early in the development of the L-1011, the effectiveness of the SAS was investigated to determine performance and reliability objectives for the SAS from a loads viewpoint. It appeared that a minimum damping ratio of 0.3 and a timewise availability of 97% were modest design objectives that would yield significant load reductions. It was subsequently found, however, that higher damping ratios could be achieved over most of the climb, cruise and descent flight regimes as seen from the data given in Table 2. Only at low speeds, where effects on fin loads are not critical, are the damping ratios less than 0.3.

It also became evident that a 97% availability requirement was a very conservative estimate of system reliability. On the basis of guaranteed failure rates, the single channel failure rate was calculated to be about 10^{-3} per hour and to preclude the possibility that an airplane might be flown without SAS for a protracted period, it is required that at least one of the two channels be operative for dispatch. Recognizing that for most flights both channels of SAS are operative, even 99.9% timewise availability would appear to be conservative.

A complete discussion of the effect of SAS availability on loads is given in reference (1) from which Figure 8 is taken. This figure illustrates the definition of design loading for vertical tail shear with 0, 97% and 100% SAS availabilities. It is based on a mission analysis criterion whereby the frequency of exceedance of a load quantity is calculated for operations over specified design flight profiles. The turbulence environment as statistically described for each segment of a profile is applied to the airplane/load transfer function to derive exceedance curves (with or without SAS operating) for each segment. The segment exceedances are summed over the total of all profiles to determine a load vs. frequency-of-exceedance curve for the mission.

It can be seen from Figure 8 that the major reduction ($\frac{H}{F} = 0.70$) is realized by having at least 97% availability and further reduction comes less readily with 100% availability realizing a ratio of $\frac{G}{F} = 0.65$. These results are for a fully linear system and saturation effects reduce the benefits somewhat. In summary, however, with 97% availability the net reduction in fin loading is better than 25% relative to what it would be if no SAS were available.

It would be very surprising if the in-service reliability indicated a SAS availability of less than 99.9%. The component MTBF values are tracking guarantees as indicated in Table 3. There have apparently been only five complete in-flight losses of SAS and a very few delays as a result of lack of immediate parts replacement. These instances with one exception were associated with dispatch for many consecutive flights with a failed computation channel. The number given above for in-flight losses covers a period in which revenue flight hours were accumulated with an average flight time of two hours. We believe that there have been no other instances of complete loss to date, and that it is conservative to use only that period for which detail records have been evaluated in estimating the total system failure rate. On the basis of actual total in-flight losses during the period evaluated, the SAS availability would be

$$1 - \frac{(5 \text{ losses})\ (\frac{1}{2} \text{ average flight time})}{\text{total flight hours}}$$

or about 99.98%. The individual SAS channel in-flight failure rate was also examined and it was found that 60 channel failures were experienced in a 30,000 flight hour (2-hour flights) period. This indicates a SAS channel MTBF of 1000 hours which is commensurate with the data of Table 3.

SAS Conclusions

With respect to the yaw stability augmentation system, the following conclusions can be drawn:

- 97% availability is an extremely conservative value upon which to base design loads.

- With current technology of design, manufacturing and airline maintenance, single channel SAS reliability should be adequate to support fin loading design criteria as established for the L-1011.

- L-1011 dual channel SAS provides fin load alleviation for all practical purposes equivalent to 100% SAS availability.

AUTOMATIC LANDING SYSTEM (ALS)

System Mechanization

The principal elements of the ALS are the APFDS and SAS and their respective sensors in the configurations established with the Approach/Land (A/L) mode selected. The system in total definition includes much more than these units but these have, by far, the most effect on system reliability and availability. Reliability is used here in the sense of the system capability to complete a landing. It relates directly to safety, particularly in low weather minima operations. It was, of course, the Category III requirement that dictated the extent of redundancy in the ALS. This redundancy is depicted in some generality in Figure 9 for the pitch and roll control axes. Each of these axes uses three accelerometers (normal or lateral) and three attitude inputs. Pitch computations use only derived pitch rate; roll uses both attitude and roll rate signals. The Autoland Sensor signals are glideslope error and radio altitude for pitch and localizer error for roll. Only two each of the Autoland Sensors are used but each has dual outputs with high integrity self-monitoring. For example, the probability of the two signals from one G/S receiver being faulted at a critical time without warning is less than 10^{-9}.

The same theme of APFDS redundancy is carried over into the SAS in the A/L mode as seen in Figure 10. Here, the exception is that only two compass systems are utilized which do not have the integrity of an Autoland Sensor. The redundancy requirement, however, is not as great for yaw control as it is for pitch and roll. (In the development program, automatic landings with no automatic yaw control have been demonstrated without any significant effect except that the pilot had to control the rollout.) The compass inputs are actually compared in the SAS computers and used to define a reference heading error which is memorized. The compass signals are switched out at 150 feet and integrated rate gyro data is used from there to touchdown. (The radio altitude signals used to control this function are omitted from Figure 10.) During this time, a maneuver is performed whereby the aircraft fuselage is aligned with the runway and a wing down is held against crosswind.

This use of the compass points out the difference between the safety and availability aspects. For Category IIIa conditions, the align capability is required, at present, and if one compass system fails on the approach above the alert height (100 feet for U.S. Carriers), a missed approach is executed. Safety implications are minimal, but as far as availability goes the day is lost.

As would be expected, the fail-operative pitch, roll and yaw (below 150 feet) mechanizations closely follow that as depicted in Figures 5, 6, and 7 for the cruise yaw control. Four computation channels for each axis are needed for the fail-operative condition and two or three for the fail-passive condition. The latter configuration is acceptable for Category II operations while the former is required down to the alert height for Category IIIa. There are minor differences in each servo control and monitoring mechanizations, but the basic concepts of Figure 5 are applied. For Category III, of course, it requires two servos per axis while one is acceptable for Category II.

Much is left unsaid about other subsystems of the ALS, such as

- Speed Control System
- Automatic Pitch Trim
- Direct Lift Control
- AFCS Mode Progress and Warning Indicators
- Flight Instrument Systems
- Hydraulic Power Sources
- Electrical Power Sources

In the interest of completeness, however, Table 5 is given to provide a brief summary of the major elements of the total ALS. It is also noted that a more complete description of the AFCS is given in Reference 2.

ALS Objectives and Development Results

There were three L-1011 program objectives with respect to the ALS.

1. Achieve a Category IIIa certification with a system having the potential for Category IIIb.

2. Develop a maintainable system.

3. Develop a system which has a reasonably high availability.

There is no doubt we held tenaciously to achievement of the first objective and we like to believe we have done the same with the other two. It may not have always been apparent, but we believe we are tracking fairly well even though it is perhaps too early to have all things proven out.

It is a fact that we certified for Category IIIa with the FAA on schedule; but, as you are probably well aware, the manufacturer's certification is only the first of a series. Each operator must verify its capability to use the system to the satisfaction of the same regulatory agency. One L-1011 operator has accomplished this; others are working at it. In the meantime, we are beginning to look toward achieving a Category IIIb capability.

One of the things an operator must show to achieve an ALS certification is his ability to maintain the system. An indication of this capability is a comparison of failure rates achieved with those used in the Lockheed certification analysis. In effect, MTBF tracking limits are defined. Table 4 shows a list of MTBF lower limits and their currently estimated values. The data given in this table are for the significant contributors to the total disconnect probability (below the alert height). If the MTBF's of all the listed units were at the lower limits, the total disconnect probability would be potentially a factor of two higher, still within acceptable limits. These "lower limits" are not absolute limits in view of the fact that the two factor does not put the disconnect probability to an unacceptable level and further one low MTBF value could be compensated by a high one. To a certain extent the limit is a tracking limit to signal for more detail examination of a potential trouble area. So far, however, things seem to be tracking fairly well.

With respect to ALS availability, there is very little data to display. The one airline operator that has received a Category IIIa certification has shown in his initial data gathering period results to support the certification requirement. The reported results support the reliability prediction but do not allow correlation with the availability estimates of Figure 11. This figure gives a prediction of the Category IIIa ALS availability as an operational day (14 hours) progresses. It is assumed that 10 hours are reserved for maintenance and that the ALS is apparently restored to a fault-free condition by the start of each day. Mature failure rates were used to make the prediction.

The curve of Figure 11 may well represent an upper value on availability for the ALS, but at this time we cannot say. We shall find out, however, as we are now embarking on a program for evaluating availability in cooperation with one overseas operator. And we feel confident that the system will prove out well.

ALS Conclusions

The progress with the L-1011 to date has shown that certifying and supporting the maintenance of a highly redundant automatic landing system can be accomplished in a scheduled manner much like any other flight control system. Further, it is expected that future progress will serve to demonstrate that the redundancy and complexity will not detract from the economic benefits of system utilization.

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1. Hoblit, Frederic M.: Effect of Yaw Damper on Lateral Gust Loads in Design of the L-1011 Transport. AGARD Presentation, the Hague 7-12 October 1973, published in AGARDograph No. 175.

2. Mineck, D. W., Derr, R. E., Lykken, L. O., Hall, J. C.: Avionic Flight Control System for the Lockheed L-1011 TriStar. SAE Presentation for Aerospace Control and Guidance Systems Committee Meeting No. 30, 27-29 September 1972, published by Collins Radio Company, Cedar Rapids, Iowa.

Table 1. - L-1011 Avionic Flight Control System Equipment List

Stability Augmentation System (SAS)

2	Yaw Computers
3	Rate Gyros
2	Aileron Position Sensors (dual)
2	Rudder Position Sensors (dual)

Autopilot/Flight Director System (APFDS)

2	Pitch Computers
2	Roll Computers
2	Pilot's Control Wheels
2	Mode Annunciators
2	Warning Indicators
1	Mode Select Panel (5 modules)
3	Normal Accelerometers
3	Lateral Accelerometers

Speed Control System (SCS)

1	Speed Control Computer
1	Autothrottle Servo
2	Longitudinal Accelerometers

Flight Control Electronic System (FCES)

1	FCES Computer
1	Trim Augmentation Computer
2	Angle of Attack Sensors
2	Stick Shakers
1	Surface Position and Pitch Trim Indicator
10	Surface Position Sensors
2	Control Panels

Table 2. - L-1011 Dutch Roll Characteristics With and Without Yaw SAS

FLIGHT CONDITIONS (MID CG)							DUTCH ROLL MODE DAMPING RATIO AND DAMPED NATURAL FREQ			
							SAS ON		SAS OFF	
CONFIGURATION	SPEED KEAS	MACH NO.	ALTITUDE KFT	WEIGHT KLBS	FLAPS DEG	GEAR	ζ	ω_d HZ	ζ	ω_d HZ
Climb	246	.45	10	404	UP	UP	.32	.13	.09	.15
Climb	356	.65	10	308.5	UP	UP	.72	.14	.12	.22
Climb	358	.8	20	400	UP	UP	.56	.15	.07	.21
Cruise	310	.86	33	350	UP	UP	.45	.18	.10	.20
Cruise	260	.86	37.5	300	UP	UP	.43	.15	.07	.18
Cruise (M_{MO})	352	.90	26.5	300	UP	UP	.55	.21	.11	.24
Dive (M_D)	412	.95	21.5	350	UP	UP	.53	.25	.13	.28
Dive (M_D)	258	.95	42	300	UP	UP	.41	.17	.11	.18
Cruise (1.4 V_S)	221	.74	38	300	UP	UP	.22	.14	.05	.15
Cruise	216	.435	15	308.5	UP	UP	.33	.13	.11	.15
Descent	246	.45	10	308.5	UP	UP	.49	.13	.12	.17
Holding	256	.4	1.5	308.5	UP	UP	.50	.13	.13	.16
Holding	160	.292	10	308.5	DOWN	UP	.29	.10	.08	.13
Approach (1.3 V_S)	139	.21	0	308.5	DOWN	DOWN	.26	.10	.09	.12
LANDING (1.3 V_S)	133	.2	0	308.5	DOWN	DOWN	.24	.09	.09	.12
LANDING (1.3 V_S)	141	.213	0	348	DOWN	DOWN	.21	.09	.06	.12
LANDING (DLC ON)	133	.2	0	308.5	DOWN	DOWN	.26	.09	.10	.12
LANDING (1.4 V_S)	143	.262	10	308.5	DOWN	DOWN	.21	.09	.05	.12

Table 3. - SAS Reliability Summary

Item	No. Of Units per SAS Channel	No. Of Units Per Aircraft	Latest Point Estimate MTBF per Unit	Latest MTBF Estimate @ 90% Confid.	Mature Unit MTBF
Yaw Computer	1	2	10,900	6,800	4,600
Rate Gyro	2*	3*	10,200	6,300	6,400
Aileron Position Sensor	1	2	--- †	47,100	222,000
Rudder Servo	1	2**	--- †	23,500	24,000
Control Panel	1	2**	--- †	23,500	206,000
Hydraulic Source	1	2	5,500/9,600	3,300/4,800	10,000
Electrical Source	2*	3*	--- †	23,500	167,000

* One gyro is shared by each SAS channel as is one electrical source.

** Any elements common to both SAS channels are negligible re MTBF estimates.

† There were no failures in reporting period.

Table 4. - Estimated MTBF's vs MTBF Lower Limits

Item	MTBF Lower Limit	Latest MTBF Point Est.	Mature MTBF
Roll Servo	4,000	*	20,000
Pitch Servo	9,750	*	49,000
Roll Computer	1,675	1,800	3,350
Pitch Computer	1,350	3,400	2,700
Yaw Computer	2,300	10,900	4,600
ILS Receiver	1,750	5,400	3,500
Radio Altimeter	1,750	9,100	3,500
Vertical Gyro	1,860	5,200	3,720
Lateral Accelerometer	31,700	**	63,500
Normal Accelerometer	31,700	**	63,500
Warning Indicator	9,600	9,100	48,000
Aural Warning Unit	30,000	***	150,000
Hydraulic Source	2,000	5,500	10,000

* No reported failures in 54,000 servo flight hours.

** No reported failures in 81,000 accelerometer flight hours.

*** No reported failures in 27,000 flight hours.

Table 5. - Automatic Landing System Major Elements

Item	No. Req.	Remarks
Pitch Computer	2	Each computer is dual channel.
Roll Computer	2	
Yaw Computer	2	
Roll A/P Servo	2	Each servo is in-line monitored.
Pitch A/P Servo	2	
Yaw A/P Servo	2	
Aileron Position Sensor	2	Each sensor is dual.
Rudder Position Sensor	2	" " " "
Yaw Rate Gyro	3	Each has limited in-line monitoring.
Mode Annunciator	2	
Warning Indicator	2	
Mode Select Panel	1	
Normal Accelerometer	3	
Lateral Accelerometer	3	
Attitude Gyro	3	Each has limited in-line monitoring
Radio Altimeter	2	Each has dual outputs with high integrity monitoring.
ILS Receiver	2	
Speed Control Computer	1	Computer is dual channel
Autothrottle Servo	1	Servo is in-line monitored
Longitudinal Accelerometer	2	
FCES Computer	1	Provides for fail-op/fail-pass DLC
DLC Servo	2	Each is in-line monitored
Trim Augmentation Computer	1	Provides for fail-op/fail-pass auto pitch trim.
Angle of Attack Sensor	2	Each has limited in-line monitoring.
Air Data Computer	2	Each has limited in-line monitoring.
Altimeter	2	
IAS/M Indicator	2	
VSI	2	
ADI	2	
HSI	2	
Radio Altitude Indicator	2	
Compass System	2	
Hydraulic Source	2	
Electric Source	3	

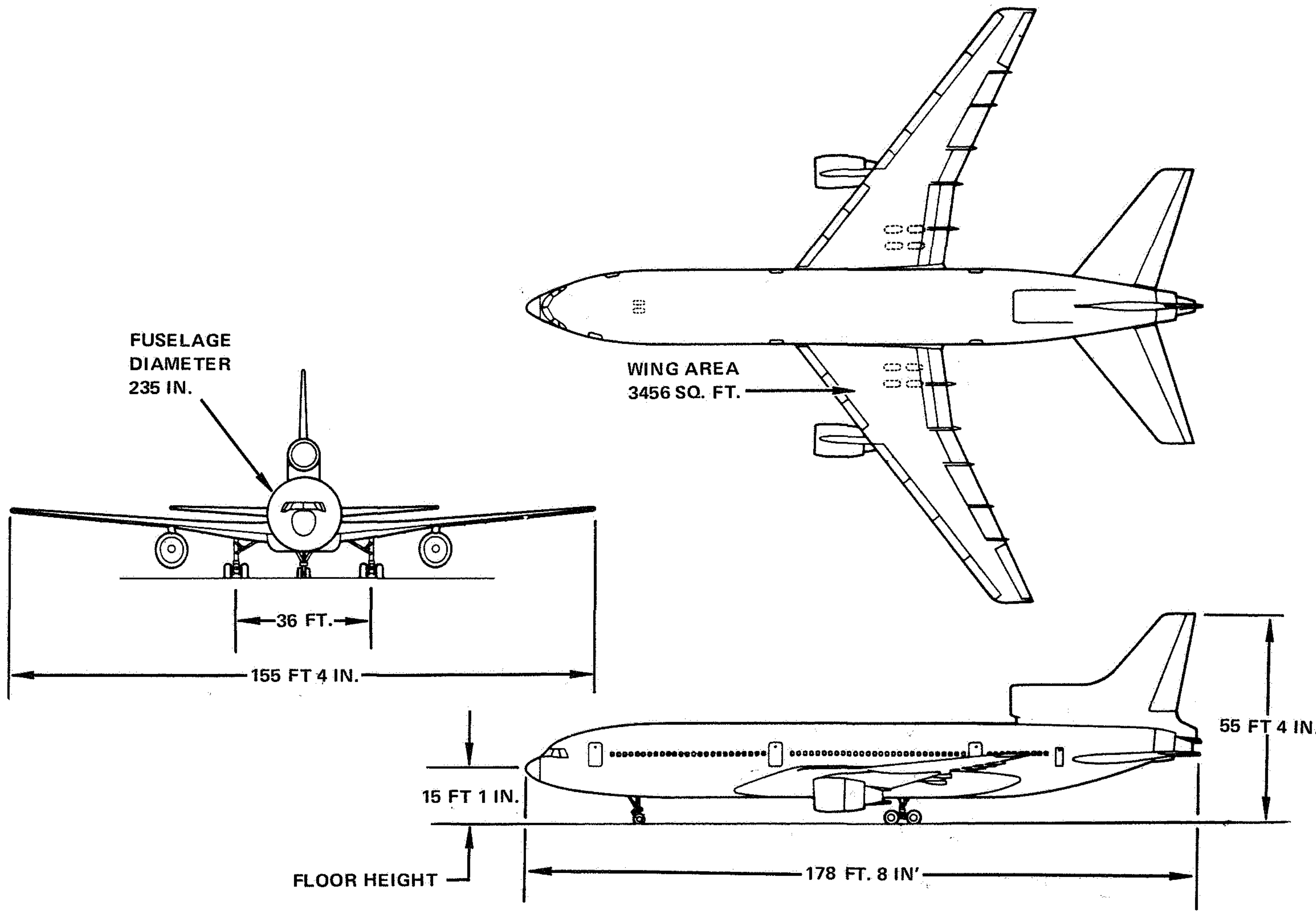

Figure 1 L-1011 General Arrangement

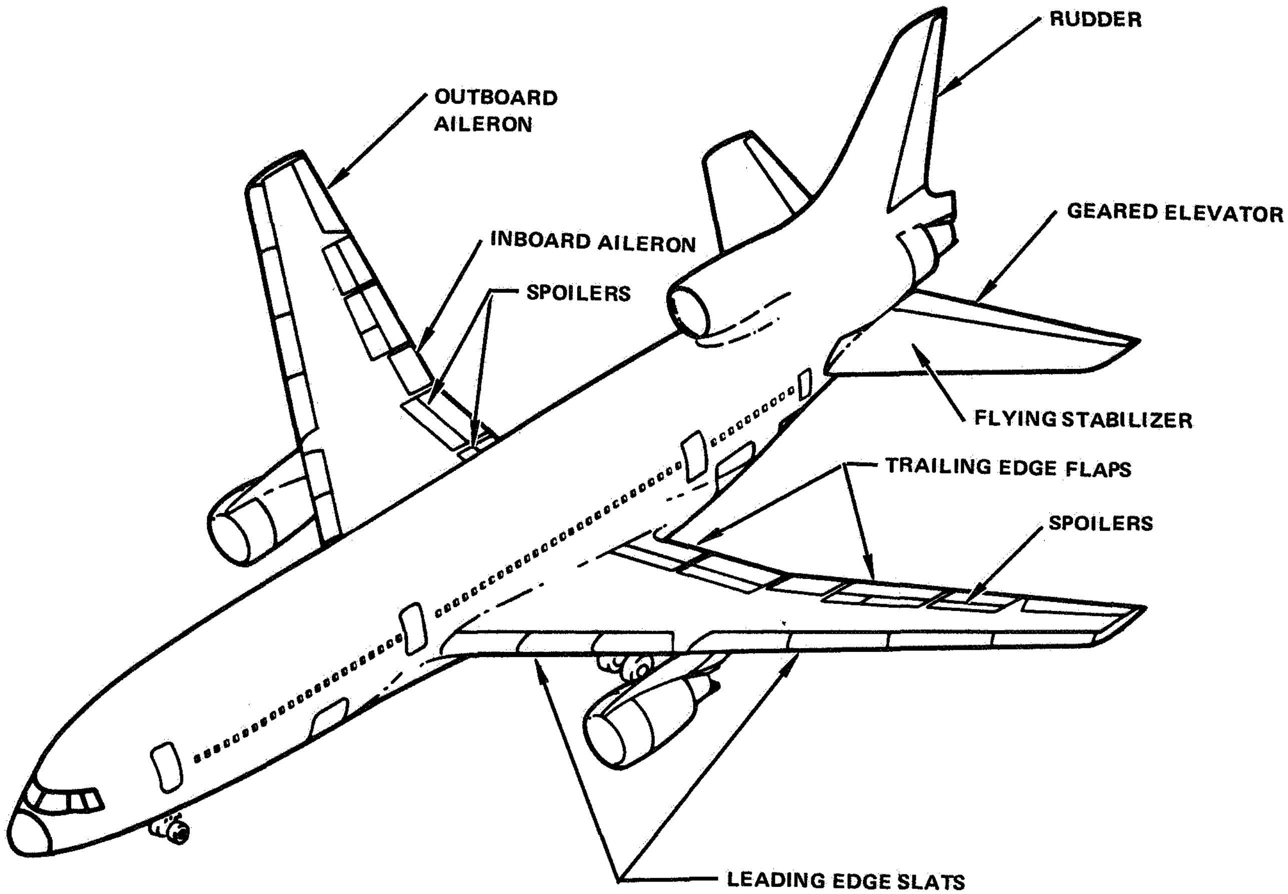

Figure 2 Control Surface Arrangement

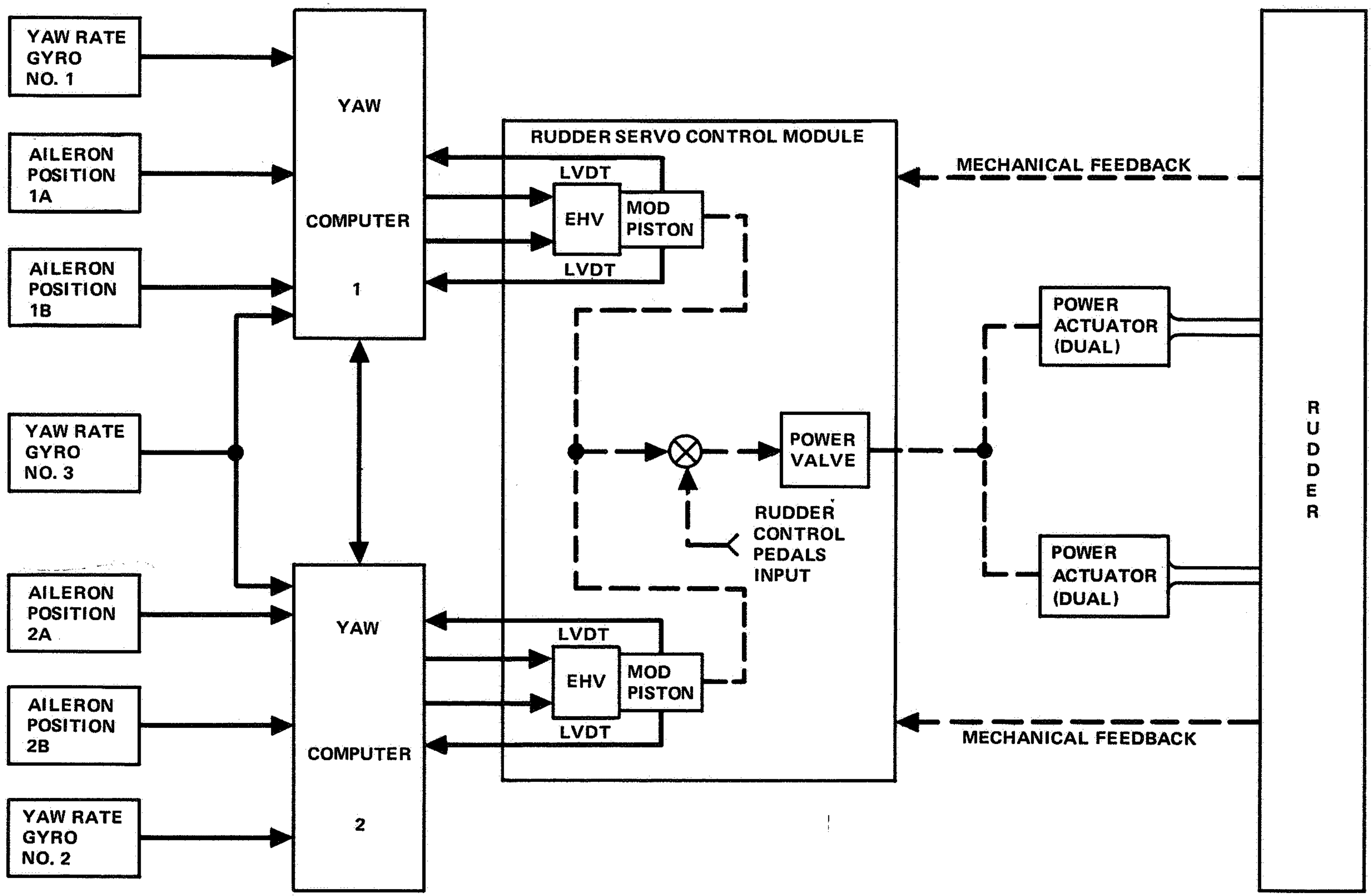

Figure 3 Stability Augmentation System-Cruise Mode

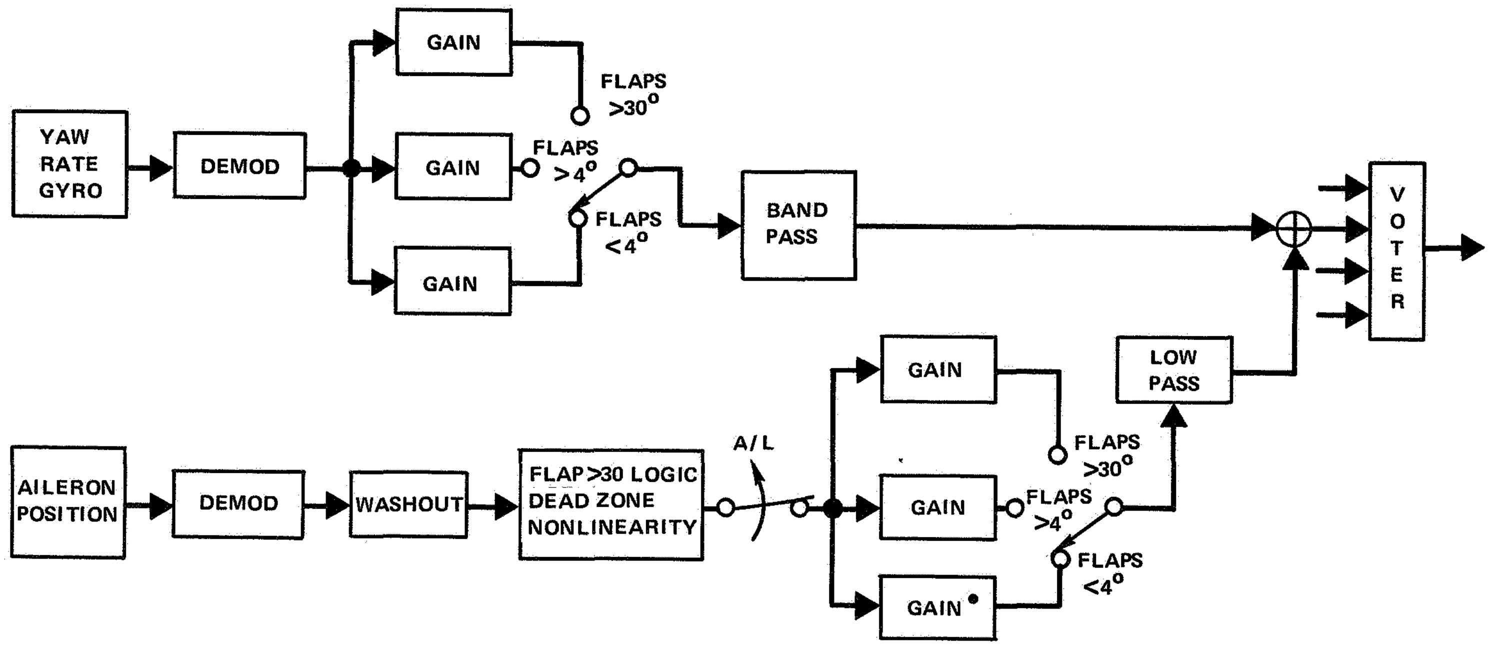

Figure 4 Yaw SAS Cruise Mode Computation

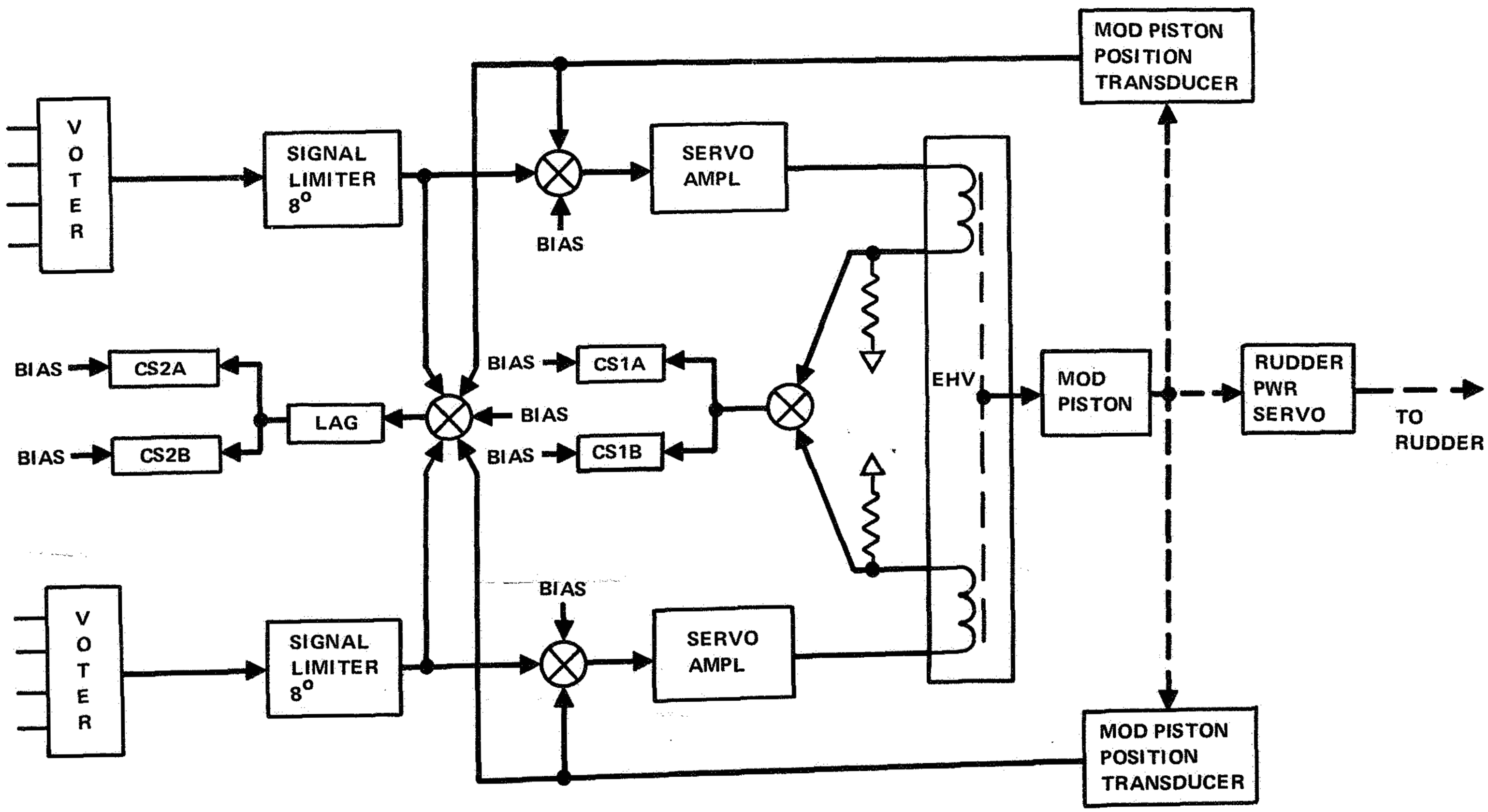

Figure 5 Yaw SAS Servo Loop

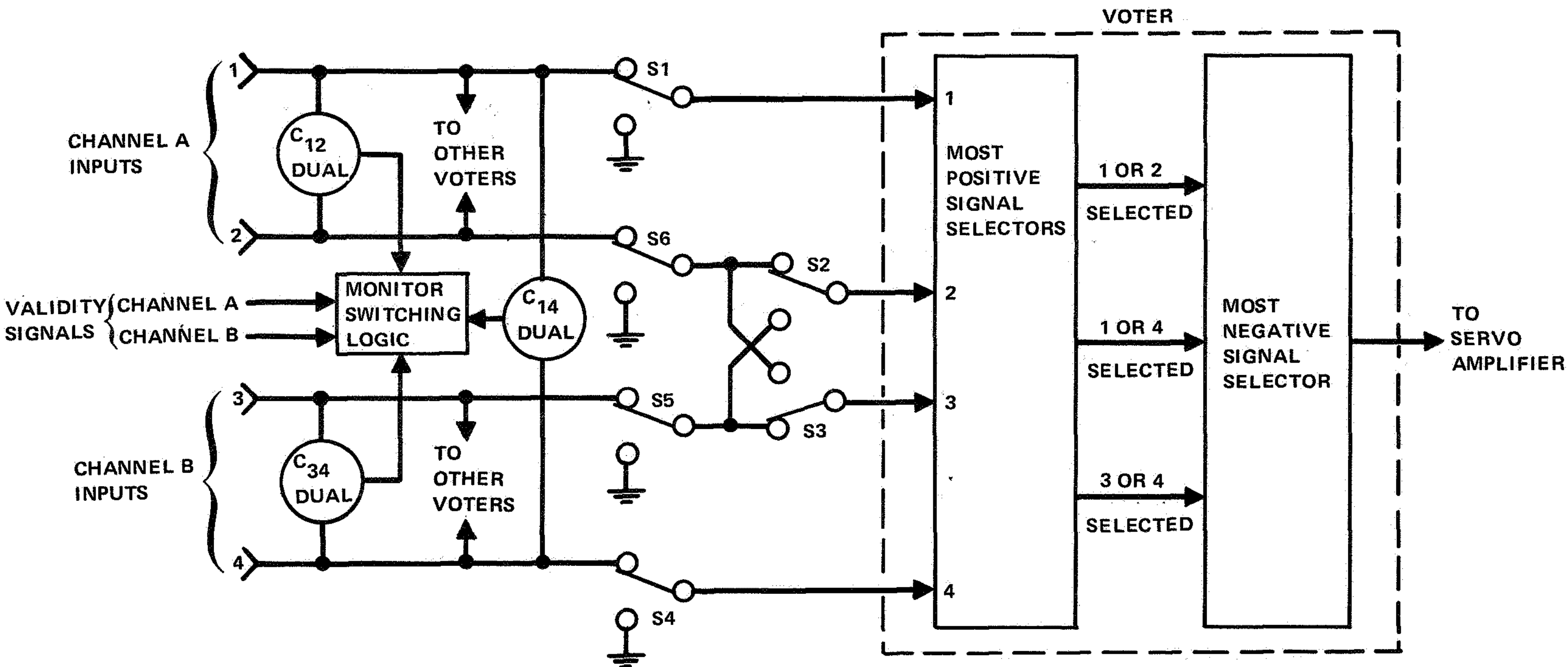

Figure 6 Voter Input Switching

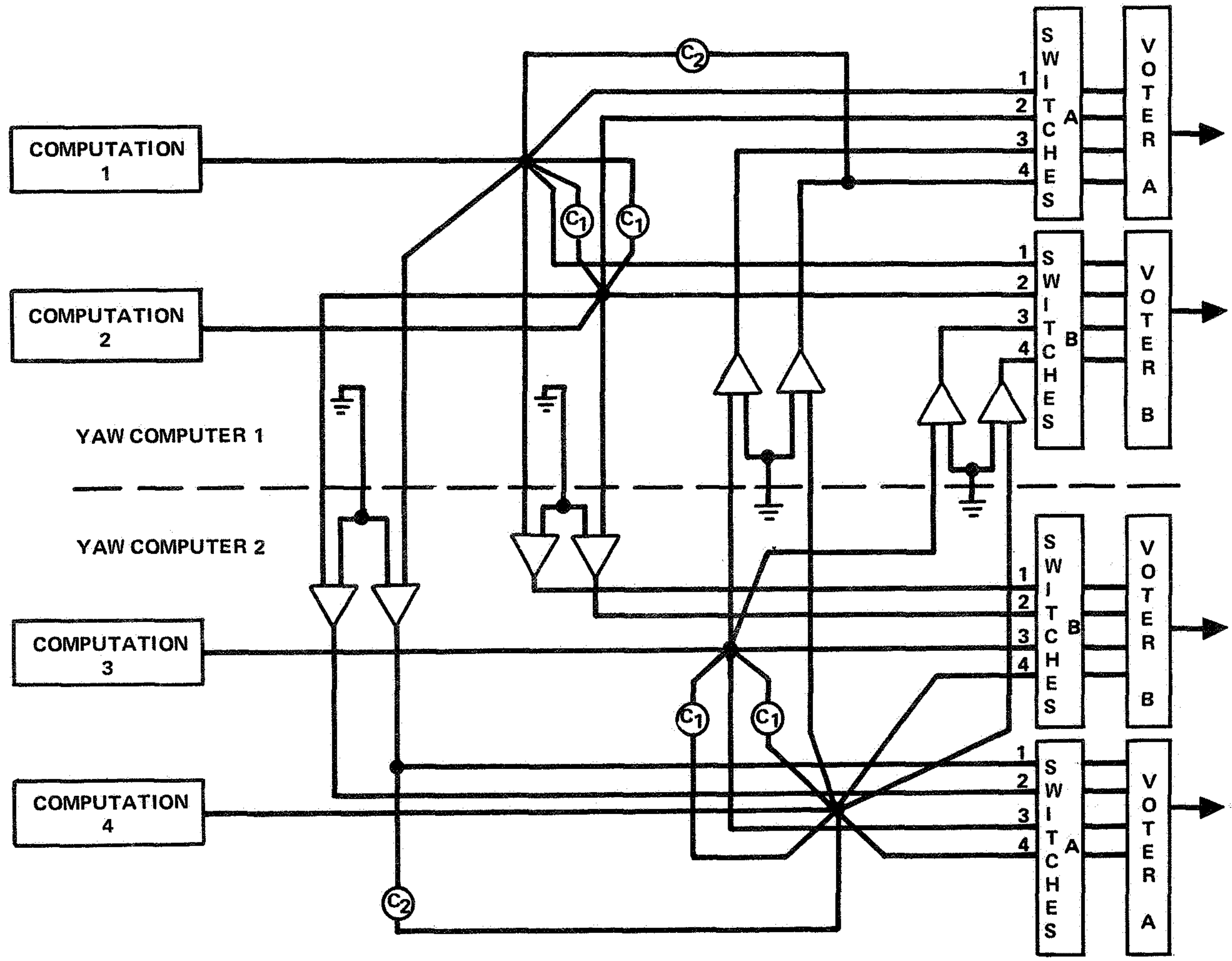

Figure 7 Crossfeeding of Computation Signals

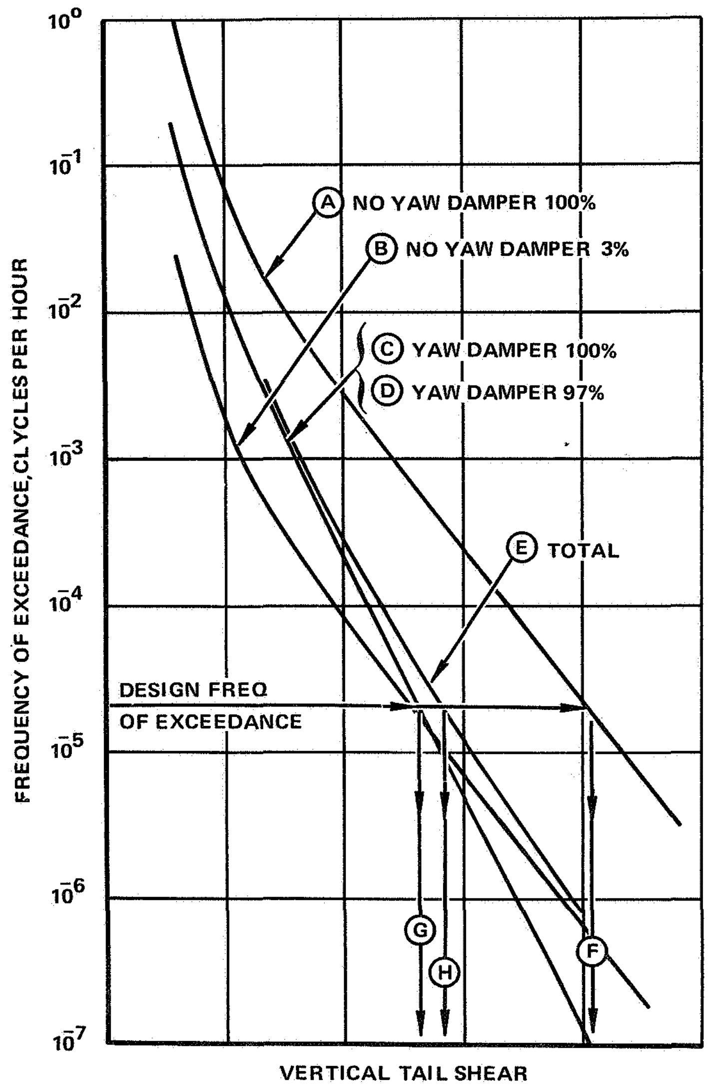

Figure 8 Frequency of Exceedance of Vertical Tail Shear With and Without Yaw Damper

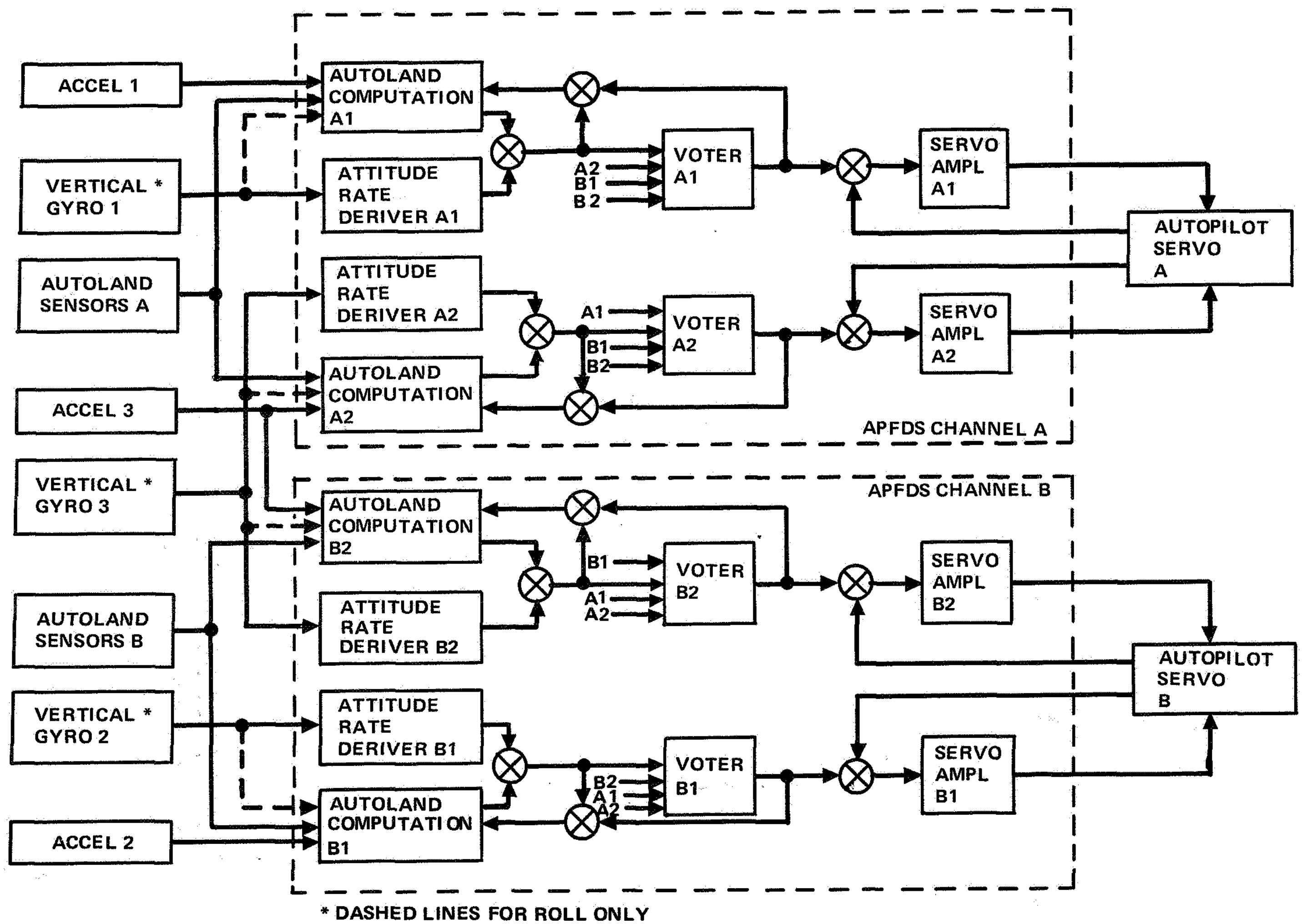

Figure 9 APFDS Approach/Land Mode Configuration

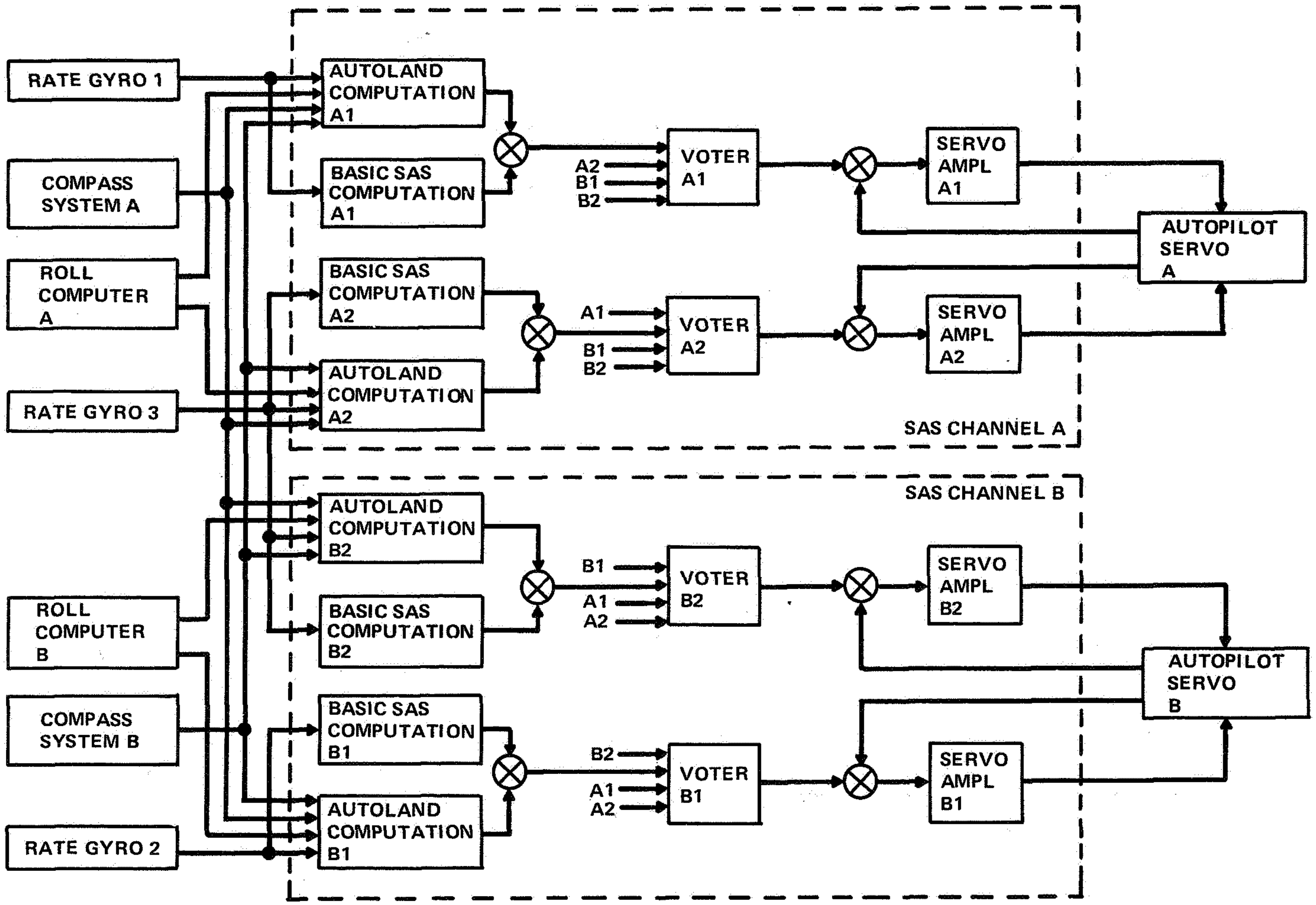

Figure 10 SAS Approach/Land Mode Configuration

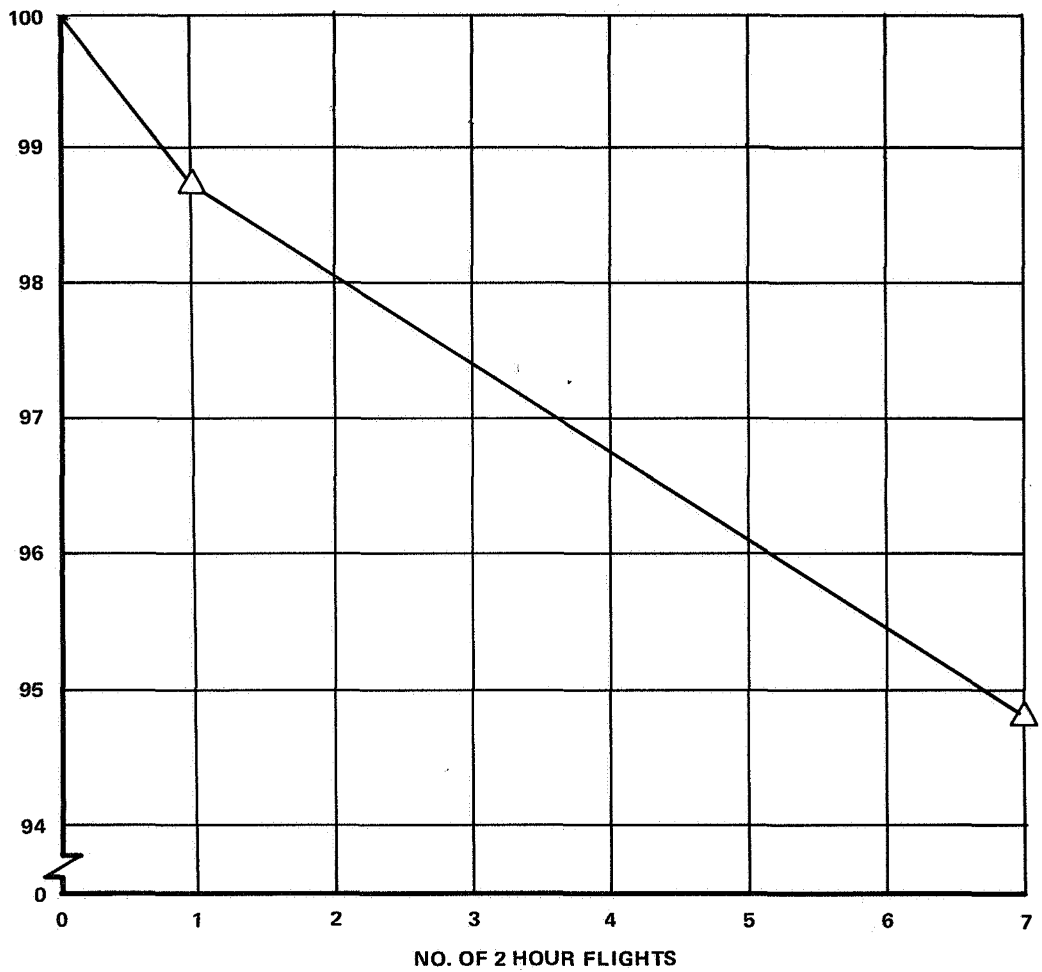

Figure 11 Automatic Landing System Availability - Cat. IIIa