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SPACE SHUTTLE ENGINEERING AND OPERATIONS SUPPORT

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DYNAMIC CONTROL OF SRB THRUST TAILOFF FOR SEPARATION

AVIONICS SYSTEMS ENGINEERING

JUNE 15, 1976

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SRB THRUST TAILOFF CONTROLLABILITY

1.0 SUMMARY

This design note summarizes the results of a study to examine the use of ΔP_c (difference in chamber pressure between SRB engines) as a controlling signal to the FCS during SRB thrust tailoff. In addition, the control capability of the Generalized Attitude Control System (GACS) was compared to that of the baseline. Results indicate that the ΔP_c signal provided essentially no improvement. However, the GACS is considerably better than the baseline in controlling during tailoff disturbances.

2.0 DISCUSSION

During SRB thrust tailoff there exists a potential 3σ thrust mismatch (TMM) of 710K pounds (Figure (1)). This mismatch constitutes a pure yaw force applied below ($+ z_{body}$) the vehicle center of gravity, inducing both yaw and roll moments which must be controlled to allow separation. Figure (2) depicts the separation sequence; note that separation may be inhibited by body rates.

SRB chamber pressures are used as cues to initiate the separation sequence. Therefore chamber pressure (P_c) signals will be available, and since the difference in chamber pressures between SRB 4 and SRB 5 (ΔP_c) is proportional to the thrust mismatch, the suitability of ΔP_c as a flight control system (FCS) input for tailoff control was evaluated.

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Max mismatch - 710 K lb

Total mismatch impulse - 4.5×10^6

16 sec (112.6 to 123.7 sec)

t	Mismatch
112 sec	0 K lb
113	350
114	605
115.7	710
118	477
120	310
122	177
126	0

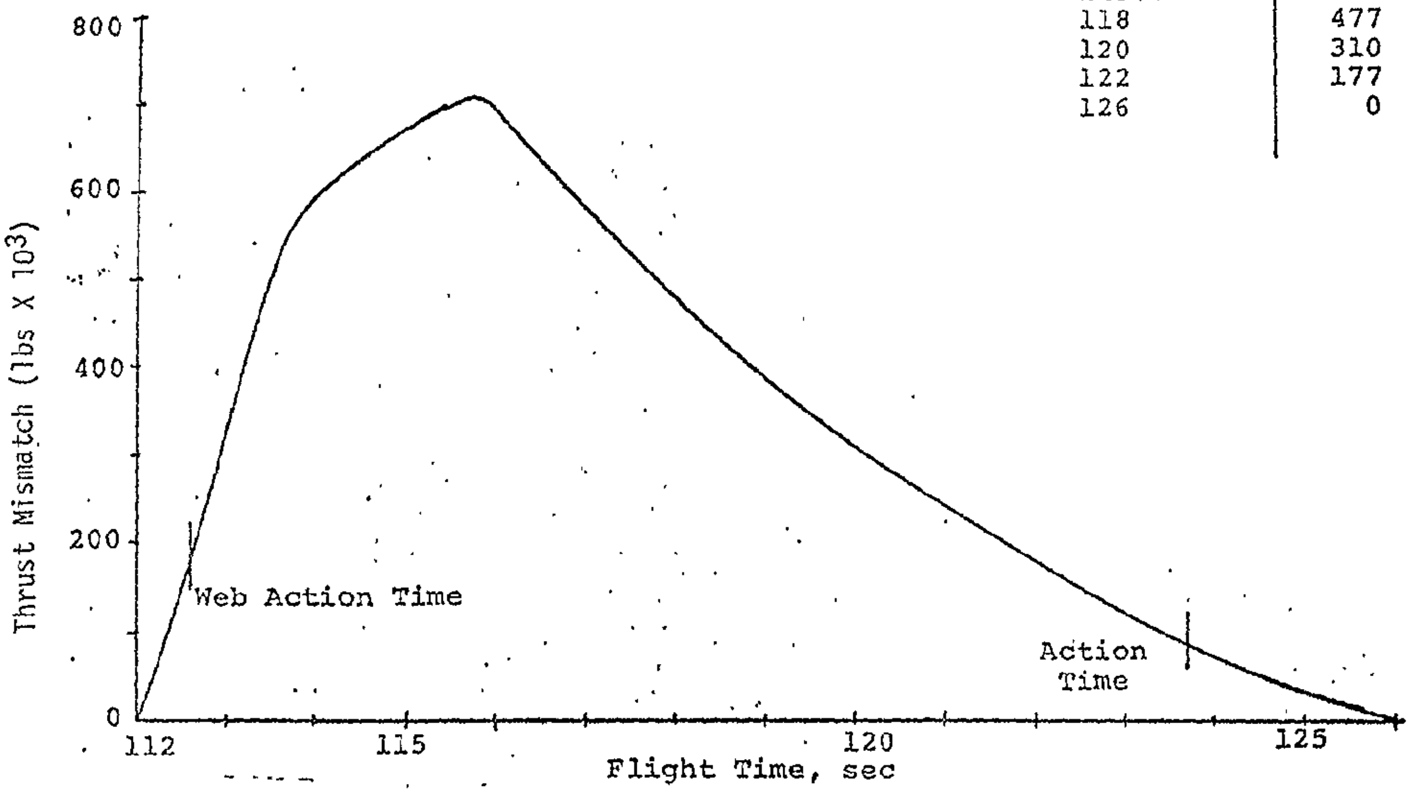

FIGURE 1. Maximum (±3 σ) SRB Tailoff Differential

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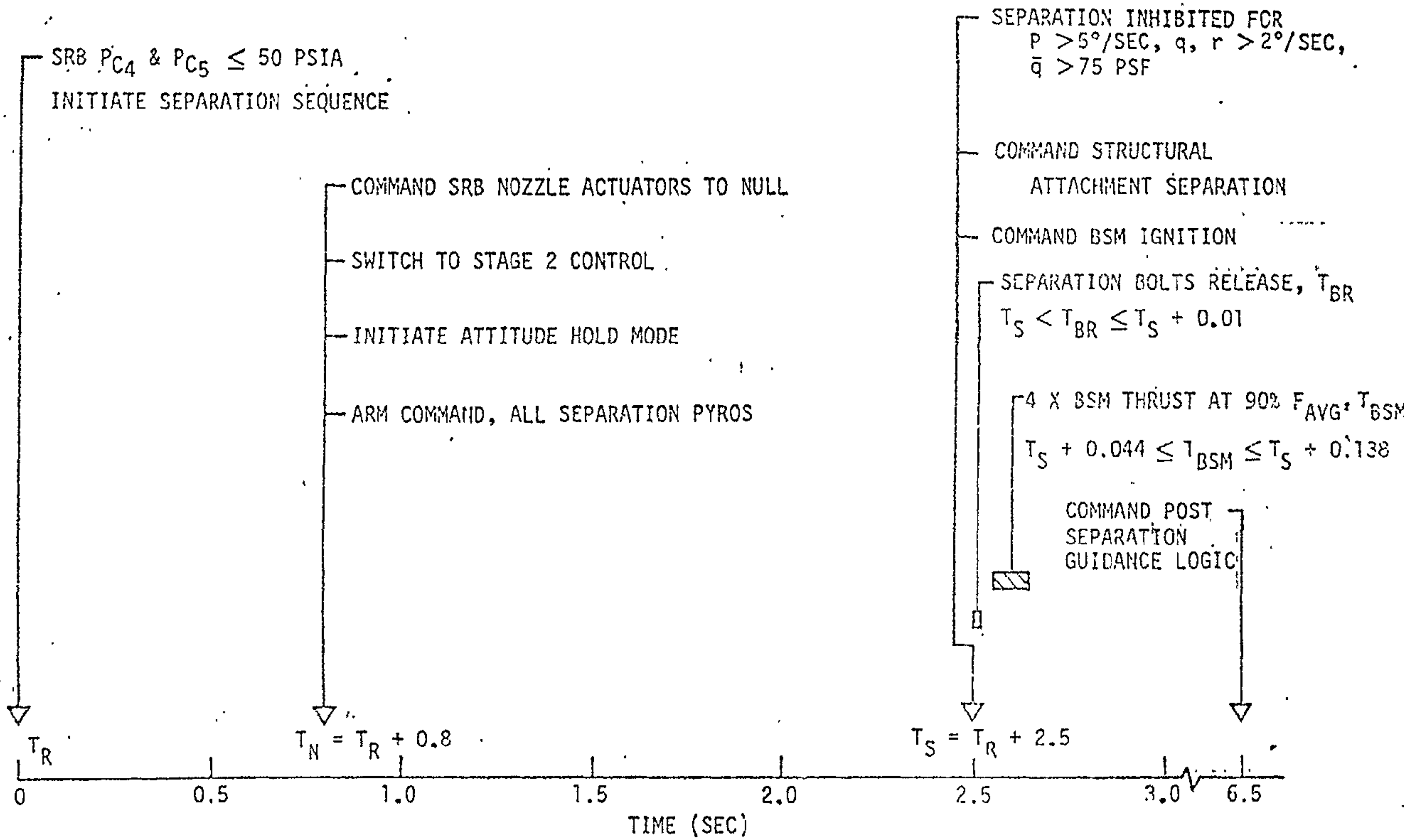

FIGURE 2. Separation Sequence

SRB chamber pressures were derived in the Space Shuttle Functional Simulator (SSFS) by implementing the following linear relation to SRB vacuum thrusts during tailoff:

$$P_C \text{ (psia)} = T_V\text{(lb)}/4127.$$

Using this derived P_C as a staging cue in SSFS results in a nominal separation at t = 123.7 seconds. Since TMM affects the P_C profiles, "nominal" separation with a 3σ TMM is at t = 124.4 seconds.

SRB vector limiting (Reference (A)) was applied for all simulations, providing a functional upper limit on ΔP_C FCS gains.

All cases were simulated on the SSFS for Mission 3A, with the following disturbances:

- o Right crosswind (Az=288.55 deg) with gust at Mach 1.25
- o 3σ TMM (SRB 5 out first)
- o Thrust misalignment (TMA#2 as defined in Section 9.2 of Reference(B)).
- o With and without SSME 3 failed at lift-off.

Two different flight control systems were used, each with and without the ΔP_C input. The first controller, subroutine BLC6A, represents the Baseline FCS (Control 6A, References (B) and (E)), which has a lateral acceleration error path in the yaw channel for tailoff control. For the purpose of this study, this path was replaced by the ΔP_C input with appropriate gain and filter. Preliminary results indicated a need for roll axis control also, so ΔP_C was routed to the roll axis as well. Block diagrams expressing the nominal BLC6A yaw and roll axis configurations and the modified configurations for ΔP_C are shown in Figures (3) and (4).

The second FCS used in this study is the Generalized Attitude Control System (GACS, Reference (C)), modeled by SSFS subroutine GACS. A block diagram illustrating subroutine GACS flow with the ΔP_C input is shown in Figure (5).

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YAW AXIS BL[illegible]K DIAGRAM

ARB BASELINE SYSTEM

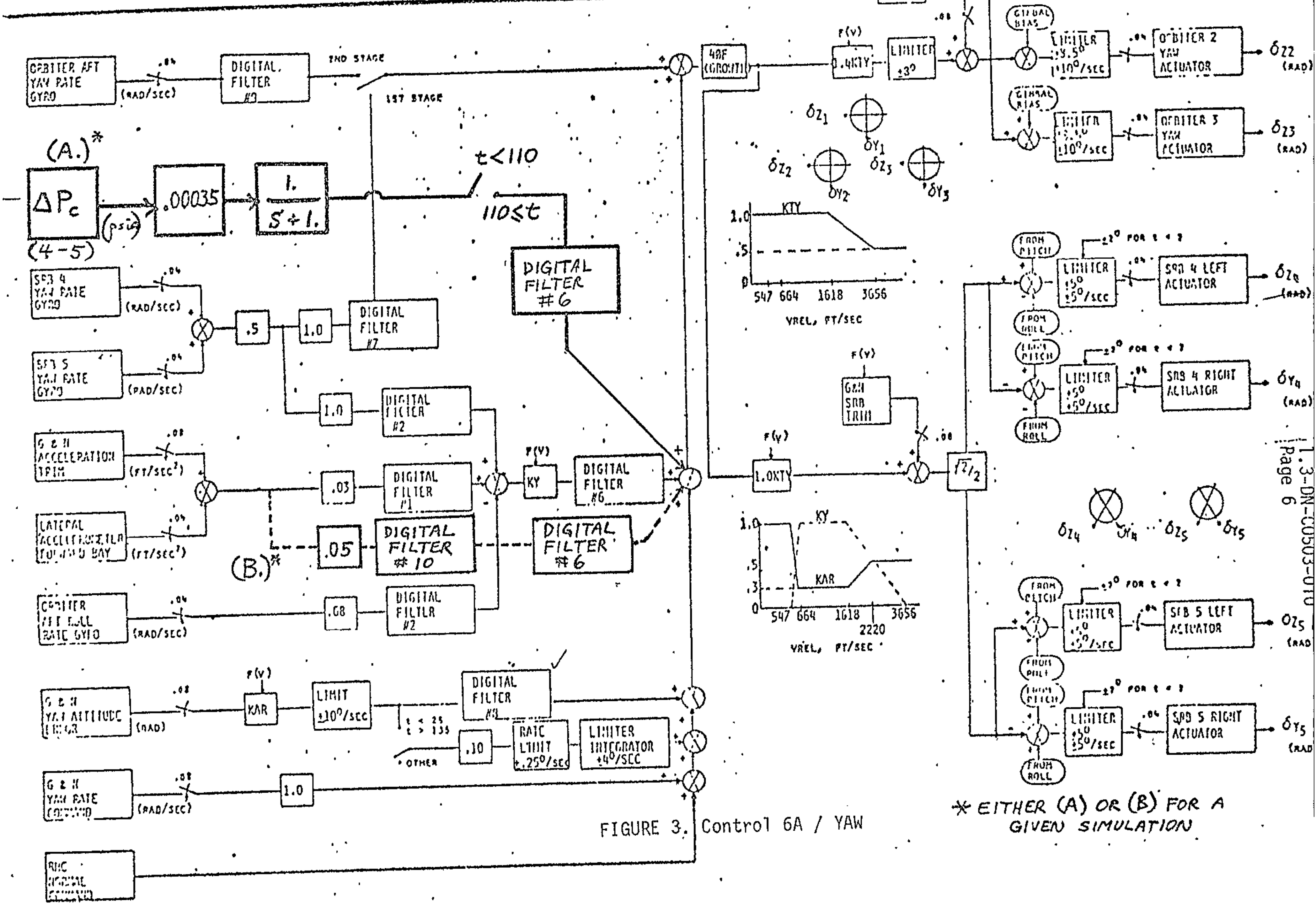

FIGURE 3. Control 6A / YAW

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ROLL AXIS BLOCK DIAGRAM

ARB BASELINE SYSTEM

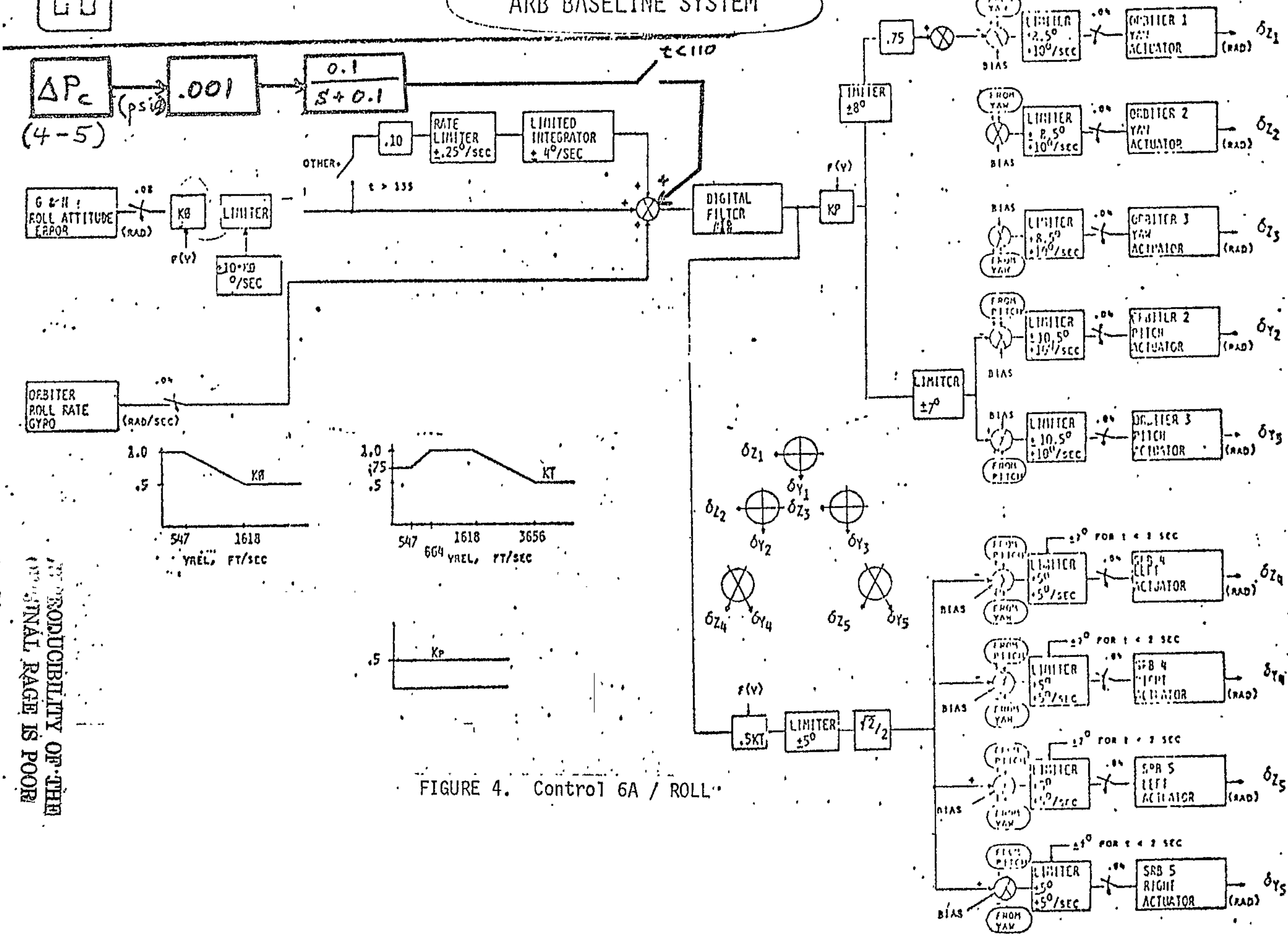

FIGURE 4. Control 6A / ROLL

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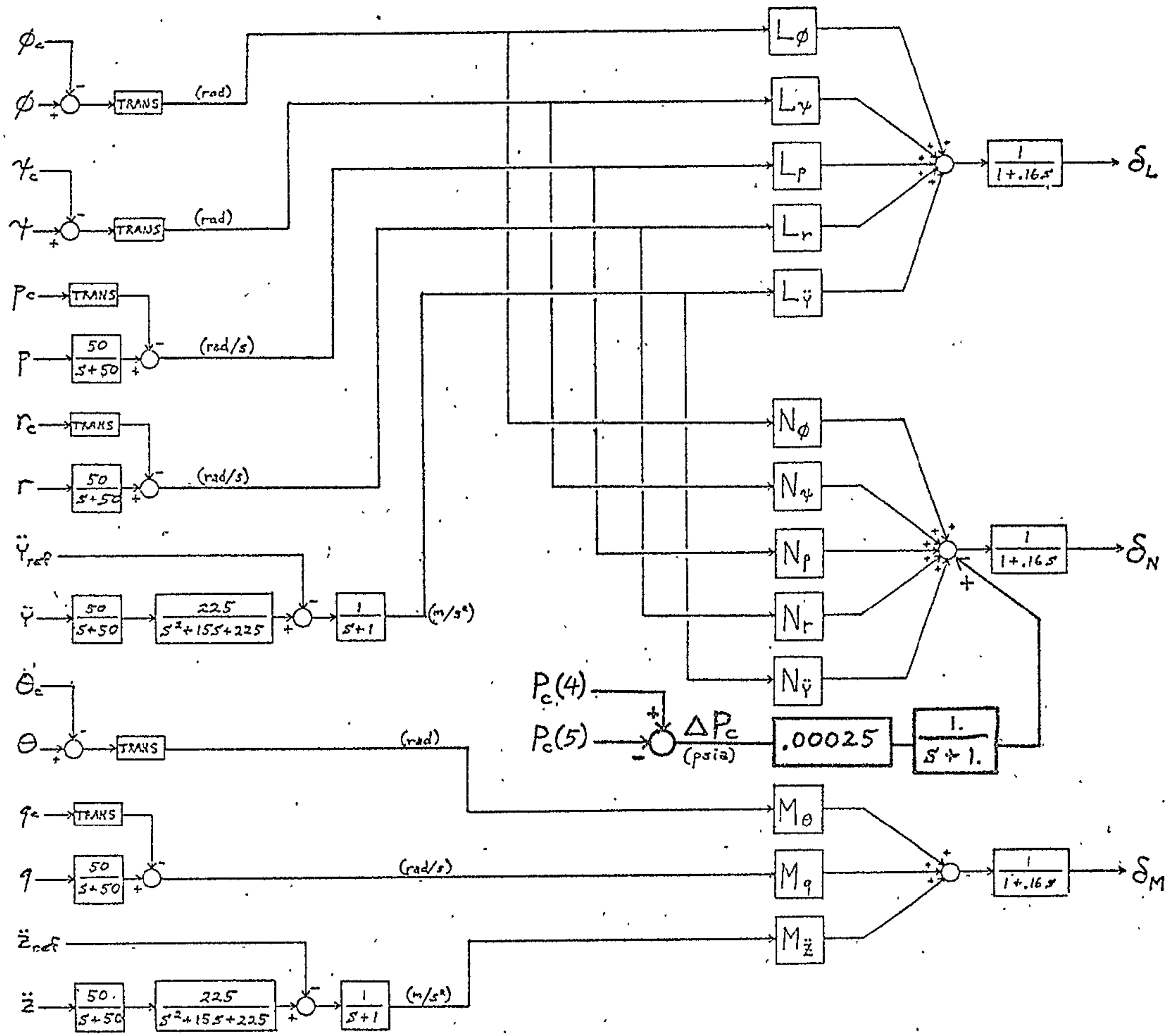

FIGURE 5. GACS ANALYTIC BLOCK DIAGRAM W/ΔPc

Two different sets of GACS control gains were used. The first set, GACS1, maintains a one radian bandwidth in all three control axes throughout first stage. The thirteen control gains, having been calculated to reflect thrust tailoff (no mismatch), increase rapidly beginning at t=115 seconds. This balanced rise of control gains helps to provide the GACS with the necessary authority to retard the growth of roll and yaw body attitude errors and rates during tailoff. The second set of gains, GACS2, was generated to decrease the bandwidths in all three axes toward tailoff to provide greater isolation from low-frequency slosh and bending modes. These decreases in bandwidth result in smaller gain increases at tailoff, thus delegating greater responsibility for tailoff control to the ΔP_C input. The two sets of gains reflect the control characteristics presented in TABLE I. GACS1 gains were calculated based on aerodynamic data presented in Reference (D), with no elevon effects; GACS2 gains include data from Revisions 1 and 2 to Reference (D).

3.0 RESULTS

TABLES II and III list separation conditions for all cases, without and with an engine failure, respectively. To briefly summarize the results:

(1) BLC6A holds body rates to marginally acceptable values (no separation inhibit) even with an engine out, but allows roll attitude error to grow very large.

(2) BLC6A $\omega/\Delta P_C$ shows an improvement in roll attitude error over BLC6A, but an engine out results in delayed separation on yaw rate. The difficulty encountered in using the ΔP_C input effectively with BLC6A is that mixing logic for this FCS is such that a request for negative yaw moment aggravates a request for concurrent negative roll moment, both of which are needed to counteract TMM-generated positive moments. This is illustrated in Figure (6a), which depicts gimbal deflections for a unit yaw command concurrent with a unit roll command. Note that roll authority becomes marginal as SRB thrust decays.

(3) GACS1 performs well with and without engine failure. See the mixing logic counterpart to BLC6A in Figure (6b), which illustrates more orbiter control authority and much more roll authority with a concurrent yaw request.

CONTROL LAW SCHEDULE

t (sec)	GACS1	GACS2
0 - 25	100% A	100% A
25 - 40	↓ A, ↑ LR	↓ A, ↑ LR, ↑ DR
40 - 75	50% DR, 50% LR	60% LR, 30% DR, 10% A
75 - 95	↓ LR, ↑ A	↓ LR, ↑ A
95	50% A, 50% DR	70% A, 30% DR
95 - t_f	↓ DR	↓ DR
t_f+	100% A	100% A
	(t_f=105)	(t_f=115)

BANDWIDTH SCHEDULE

t (sec)	GACS1	GACS2
0 - 115	ω_L = 1.0 rad/s ω_M = 1.0 ω_N = 1.0	ω_L = 0.7 rad/s ω_M = 1.0 ω_N = 1.0
115 - 123	"	↓ ω_L, ↓ ω_M, ↓ ω_N
123+	"	ω_L = 0.5 rad/s ω_M = 0.5 ω_N = 0.5

ζ = 0.7 in all axes for all t

TABLE I. GACS Control Characteristics

- ↑ blend in (up)
- ↓ blend out (down)
- A attitude control
- LR load relief control
- DR drift reduction control
- L roll axis
- M pitch axis
- N yaw axis

		BASELINE (BLC6A) →	$\omega/\Delta P_c$	GACS1 →	$\omega/\Delta P_c$	GACS2 $\omega/\Delta P_c$
h	(ft)	141204	141176	142327	142331	144143
V_{REL}	(ft/s)	4812	4815	4800	4808	4792
γ	(deg)	25.50	25.46	26.09	26.06	26.67
α	(deg)	5.3	4.1	1.0	1.2	3.3
β	(deg)	-11.9	-12.3	-9.0	-8.4	-9.3
P	(deg/s)	-0.27	-0.35	-0.61	0.15	1.31
q	(deg/s)	-0.05	-0.22	-0.16	-0.13	0.20
r	(deg/s)	1.37	1.62	0.96	0.10	0.28
ϕerr	(deg)	17.04	8.50	-0.23	0.11	-2.35
Θerr	(deg)	2.58	3.23	1.15	1.14	3.11
ψerr	(deg)	0.92	2.26	0.33	0.27	1.53

TABLE II. GACS vs BASELINE,
SEPARATION CONDITIONS (t=124.4)

- TMM
- TMA
- RXW

		BASELINE (t = 124.4)	$\omega/\Delta P_C$ (t = 125.3)	GACS1 (t = 124.4)	$\omega/\Delta P_C$ (= 124.4)	GACS2 $\omega/\Delta P_C$ t = 124.4)
h	(ft)	128446	130245	141996	142001	135940
V_{REL}	(ft/s)	3638	3640	3369	3377	3509
γ	(deg)	35.01	34.67	45.26	45.17	39.63
α	(deg)	4.2	3.5	2.2	3.8	0.6
β	(deg)	-14.9	-18.4	-12.0	-13.8	-15.1
P	(deg/s)	4.50	3.90	-0.35	-0.10	0.99
q	(deg/s)	-0.34	-0.25	-0.99	-0.78	-0.32
r	(deg/s)	1.72	1.97	0.63	0.49	1.72
ϕerr	(deg)	34.64	23.49	0.33	-0.71	-4.35
Θerr	(deg)	-1.03	1.00	-0.59	1.13	1.87
ψerr	(deg)	2.53	5.15	0.18	1.48	3.81

TABLE III. GACS vs BASELINE,
SEPARATION CONDITIONS

- TMM
- TMA
- RXW
- FAIL 3@ L.Ø.

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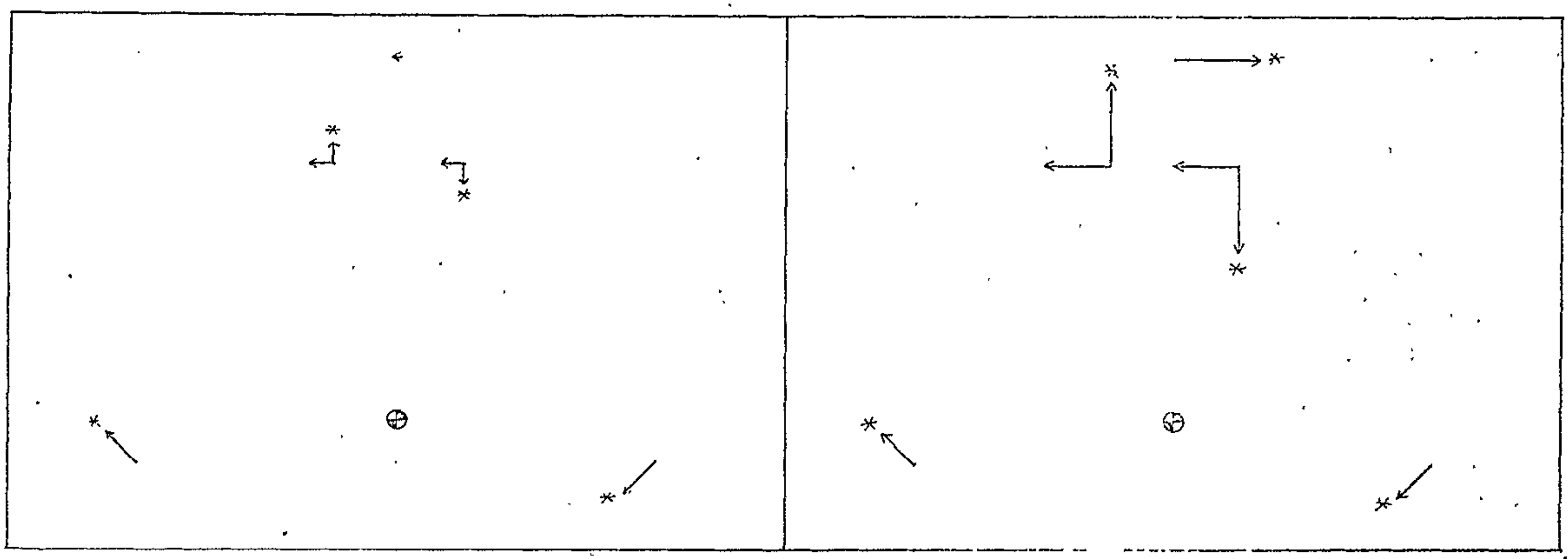
*CONTRIBUTES TO NET −L (DESIRED) ; OTHERS CONTRIBUTE TO NET +L



(a). Control 6A

(b). GACS

FIGURE 6. FCS Mixing Logic Configurations for Unit Yaw Command Concurrent With Unit Roll Command

(4) GACS1 $\omega/\Delta P_c$ performs better than GACS for no engine out, but allows increased sideslip angle and body attitude errors with an engine out.

(5) GACS2 $\omega/\Delta P_c$ performs well for no engine out, but allows increased sideslip angle and marginal yaw rate with an engine out.

The SRB vector limit of approximately 7 degrees (function of chamber pressure and actuator deflection polarities for each SRB), which is applied from shortly after lift-off until P_{c4} and P_{c5} < 200 psia, was never encountered. However, the 3.2° vector limit (after P_{c4} and P_{c5} < 200 psia) was encountered in several of the no-failure cases and in all engine-out cases.

Appendix A contains illustrations of body attitude errors, body rates, and sideslip angle from 100 seconds to separation for the various FCS configurations.

4.0 CONCLUSIONS

(1) ΔP_c is not an improvement over $\ddot{Y}err$ as an FCS input for tailoff control for the Baseline system due to difficulties in translating moment requests by the FCS into gimbal deflections through the mixing logic, especially with an engine failed.

(2) GACS shows significantly better dynamic response than the Baseline to tailoff disturbances, even with no input for TMM compensation.

(3) GACS bandwidths for desired tailoff control must remain around one radian.

(4) The SRB vector limit of 3.2° at tailoff remains a firm requirement.

5.0 RECOMMENDATIONS

(1) Perform a frequency domain analysis on the GACS with flexible body dynamics at a tailoff time point.

(2) Continue time domain simulations on SSFS to find control law gains for GACS to provide better payload performance.

6.0 REFERENCES

A. Ascent Flight Control FSSR. Rockwell Int. Document SD76-SH-0008, April 9, 1976.

B. Space Shuttle FCS Data Book, Vol I. RI Document SD73-SH-0097-1E, November, 1975.

C. A Generalized Attitude Control System for the Space Shuttle Ascent Mission Phase. NASA JSC-09198, November 1974.

D. Aerodynamic Design Data Book, Vol II. RI SD72-SH-0060-2H, February, 1975.

E. Ninth Ascent Flight Control and Structures Integration Panel Meeting, May 11, 1976.

APPENDIX A.

O GRAPHICAL COMPARISON OF:

(1) SIDESLIP ANGLE

(2) BODY RATES

(3) BODY ATTITUDE ERRORS

O FOR THE FOLLOWING FCS CONFIGURATIONS:

(1) BASELINE ($\omega/\ddot{Y}err$)

(2) BASELINE $\omega/\Delta P_C$

(3) GACS1

(4) GACS1 $\omega/\Delta P_C$

(5) GACS2 $\omega/\Delta P_C$

O WITH TMM, TMA, RXW, AND:

(1) NO ENGINE FAILURES

(2) SSME #3 FAILED AT LIFT-OFF

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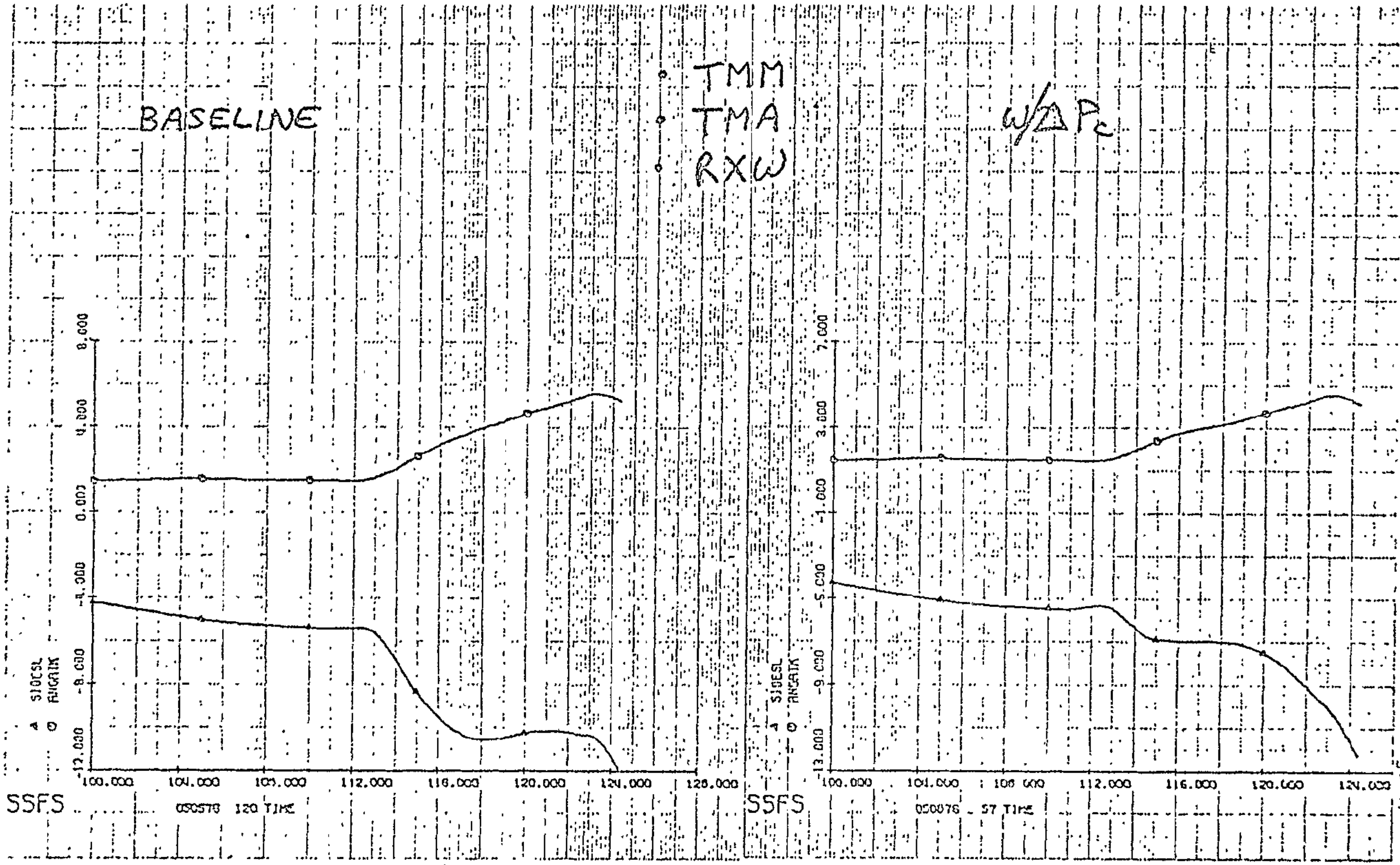
α, β (deg) vs TIME (s)



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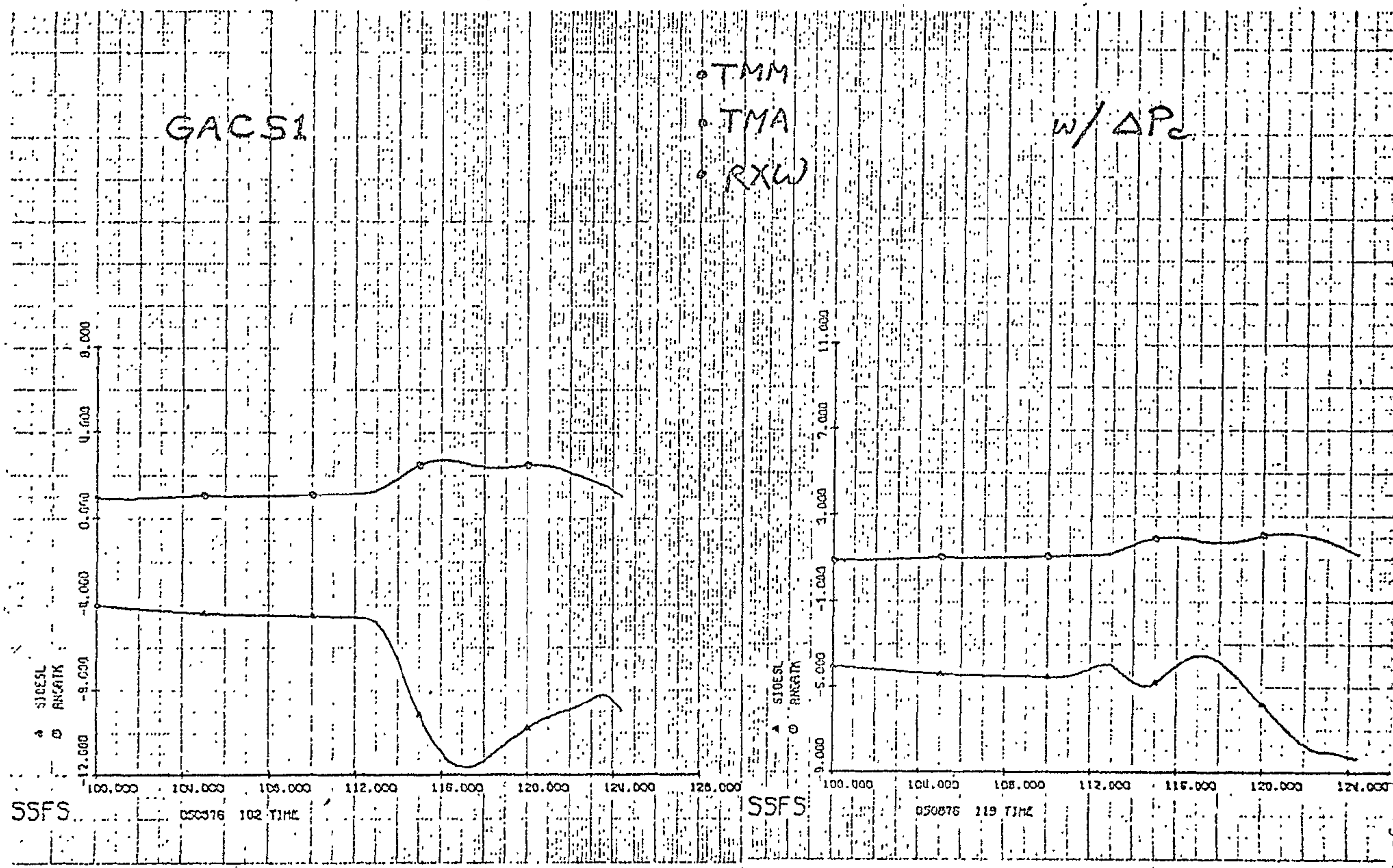
α, β (deg) vs TIME (s)



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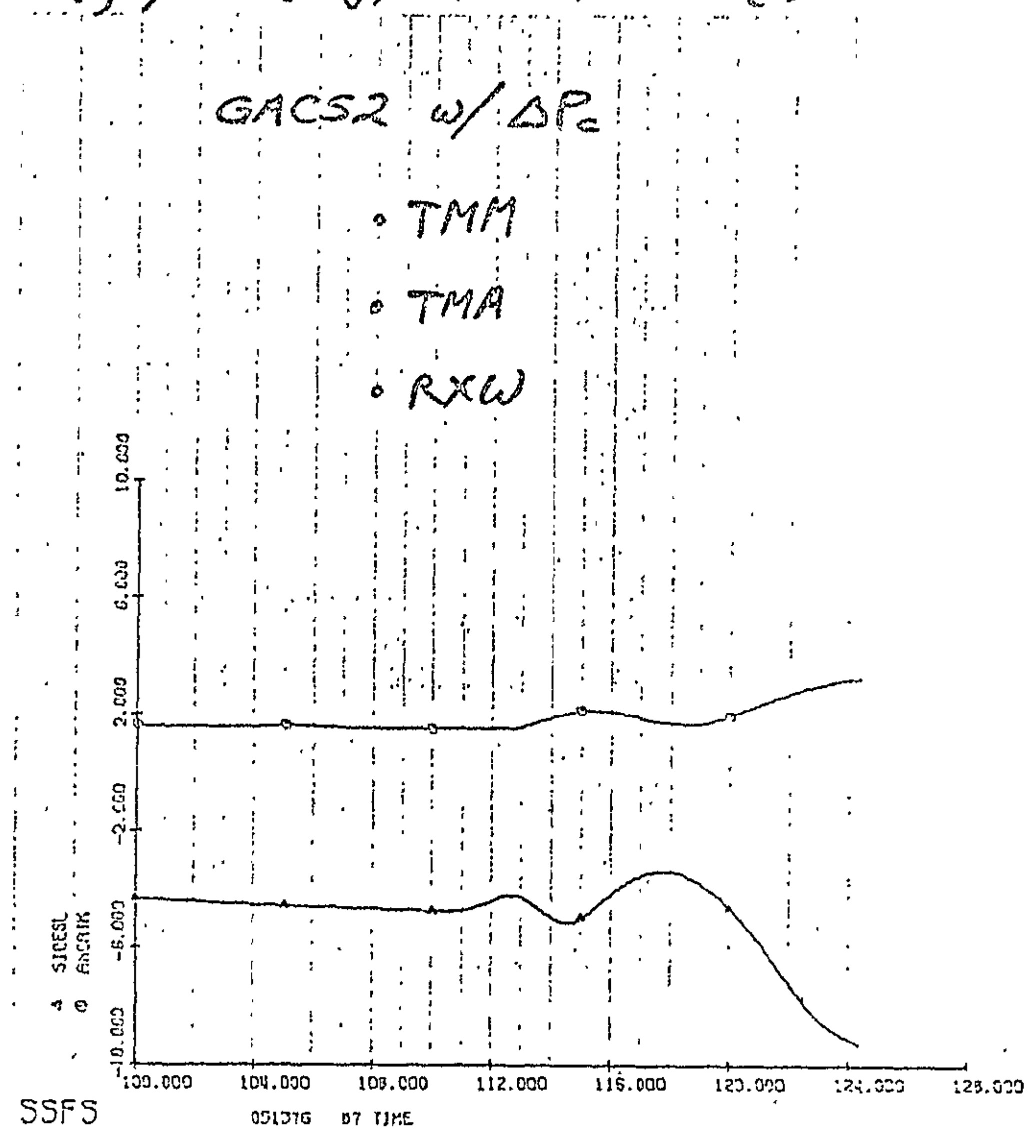
α, β (deg) vs TIME (s)



SSFS

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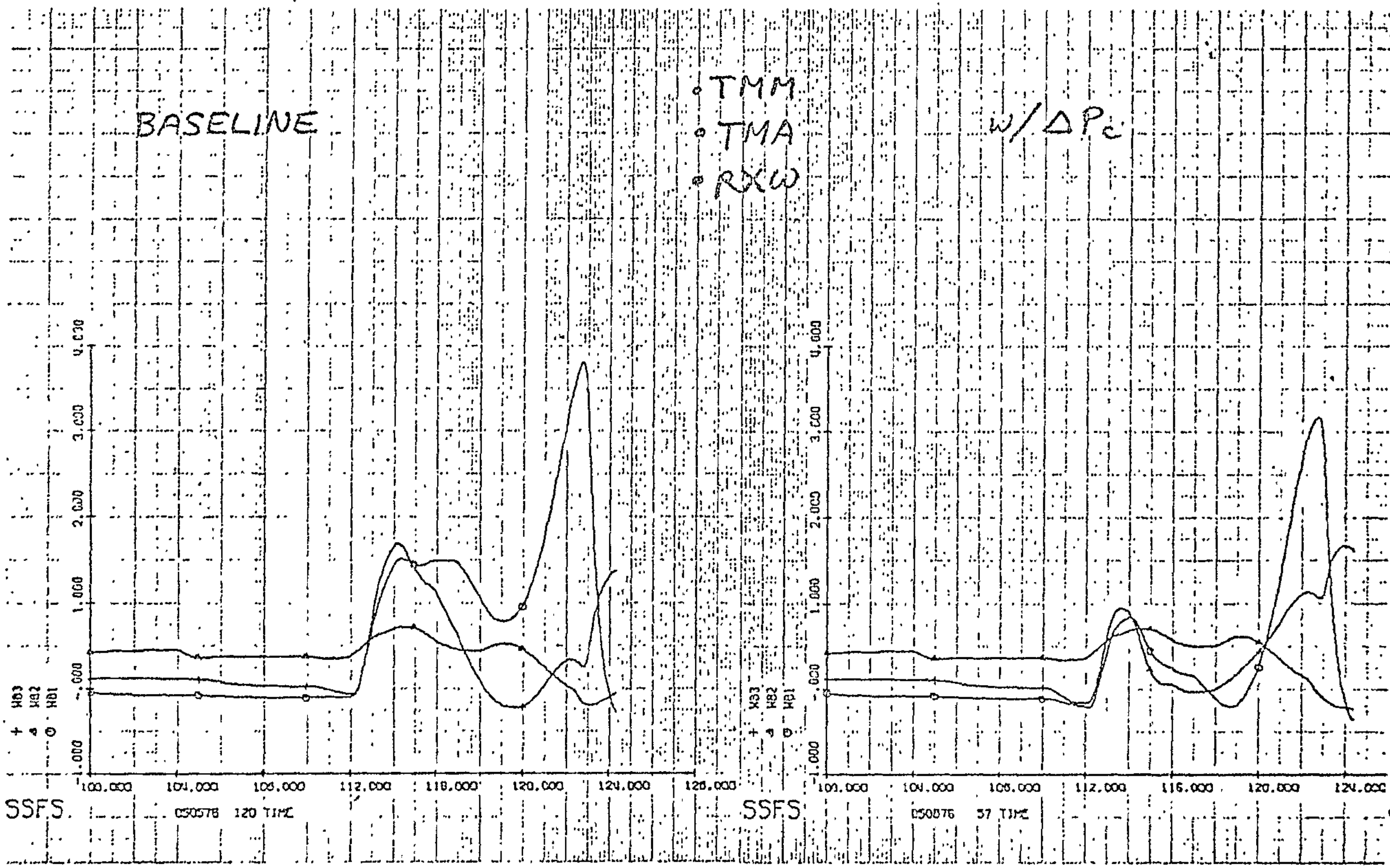
BODY RATES (deg/s) vs TIME (s)



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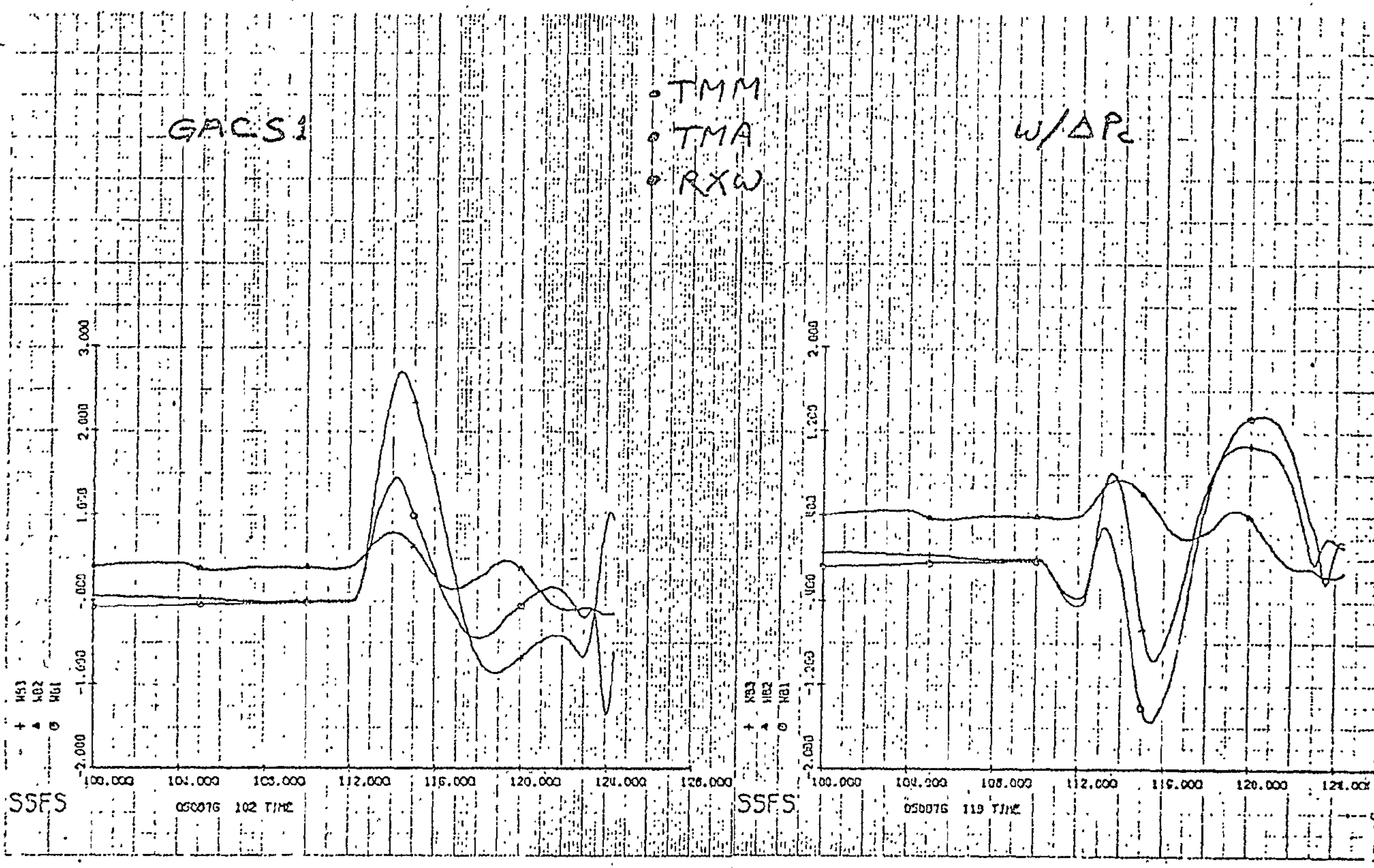
BODY RATES (deg/s) vs TIME (s)



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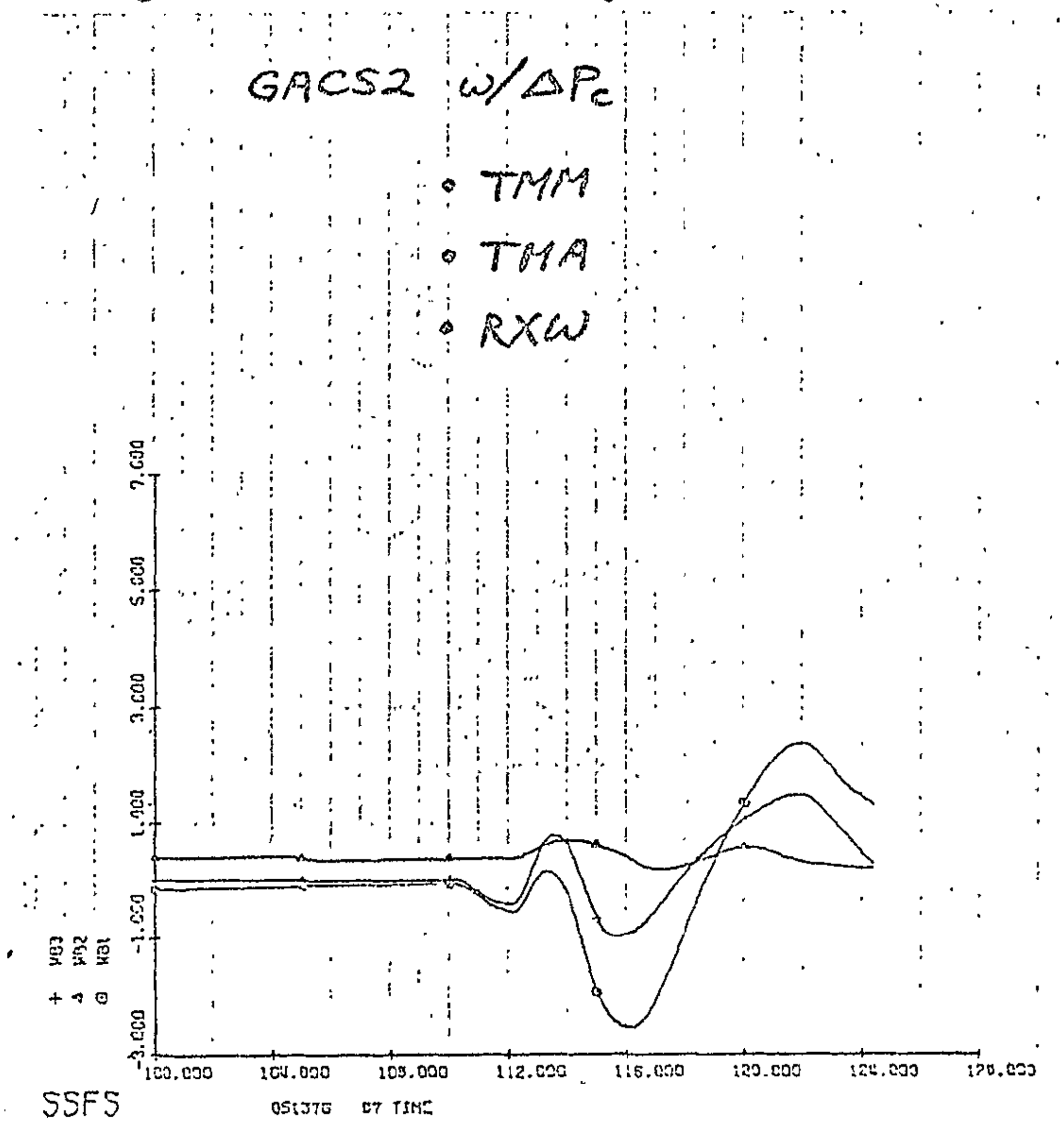
BODY RATES (deg/s) vs TIME (s).



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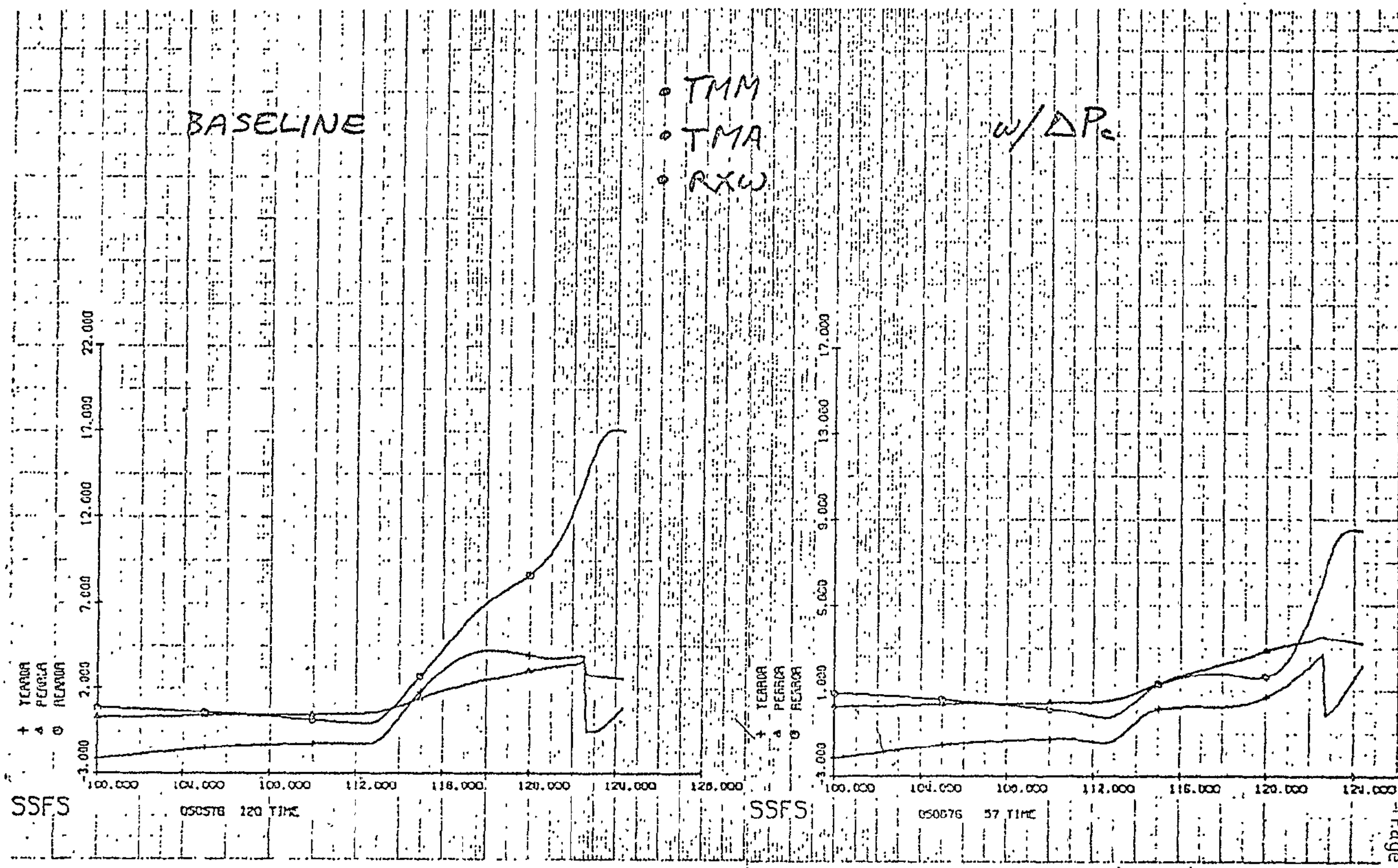
BODY ATTITUDE ERRORS (deg) vs TIME (s)



WLW
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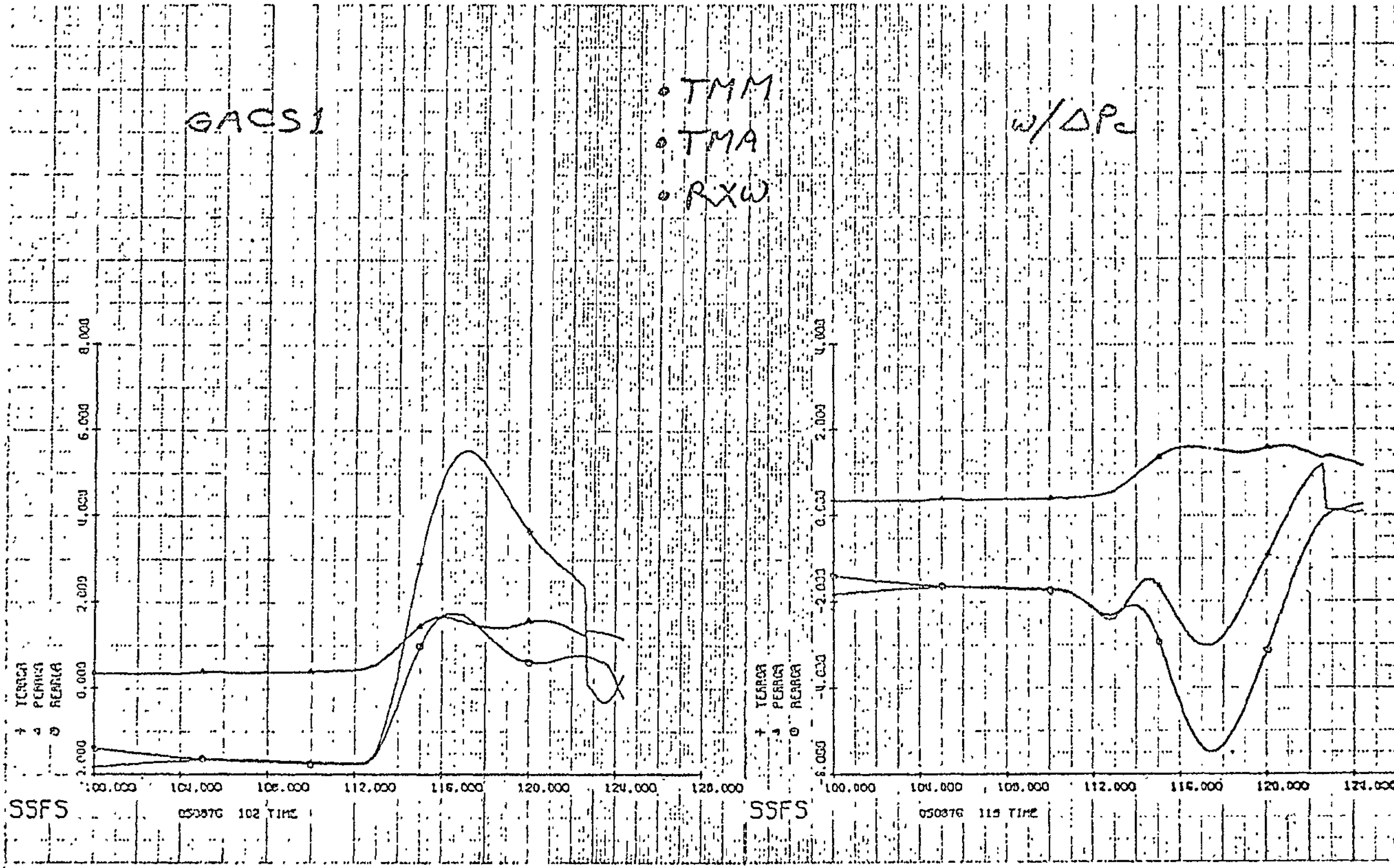
BODY ATTITUDE ERRORS (deg) vs TIME (s)



wLW
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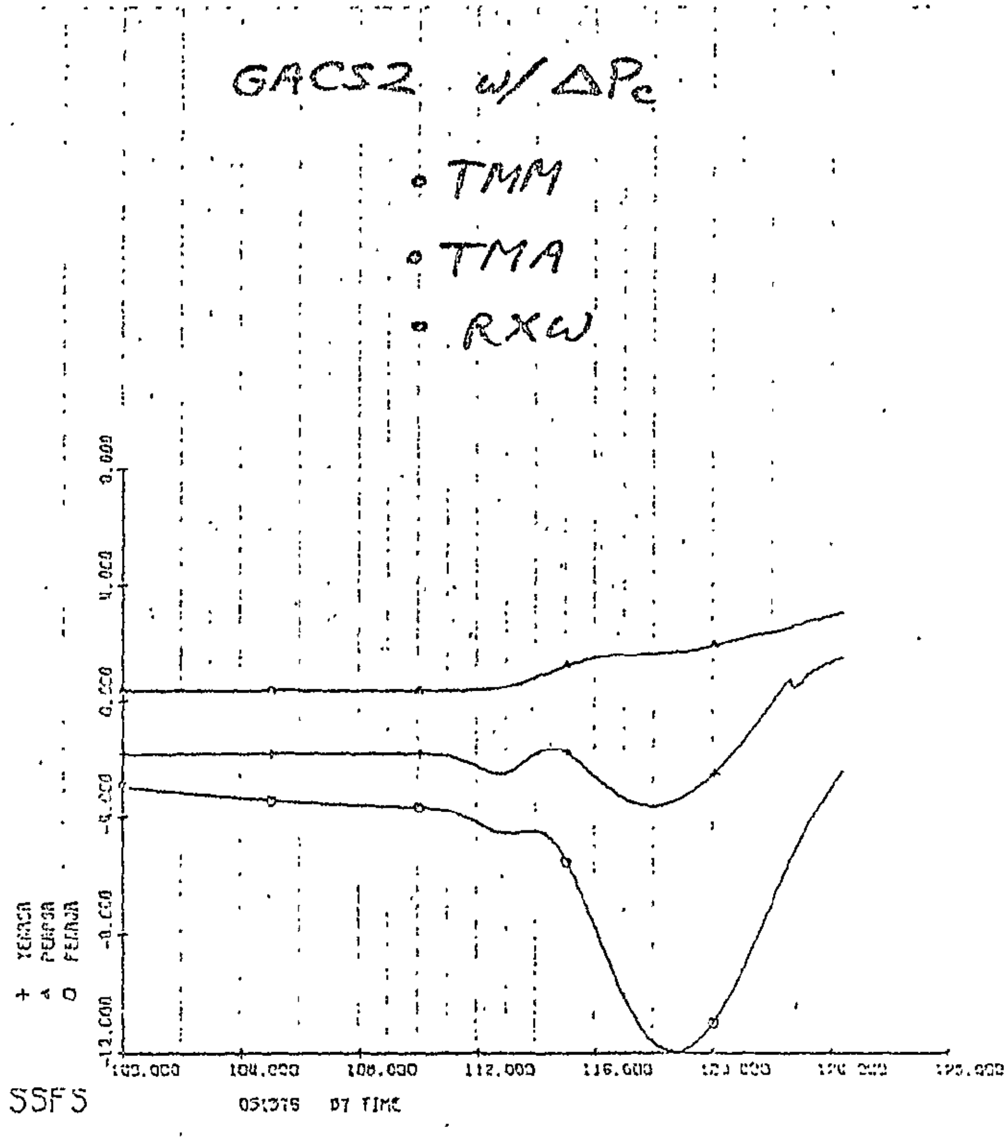
BODY ATTITUDE ERRORS (deg) vs TIME (s)



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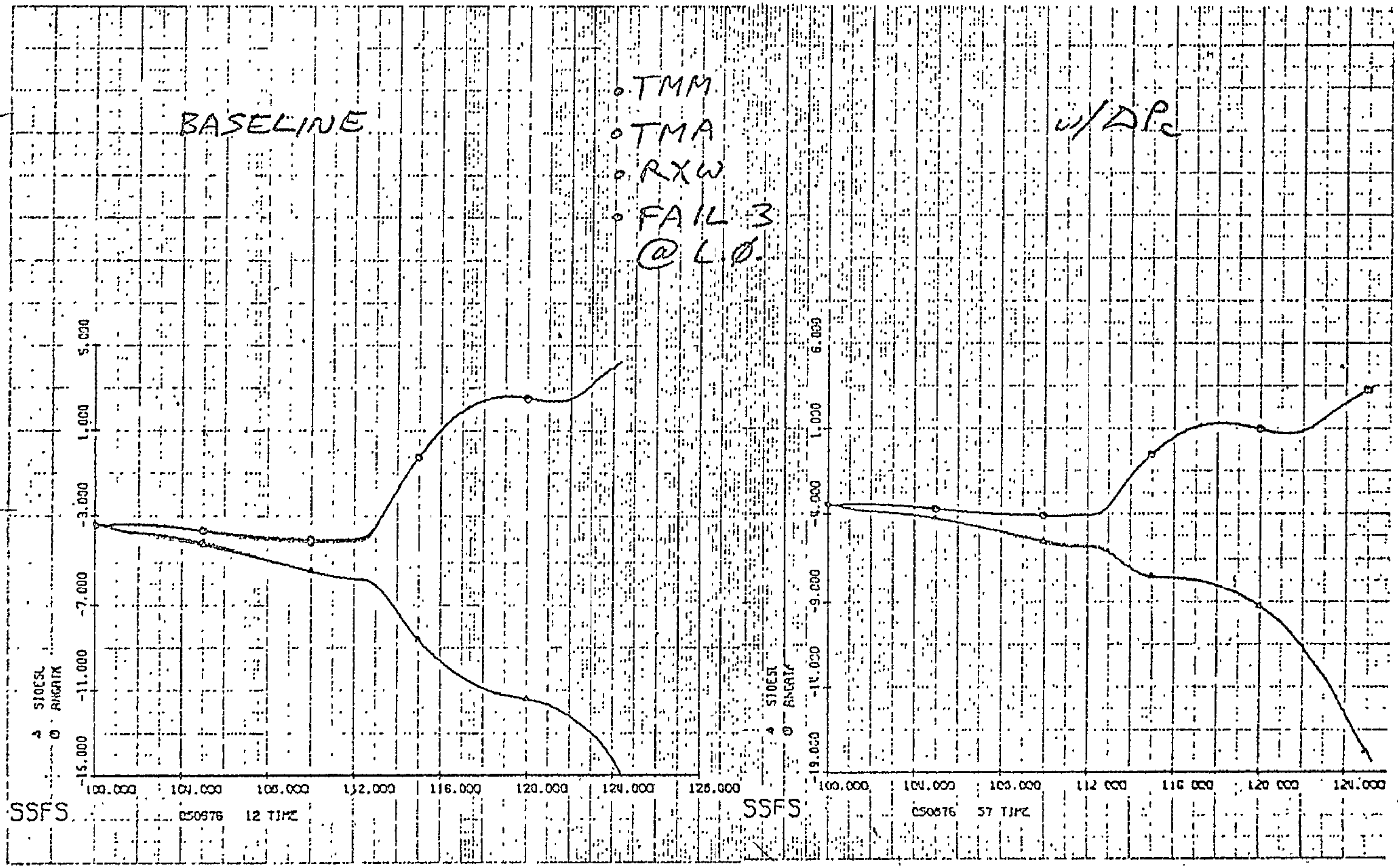
α, β (deg) vs TIME (s)



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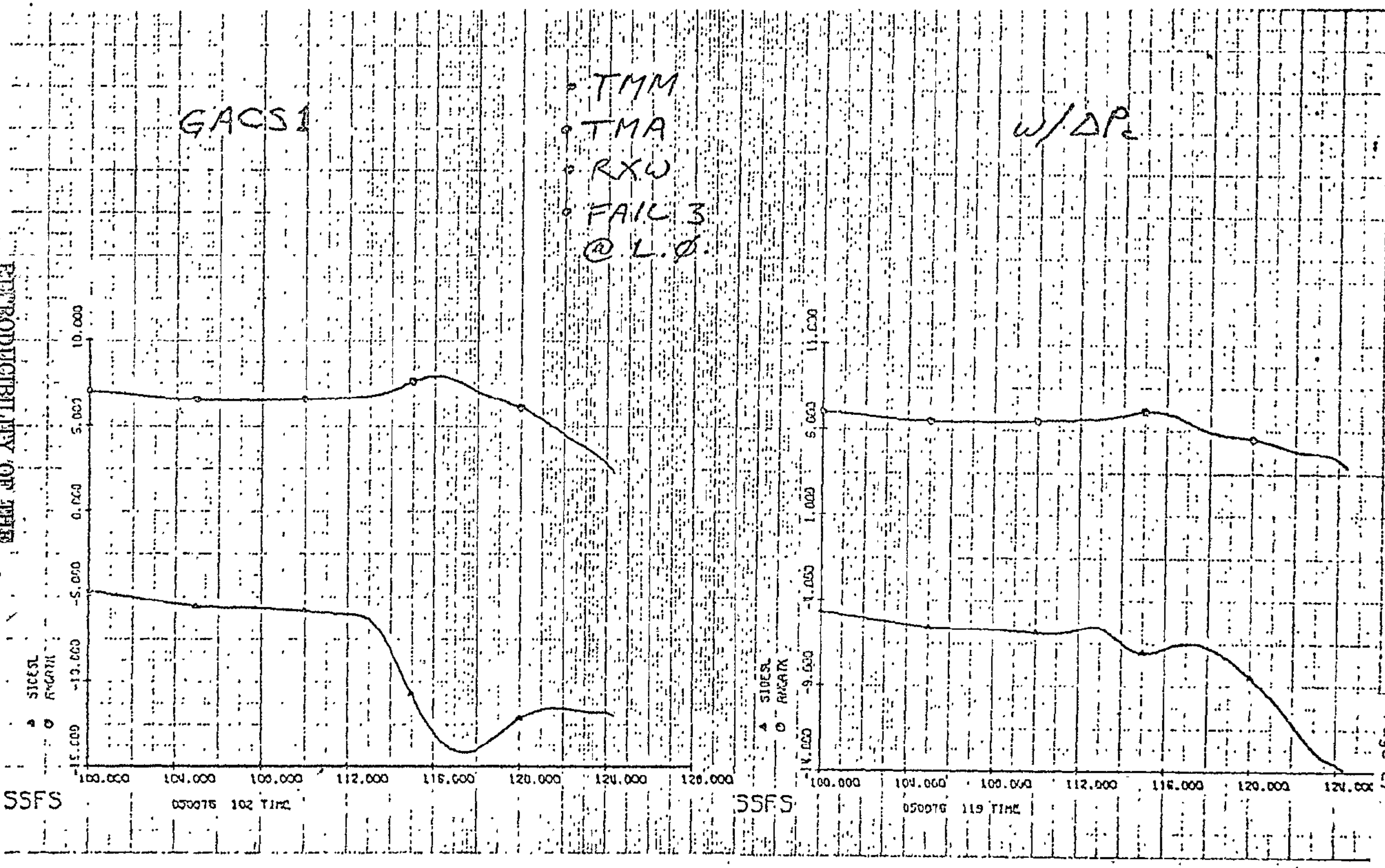
α, β (deg) vs TIME (s)



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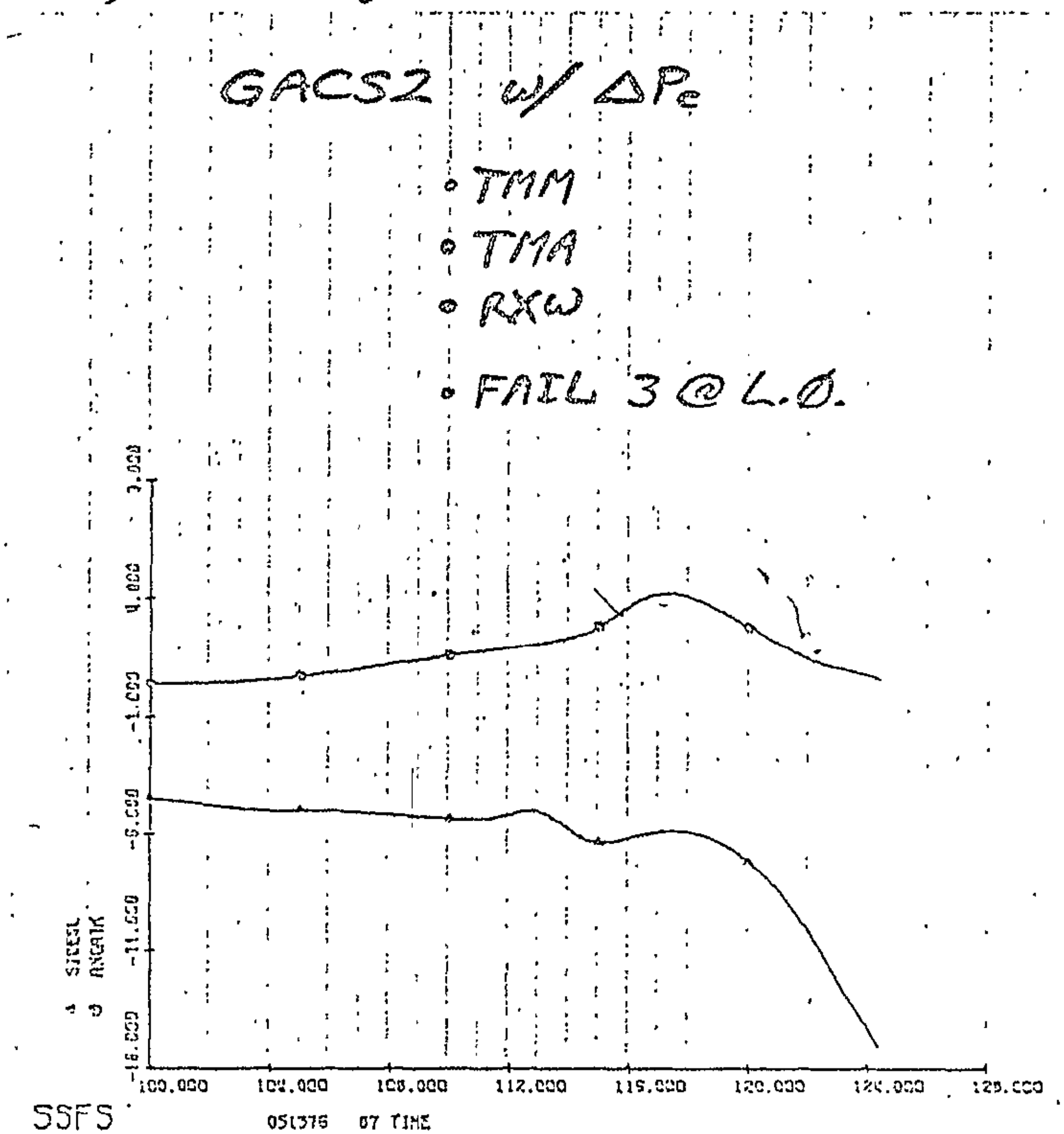
α, β (deg) vs TIME (s)



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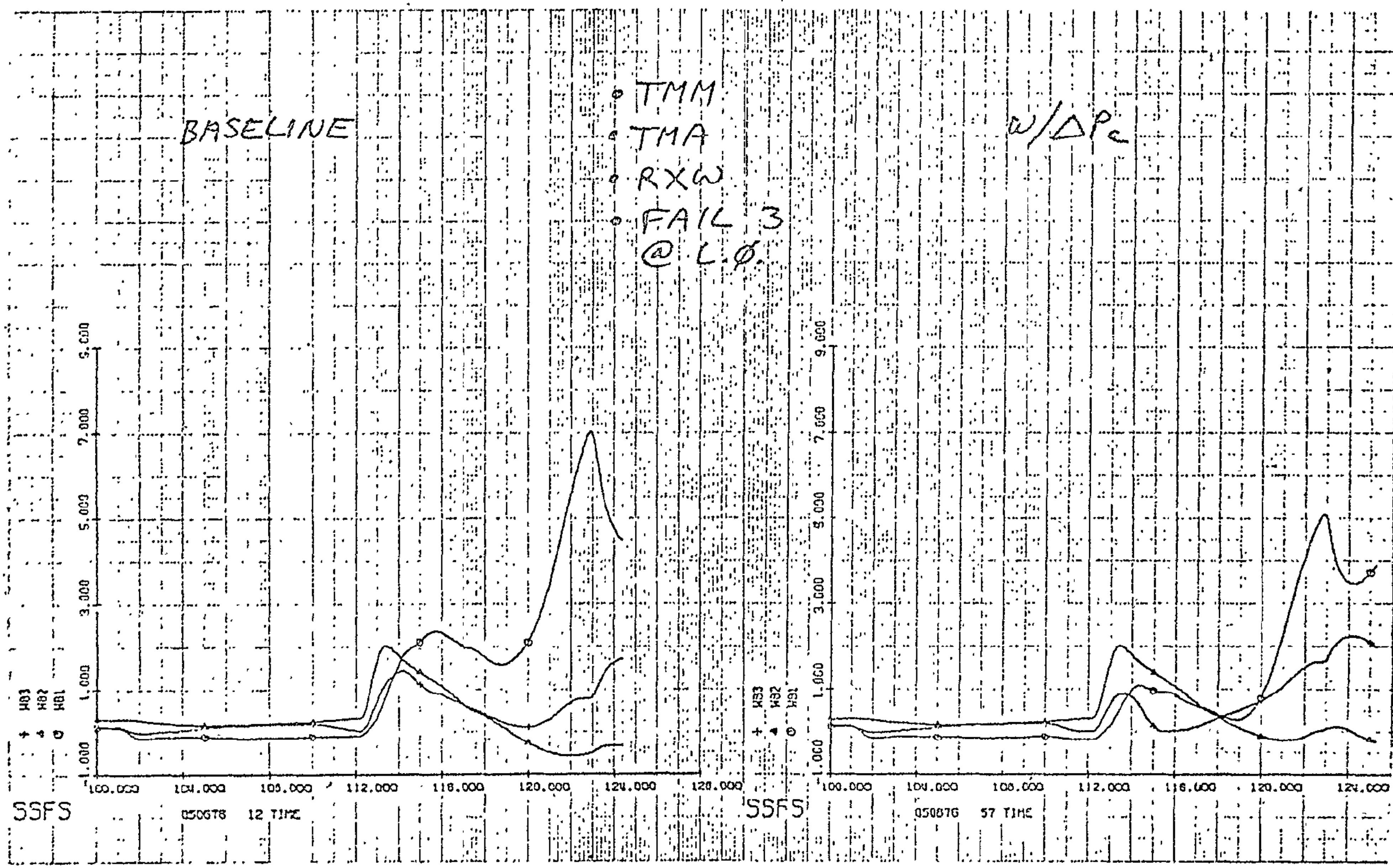
BODY RATES (deg/s) vs TIME (s)



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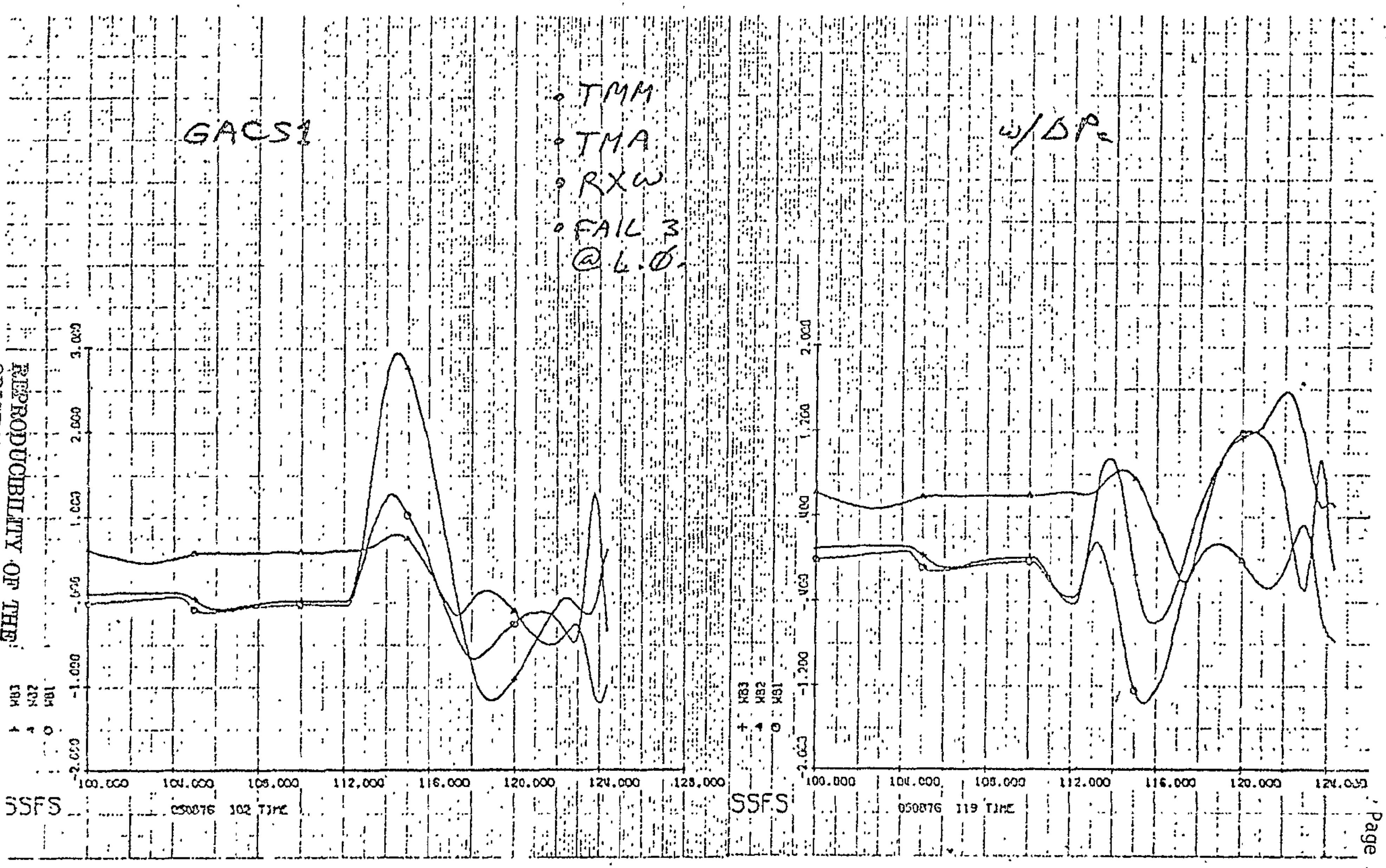
BODY RATES (deg/s) vs TIME (s)



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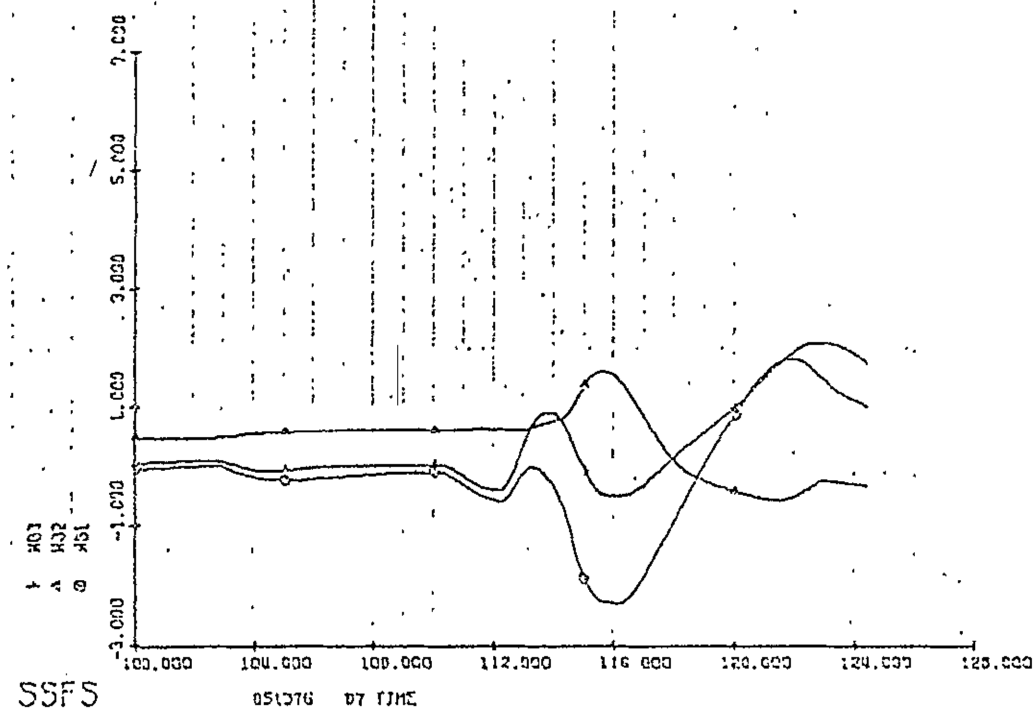
BODY RATES (deg/s) vs TIME (s)

GACS2 w/ ΔP_c

- TMM
- TMA
- RXW
- FAIL 3 @ L.Ø.



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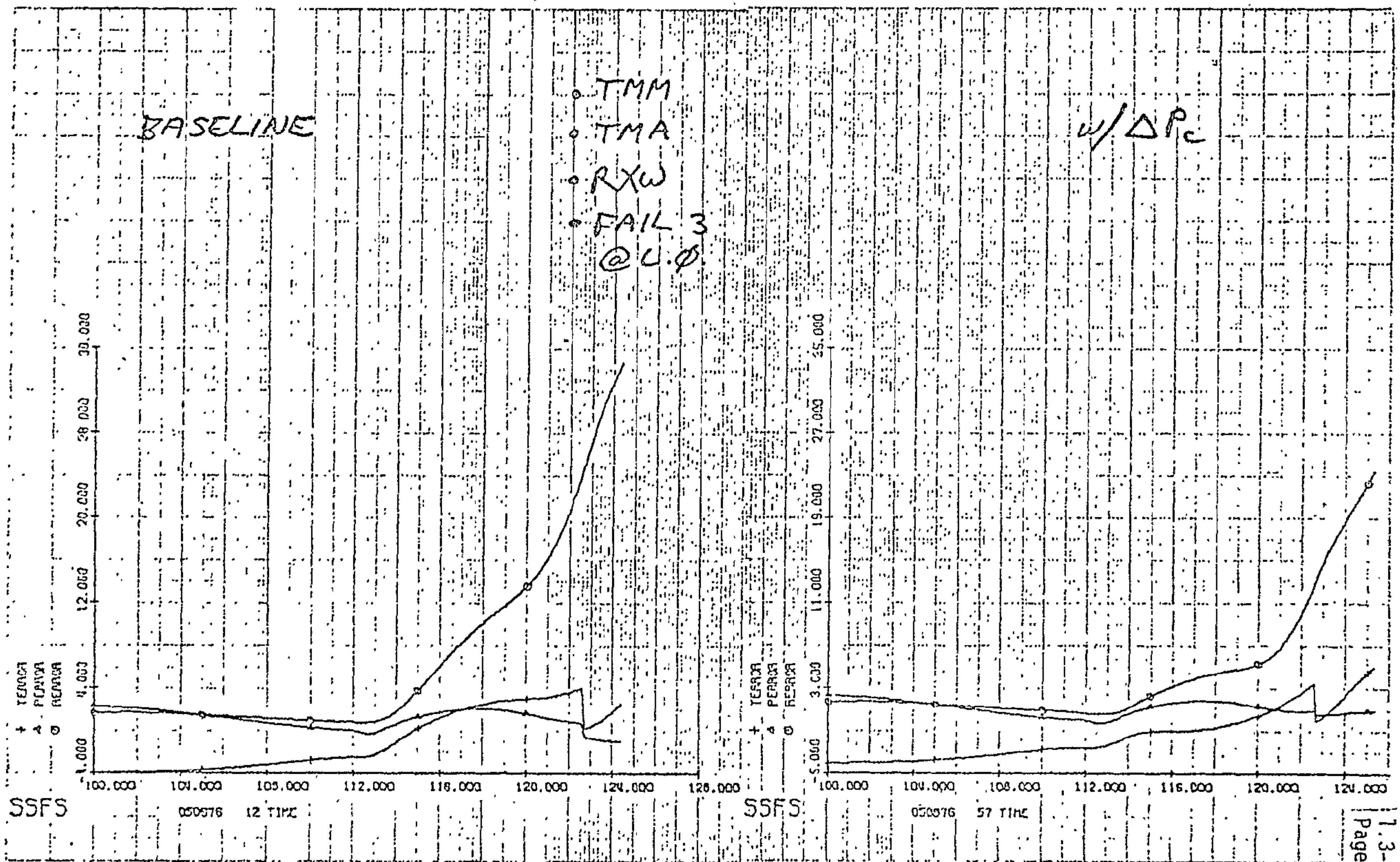
BODY ATTITUDE ERRORS (deg) vs TIME (s)



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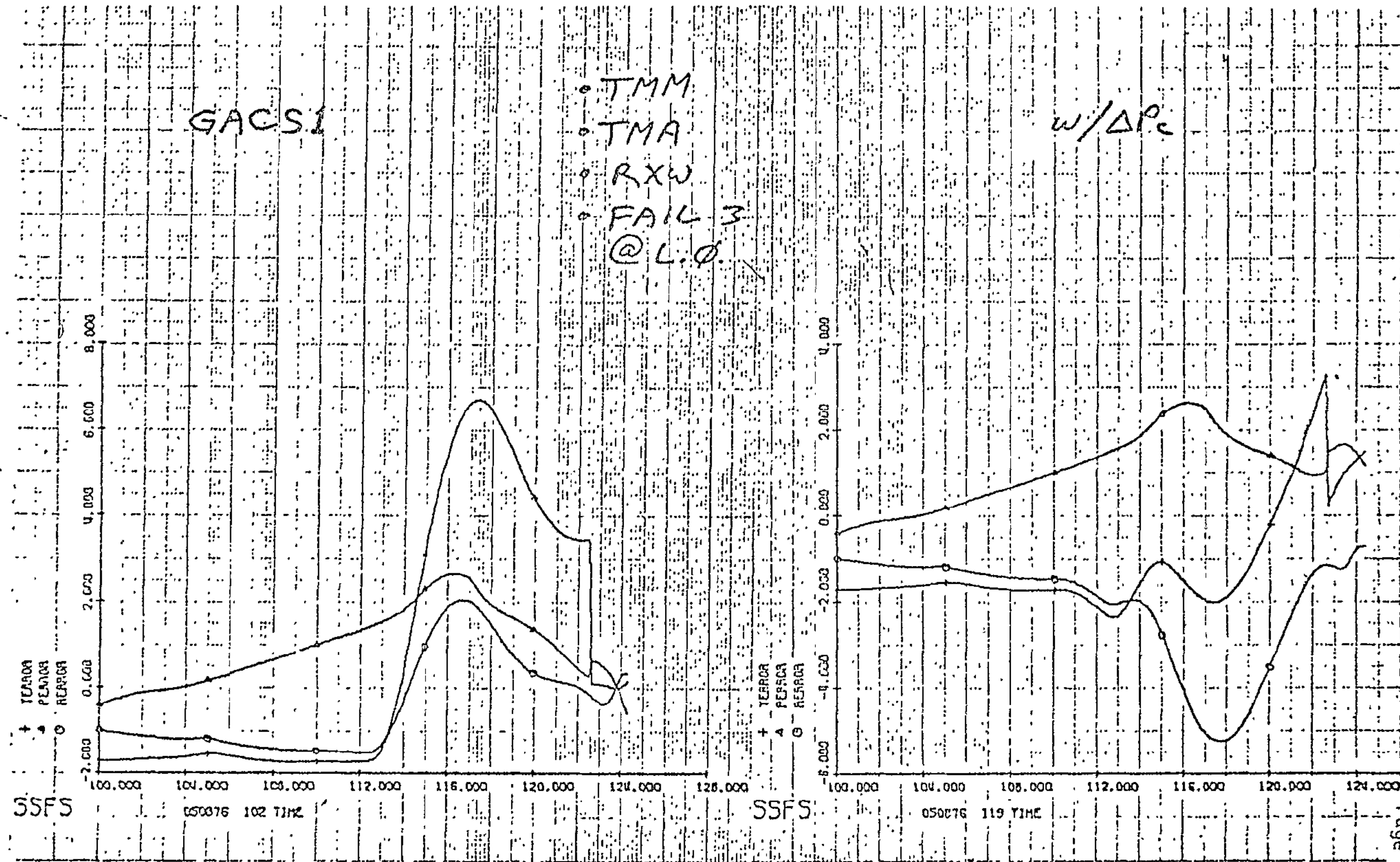
BODY ATTITUDE ERRORS (deg) vs TIME (s)



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BODY ATTITUDE ERRORS (deg) vs TIME (s)

GACS2 w/ ΔP_c

- TMM
- TMA
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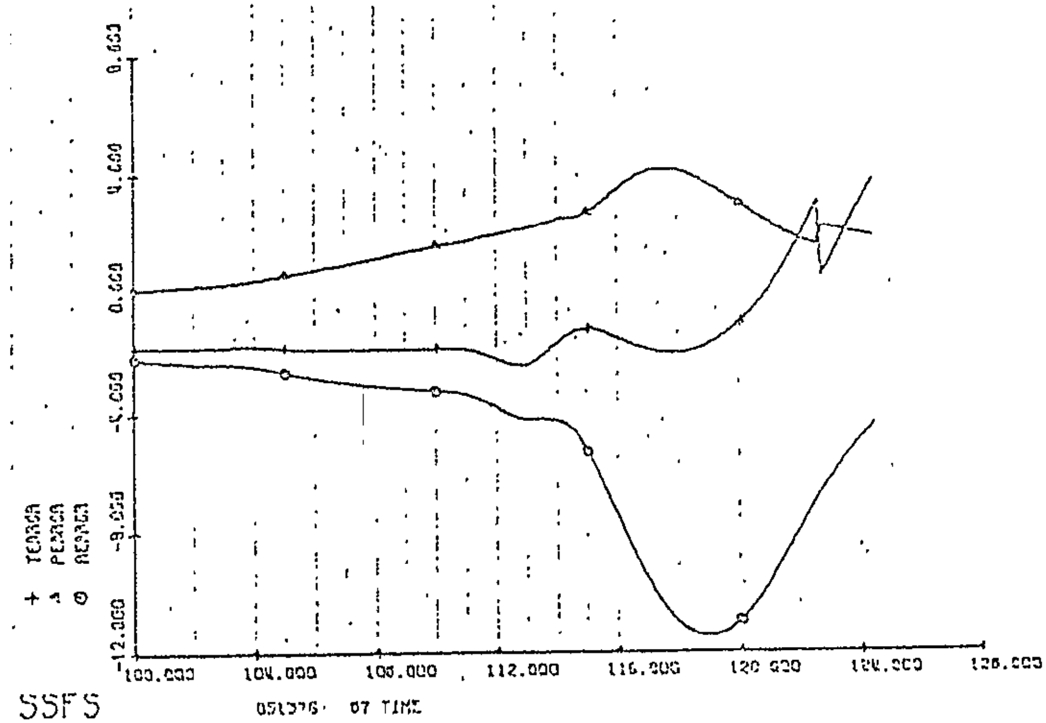
- FAIL 3 @ L.Ø.



SSFS