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# OPERATIONAL EXPERIENCE AT MACH 3

by

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## ABSTRACT

Flight experience with the XB-70 from takeoff to Mach 3 is presented. The influence of flying qualities on operational characteristics at supersonic speeds are discussed, and suggestions for improvements related to advanced supersonic airplanes are made.

# OPERATIONAL EXPERIENCE AT MACH 3

The XB-70 is one of the most advanced airplanes being flown today. It weighs over 500,000 pounds at takeoff, and is capable of Mach 3 speeds and altitudes over 70,000 feet. From the time of the first flight of airplane No. 1 in September 1964, there has been a steady progression toward the objectives of expanding the flight envelope, determining the flight characteristics, and demonstrating the capability for sustained Mach 3 flight. This last goal was achieved on 19 May 1966 when airplane No. 2 was flown continuously at Mach 3 for 32 minutes.

A speed-altitude envelope typical of any supersonic-cruising airplane is shown in Fig. 1. The airplane will normally climb at subsonic speed to about 35,000 feet and will then be accelerated at constant altitude to the best supersonic climb speed. This speed is at the maximum operating limit, and the climb will be continued along this limit to the cruise speed and altitude. At cruise, current supersonic cruising airplanes are limited by the temperatures reached in stabilized flight, rather than by speed, or engine thrust. At the end of cruise, the airplane is normally decelerated at constant altitude to the descent speed, and then descended at a constant indicated airspeed.

The aerodynamic features of the XB-70, which have helped make this type of performance possible, are shown in Fig. 2. The folding wingtips, the two-position canopy, the variable geometry automatic inlet system, the flight control system which uses both elevators and a movable canard for

control, and especially the speed and altitude capability make flying this airplane a new and exciting experience.

An appropriate way to discuss the flight characteristics of this airplane, and some of the factors involved in operating at high Mach number is perhaps to follow a Mach 3 test flight. Fig. 3 is a radar map of a typical flight. Takeoff was from Edwards Air Force Base, California. After heading east from Edwards for a short distance, the flight path was northwest through California, Nevada, and into the southern portion of Oregon. Turning northeast, the flight proceeded north of Boise, Idaho, and then turned southeast toward Rock Springs, Wyoming. About 180 miles east of Salt Lake City, Utah, the path turned southwest toward Prescott, Arizona. Then, a long turn was made to arrive over Edwards Air Force Base.

Fig. 4 is a photograph of the airplane at takeoff. The nose-high attitude of the airplane is apparent, although somewhat exaggerated by the lines of the forward fuselage, and the ground directly ahead is not visible during lift-off and climb-out. During takeoff and landing, the canard is fixed at zero degrees and the flaps at the trailing edge are lowered. The elevons must then be moved trailing edge downward to counteract the increased canard lift, so that they act as flaps. This increases the lift of the wing at approach angles of attack, resulting in lower takeoff and landing speeds. The effect of the canard flap on the elevon position can be clearly seen. The elevons are down several degrees, rather than up as would normally be expected just after takeoff. Flaps and gear are usually retracted immediately after takeoff. Trim change due to gear is negligible.

Trim change due to flaps is relatively large, but is not difficult to control as flap retraction is slow. Longitudinal control is good, and accurate control of speed is quite easy. Lateral control is sensitive, as the ailerons are very powerful.

After the flaps and gear are up, the wingtips are normally put in the one-half position. Fig. 5 shows the airplane in flight with the wingtips one-half down. Folding the tips increases the directional stability by about one third, and reduces the effective dihedral to less than 25 percent of the tips-up value. The static margin is reduced approximately 1 percent mean aerodynamic chord (MAC).

Pitch control is excellent throughout the subsonic speed range, although the response in pitch is quite slow due to the high moment of inertia. Because the natural aerodynamic damping is very good, the effect of the pitch damper is barely noticeable in smooth air. Speed stability is positive, and this, combined with the good pitch control, makes it easy to select and maintain climb speeds. With the wingtips one-half down, the outer one third of the elevon is disconnected, so that aileron control effectiveness is reduced. This effect, combined with the increased directional stability and the reduced dihedral effect, appreciably improve the lateral-directional flying qualities.

The windshield is normally placed in the up position at 0.95 Mach number, and the airplane is then accelerated to the supersonic climb speed at constant altitude. The flying qualities are better at both low speed and high speed than at transonic and low supersonic speeds, particularly the lateral-directional characteristics, because of several combined effects. First the

so-called "short period" oscillation is relatively long due to the high inertia of the long fuselage (approximately 5 seconds). Second, the rolling inertia is very low in comparison, so that the rolling response is rapid in comparison to the yawing response. Third, the side force due to sideslip is low, and this, combined with low response rates in yaw, make it difficult to sense sideslip without referring to the cockpit instruments. Fourth, the yawing moment due to aileron deflection is very strongly adverse.

Fig. 6 compares the yawing moment coefficient due to aileron predicted from wind tunnel tests with values obtained in flight. The predicted values are favorable at low Mach numbers, slightly adverse in the transonic speed range, and favorable, but small, with the tips full down, approaching zero at Mach 3. The flight test values are approximately zero at low speed, but are highly adverse transonically, approaching zero again at speeds above Mach 2.

The significance of this effect is that the aileron becomes a sideslipping control rather than a rolling control. Thus, when aileron is applied to stop a wing from dropping, sideslip is introduced, and the dihedral effect causes the airplane to tend to roll more, and additional aileron is required. If the pilot is not careful to watch the sideslip indicator, it is possible to reach high sideslip angles inadvertently, especially when flying in turbulence. The airplane is disturbed by turbulence primarily in roll, with less disturbance in pitch or yaw.

As the airplane accelerates through 1.3 Mach number, the tips are placed in the full down position, as shown in Fig. 7. The dihedral effect is

negative with the tips full down, and, combined with the adverse yaw due to aileron, makes it possible to excite a lateral-directional oscillation by attempting to hold the wings level with the aileron when the augmentation is off, as shown in Fig. 8. It is difficult to properly coordinate rudder and aileron to damp this motion because of the difference in response times in roll and yaw.

When the airplane reaches Mach 2, the inlets are started. This means that supersonic flow exists inside the inlet and a normal shock wave exists at or slightly downstream of the throat. The inlet control system then operates to automatically control the position of the normal shockwave near the throat by operating the variable ramps and the bypass doors. This type of inlet control system is essential if the engines are to function efficiently at high supersonic speeds.

Once the inlets are started, it is a routine matter to continue to climb and accelerate to Mach 3. Routine, of course, means with respect to the speed and altitude range concerned. The supersonic climb and acceleration occurs in the northern portion of the test range, as indicated in Fig. 9 by the overlay. It is necessary to climb and accelerate along an operational limit where Mach number, indicated airspeed and altitude are continuously changing. If the speed is allowed to get high, the operational limit can be exceeded, and if the speed gets low, it is necessary to mentally determine the increase in speed and altitude which will be needed to get back on climb schedule without overshooting the operational limit. The selection of the attitude required to return to, and then maintain, the proper climb schedule

is a trial and error process which could be greatly enhanced by an instrument to guide the pilot back to the proper climb schedule in a manner similar to a flight director operation.

The airplane is not difficult to fly at high Mach number. Maneuvering forces are high and airplane response is relatively slow, but adequate. The dihedral effect is almost zero, so lateral-directional coupling is minimized. The augmentation has been turned off at speeds as high as 2.9 Mach number with an appreciable reduction in damping, as would be expected. Fig. 10 is a time-history of a sideslip to one-half rudder deflection at 2.9 Mach number at 70,000 feet with all augmentation on. Note that the sideslip follows rudder motion quite well, with the sideslip stabilizing when the rudder is held fixed. The effective dihedral is essentially zero, as evidenced by the small amount of aileron required to hold the roll rate zero. The very small elevator motions show that there was no difficulty in the pitch axis.

Fig. 11 is a time-history of a sideslip at the same flight condition with all augmentation turned off. In this case, the rudder is applied smoothly, but there is a pronounced oscillation of sideslip angle which is very lightly damped. The average aileron angle is small, but there is a noticeable motion required to damp the rolling tendency. Precise control still exists and flying qualities are acceptable, but the concentration required to manually damp the oscillations make unaugmented flight tiring, and most pilots would probably prefer to reduce speed if the augmentation failed.

Mach 3 was reached on this particular flight just over Rock Springs, Wyoming, and was maintained for 32 minutes, as shown in Fig. 12. It took

approximately 58 minutes to get to Rock Springs from Edwards, and 32 minutes to travel the 1035 miles back, including the long turn from Prescott, Arizona, to Edwards.

A random and unpredictable altitude excursion has frequently been experienced when attempting to maintain level flight at high speeds and altitudes. Careful examination of the flight test data has shown that, in many cases, there were no control surface motions or airplane attitude changes large enough to produce the altitude and rate of climb excursions. Locking the bypass doors had little or no effect on the pilot's ability to control the altitude, eliminating this as a possible cause. It appears that these altitude excursions are a result of pressure variations in the atmosphere, which are being encountered at high altitude, causing a change in altimeter reading even though the airplane is maintaining a constant geometric altitude. Later flights where the pilot has attempted to hold constant attitude without paying as much attention to variations in pressure altitude have resulted in better control, but this technique is not entirely satisfactory for two reasons. The attitude presentation in the airplane is not sensitive enough for accurate flight path control at high speed, and the desirability of flying close to the operating limits, typical of an SST type vehicle as shown in Fig. 13, means that decreased altitude, or increased pressure, can cause the airplane to inadvertently approach the inlet overpressure limits.

Forward visibility is restricted when the windshield is in the up position, so that high-speed flight is on instruments. Instrument flight in high Mach number is more demanding than at lower speeds because the high velocity

magnifies the effect of small deviations in attitude or heading, and response to small corrections is slow. Better instrument presentations would improve this situation, but there is no substitute for direct forward visibility at any altitude. The improved performance which may be achieved at the expense of direct forward visibility may be overbalanced by the deterioration in flying qualities which will result.

Turning at high speed is another characteristic which must be given consideration. The time to make a turn increases linearly with speed, and the turning radius increases with the square of the speed. Since banks must be shallow if the Mach number is to be kept high, times to turn and turning radius become very high. Referring again to Fig. 12, it was necessary to start turning at Prescott, Arizona, in order to fly over Edwards, and 17 minutes was spent in a 15-degree bank. It is perhaps pertinent to relate this flight to England. If the turn was started over London, it would have been completed west of Dublin, as shown in Fig. 14. It is obvious that the pilot is not going to hold force for 17 minutes, so almost all high-speed turns are accomplished by trimming into the turn, and high maneuvering forces and slow airplane responses are not a serious problem.

Another experience which will be common to all high Mach number airplanes, at least until more development is done, is the inlet "unstarts." As previously mentioned, the inlet is "started" slightly above Mach 2, when the external shock is swallowed and then maintained near the throat. However, under certain conditions, this shock can pop out of the inlet at higher Mach numbers; i.e., an "unstart." When this happens, the airplane is jarred

quite violently, pitches nose-up slightly, yaws away from the unstarted inlet, and rolls into the unstart. The pitch and yaw experienced on the XB-70 are mild, and about one-fourth aileron is required to overcome the rolling tendency, as shown in Fig. 15. The net thrust goes down and the drag increases, producing a sudden deceleration of about 0.2 g, causing the pilot to momentarily push the column forward. The automatic inlet control system causes a restart almost immediately, but during the short period before normal operation is resumed, the airplane can decelerate 0.1 to 0.2 Mach number.

Over 90 inlet unstarts, mostly deliberate, have been made. While they have been demonstrated to cause no structural damage or extreme airplane motions to the XB-70 because the inlets are located close to the centerline of the airplane, each unstart is startling, even to a crew experienced in flight testing.

After completing the high Mach number portion of the flight, the airplane is usually decelerated at constant altitude to 400 knots indicated airspeed, and then descended at constant airspeed to subsonic speed at 35,000 to 40,000 feet. The unstarts which occur just above Mach 2 while decelerating are mild. A normal jet penetration to the field is made subsonically. Approach and landing are not difficult, and visibility and depth perception are good. The technique used is normal and straightforward, and the response of the airplane is good. Rumor once had it that an airplane with a very long fuselage would be difficult to land due to the low response rate in pitch. This is definitely not the case with the XB-70A. The longitudinal control is excellent

and speed stability at approach speeds is good. In addition, the airplane enjoys good power response at low speeds, making it easy to control approach speeds accurately. The average rate of sink at touchdown has been approximately 3 feet per second, which is comparable to present day jet transports.

In summary, the pilots feel that the XB-70 is a very impressive airplane. While Mach 3 flight was not achieved without setbacks, and developmental problems, it is significant that sustained Mach 3 flight was attained with only two minor changes to the initial aerodynamic configuration.

1. The aileron feel bungee was replaced with a heavier spring to double the gradient because the pilots felt the aileron control forces were too low.
2. The operational procedures were modified to put the tips to the one-half position at 0.95 Mach number, instead of 1.4 Mach number, to improve the lateral-directional flying qualities at transonic speeds. This was later altered, by suggestion of the pilots, to put the tips to the one-half position at 300 knots.

It is important to point out, however, that to say that the XB-70 is not difficult to fly at Mach 3, is not the same as saying that Mach 3 flight is not difficult ---- it is!

First, the high true velocity means that small errors in heading soon produce large errors in ground track, and the long times to turn inherent in high-speed flight mean that these errors take a long time to correct. In the other plane, the high velocity is translated into very high rates of climb or descent by very small errors in pitch attitude. The desirability of flying

right on the airspeed, altitude, and temperature limit in order to maximize performance means that speed and altitude must be controlled very carefully. The rapidity with which ground navigational aids are passed causes the crew to continually seek a new station which is within range. When flying cross-country rather than within a test range, the airplane goes from one FAA control center to another very rapidly.

It should be recognized that while Mach 3 flight can be routinely programmed, with high expectations of accomplishing the mission on time as scheduled, this is yet a pioneering experience. Development in the areas of instrument presentation, navigational aids, automatic flight control systems, automatic inlet control systems, and others are required to make high Mach number transportation a relaxing experience rather than an exhilarating adventure.

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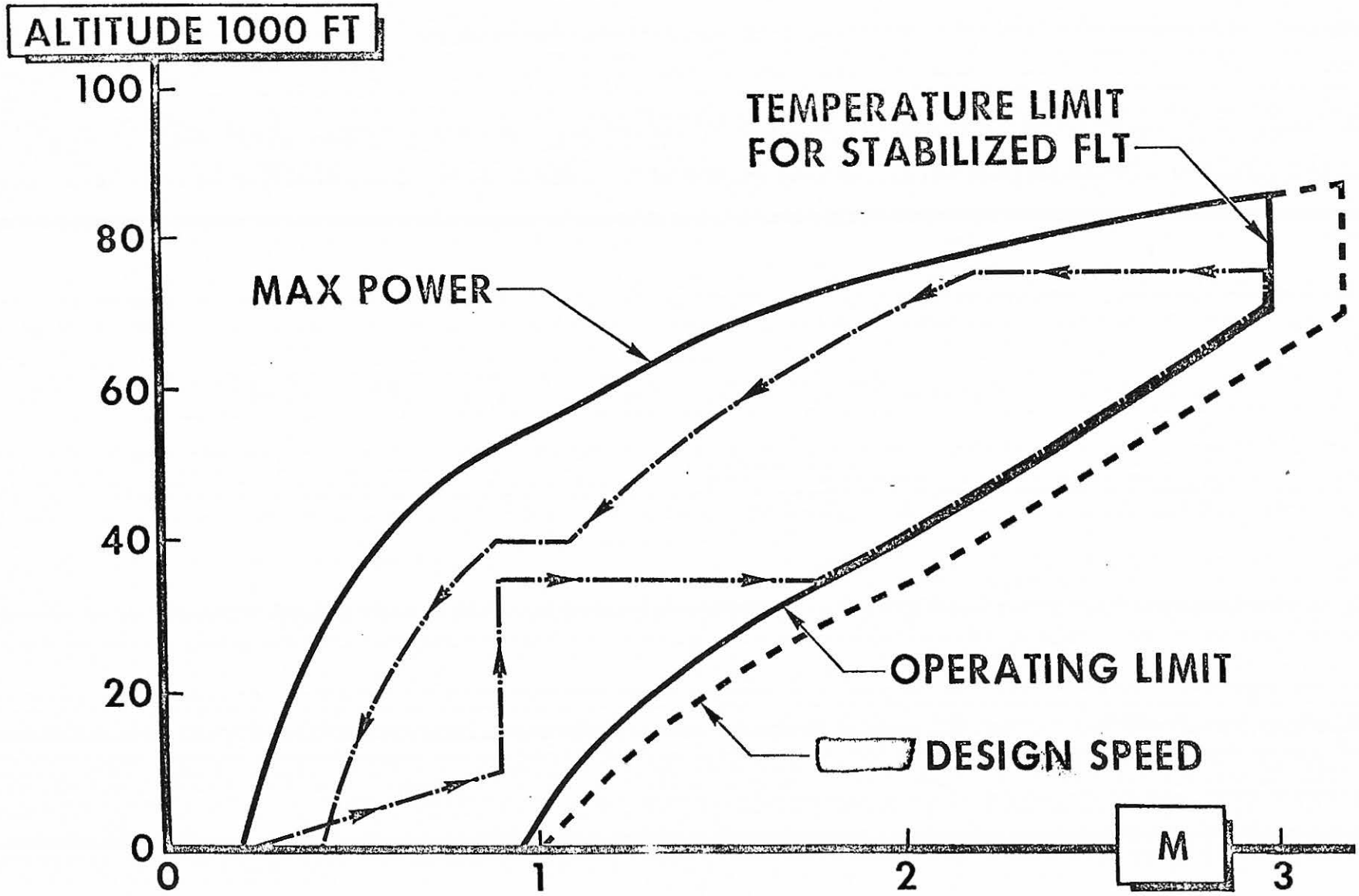


Figure 1. Typical Speed-Altitude Envelope for an SST Airplane

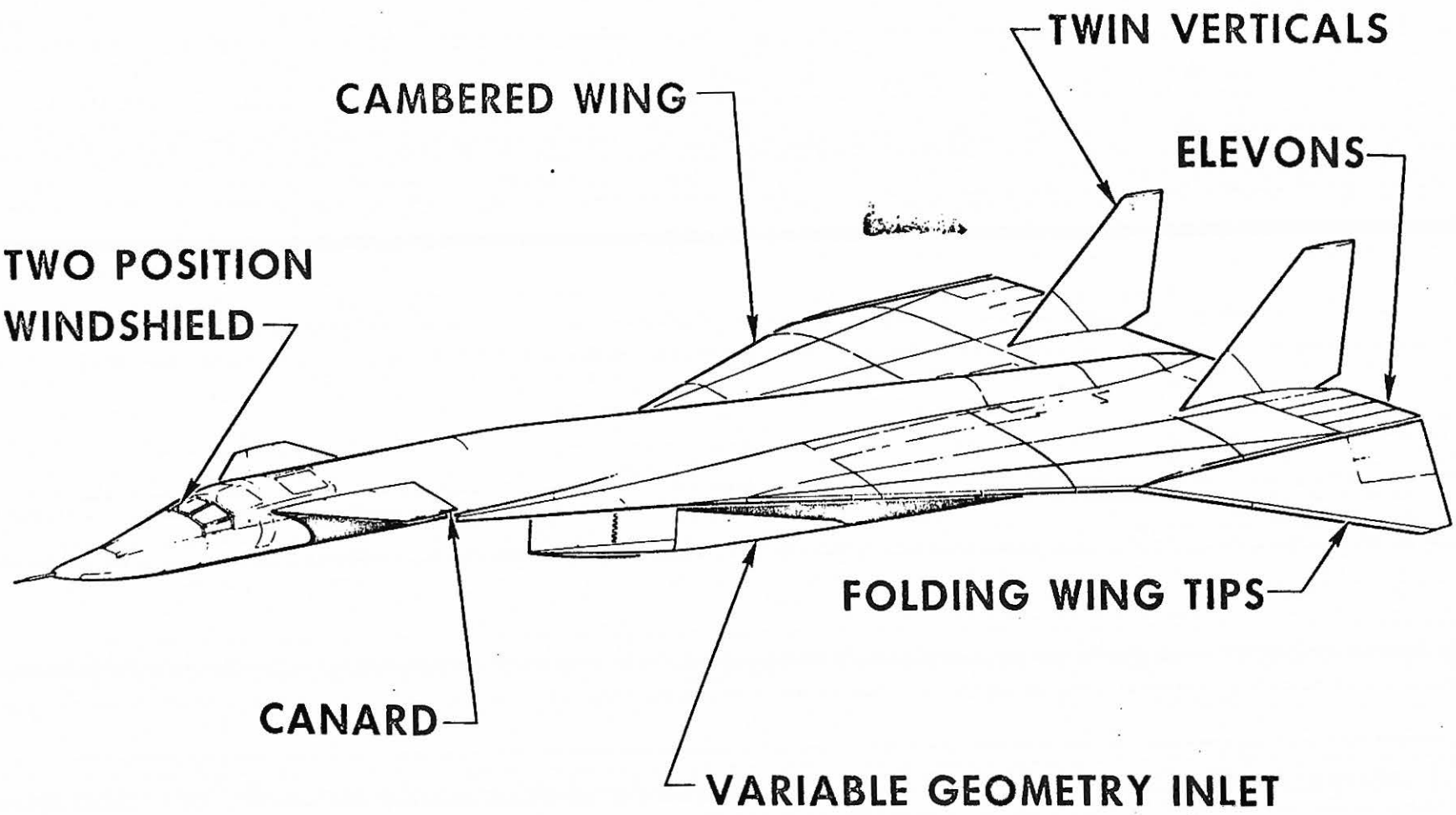


Figure 2. Aerodynamic Features

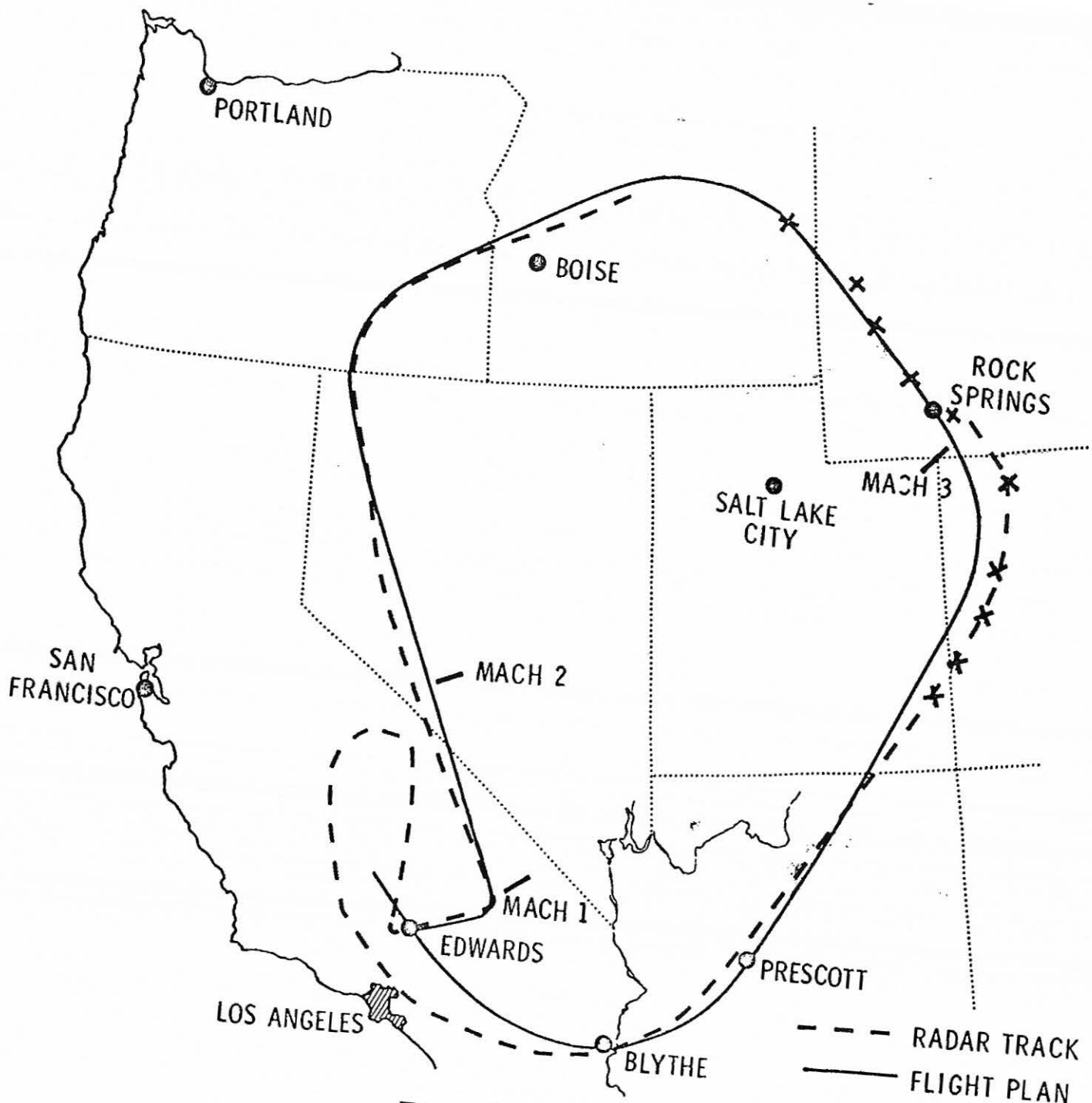


Figure 3. Flight Map

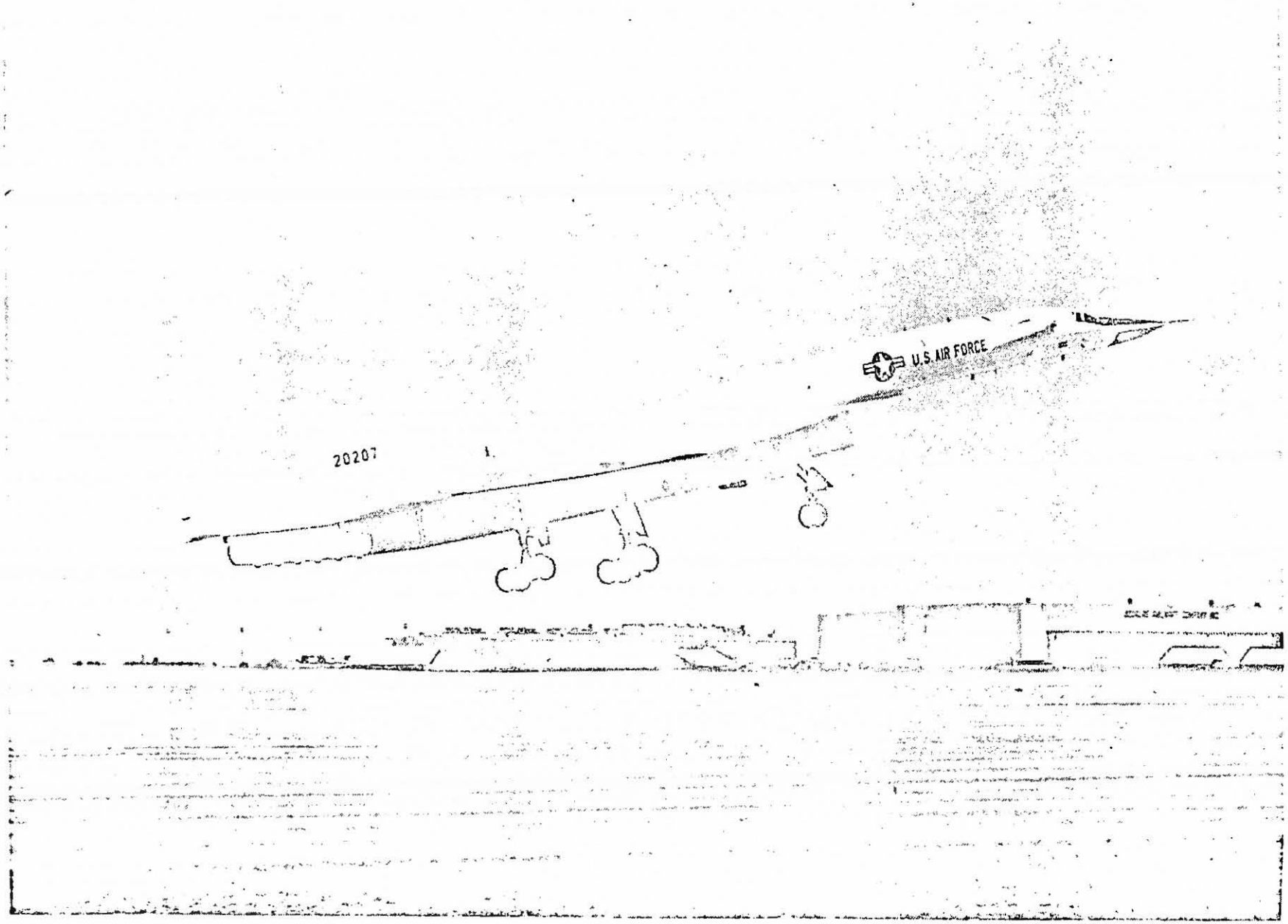


Figure 4. Takeoff

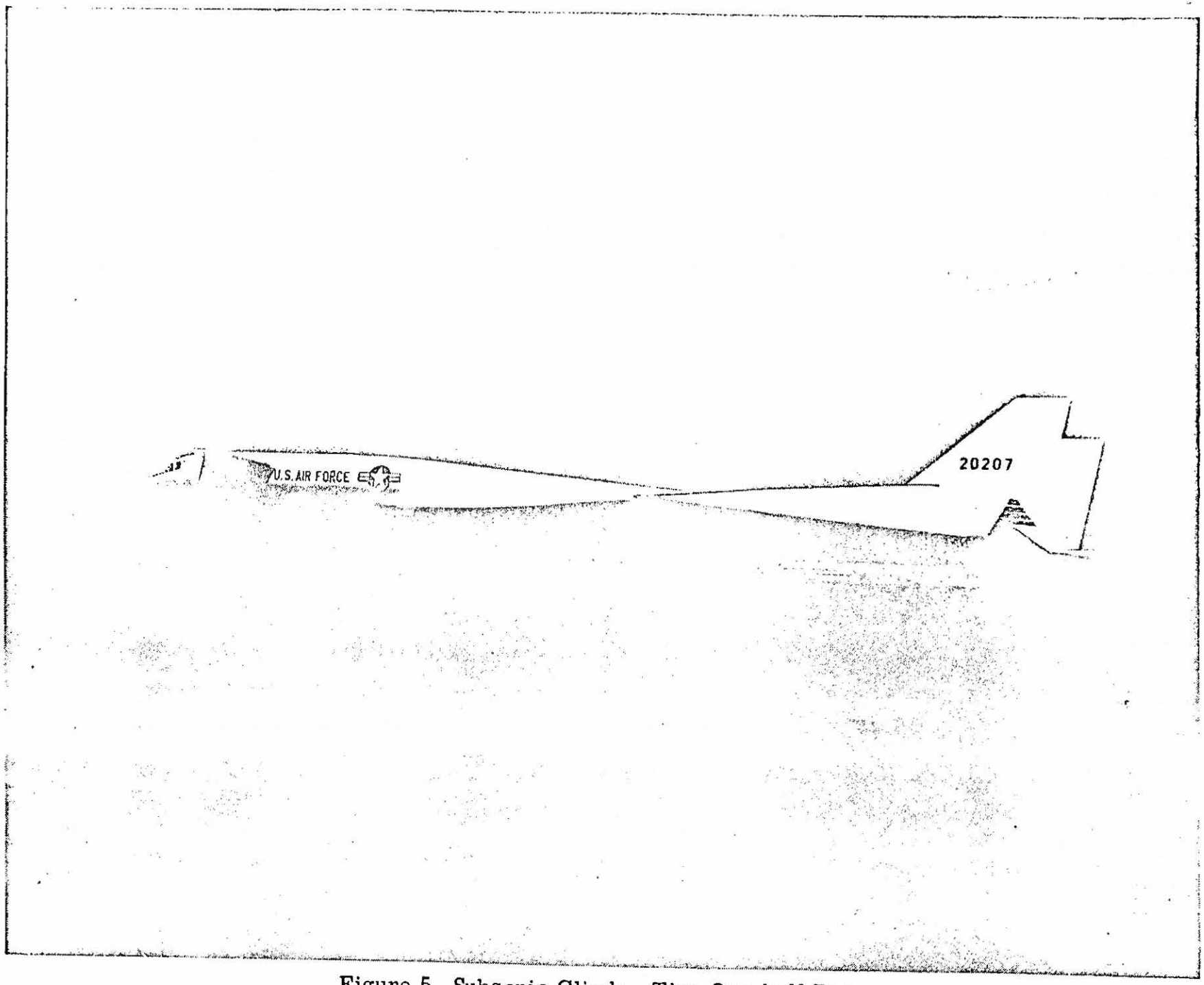


Figure 5. Subsonic Climb - Tips One-half Down

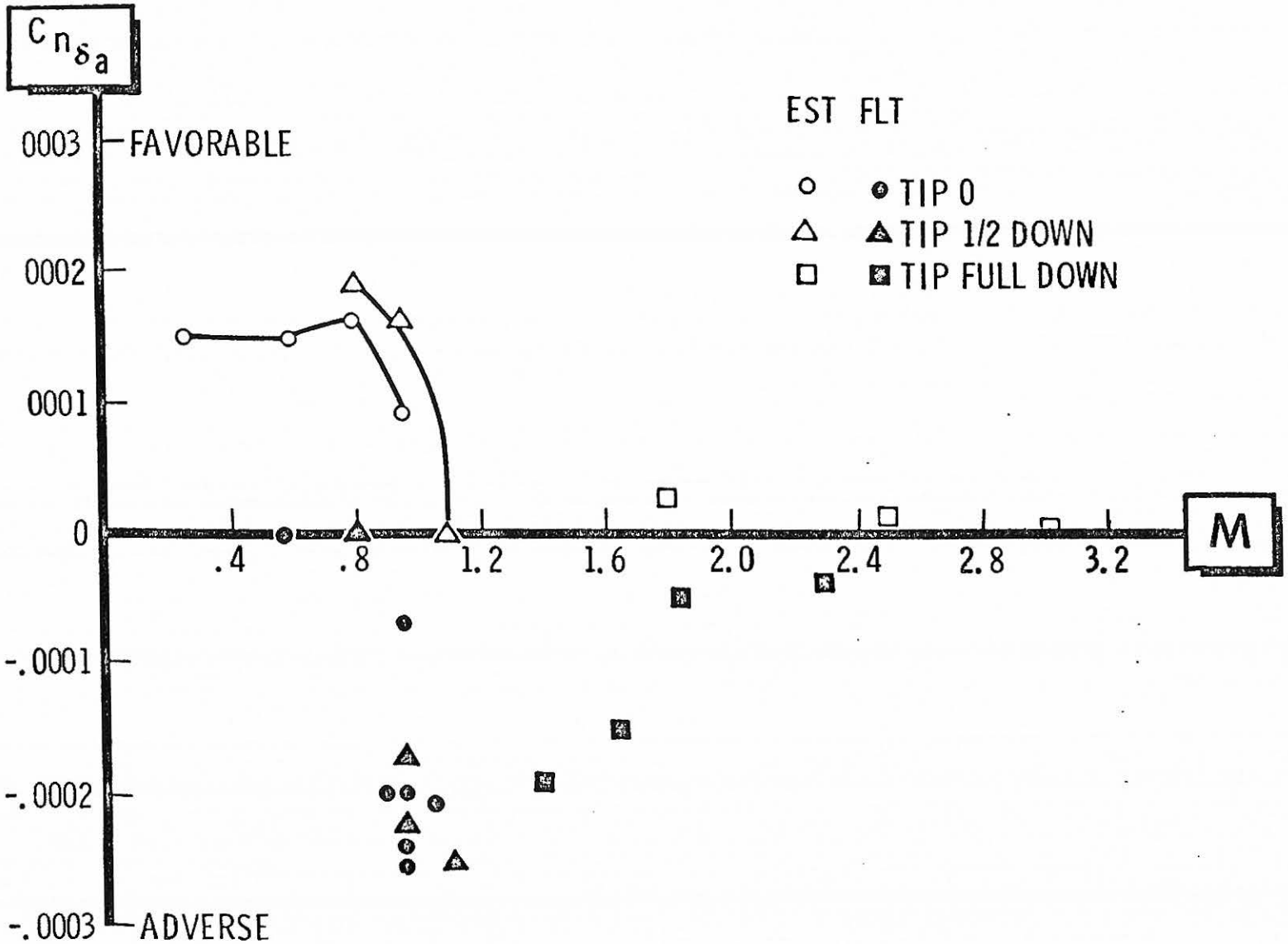


Figure 6. Yawing Movement Due to Aileron

Figure 7. Supersonic Flight - Tips Full Down

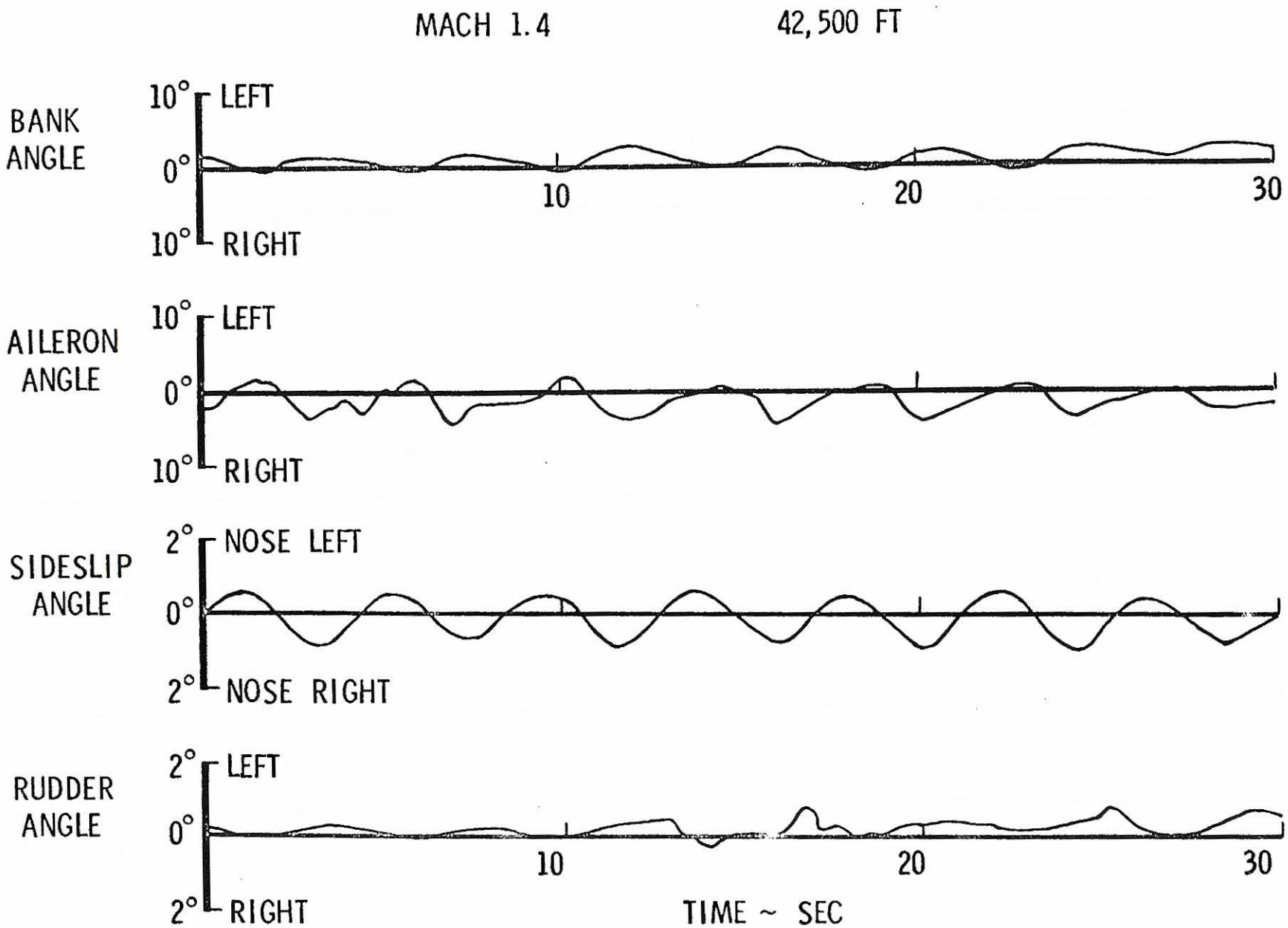


Figure 8. Lateral-directional Oscillation

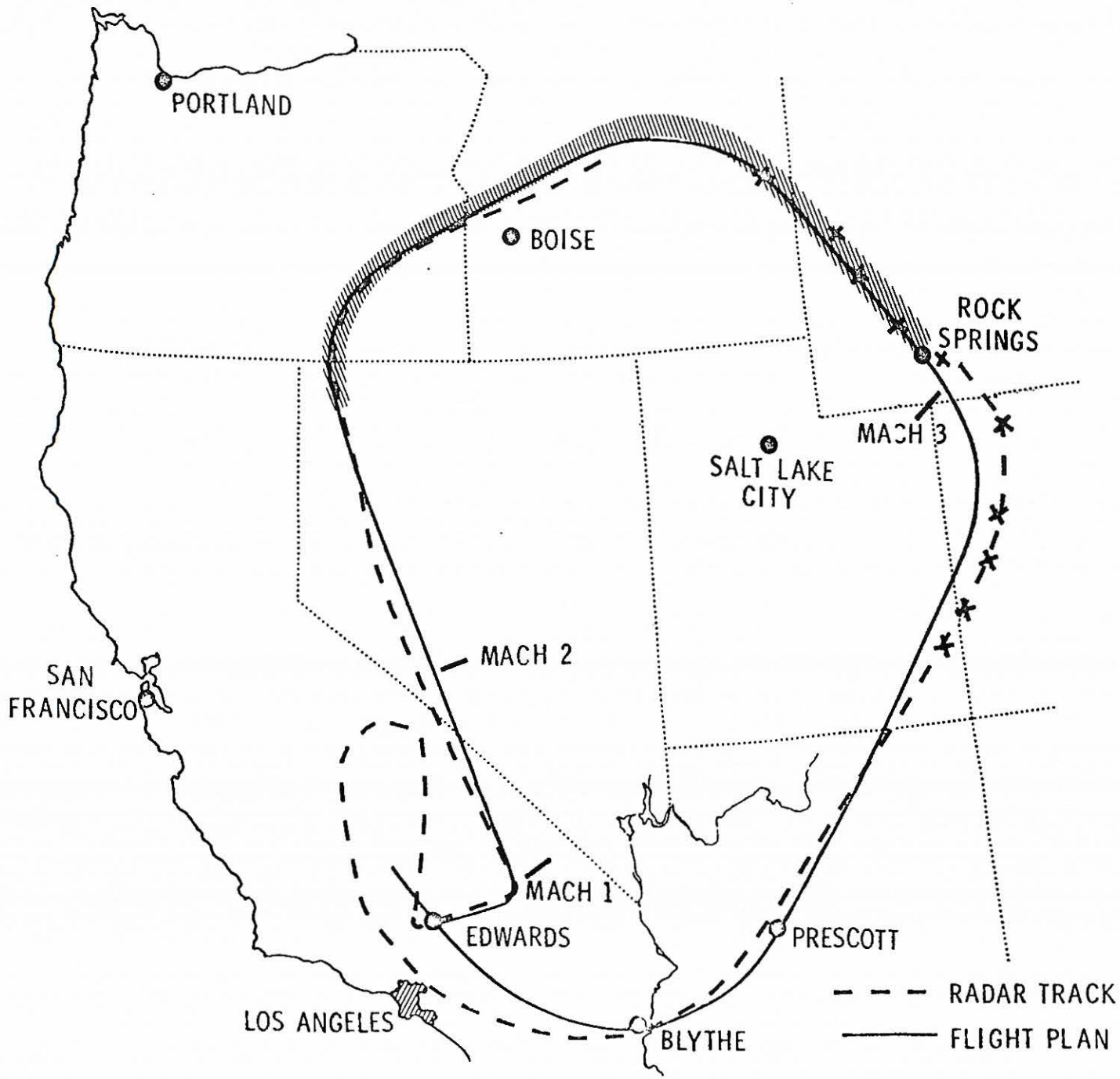


Figure 9. Flight Map - Supersonic Climb

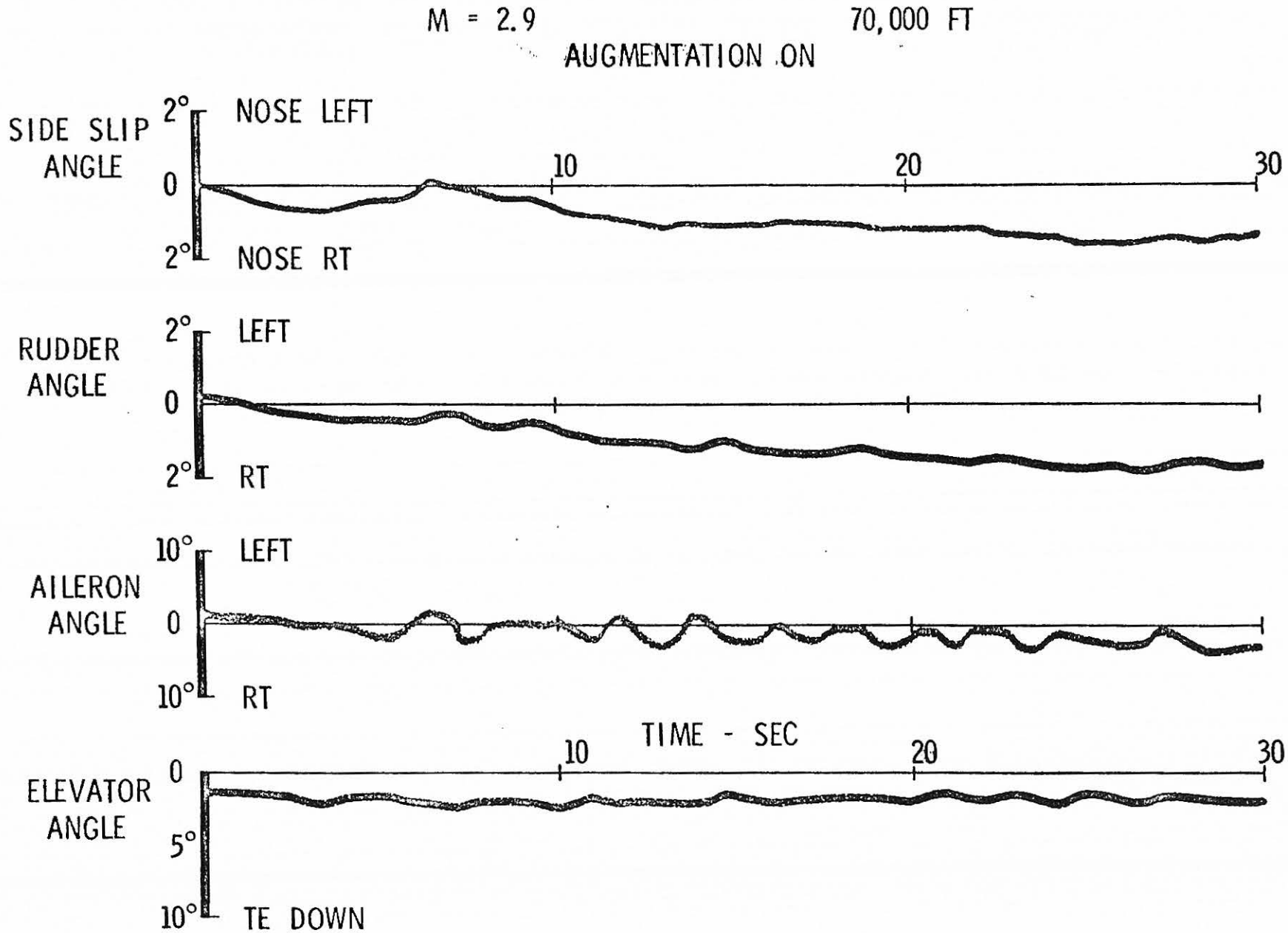


Figure 10. Time-History of a Sideslip Augmentation On

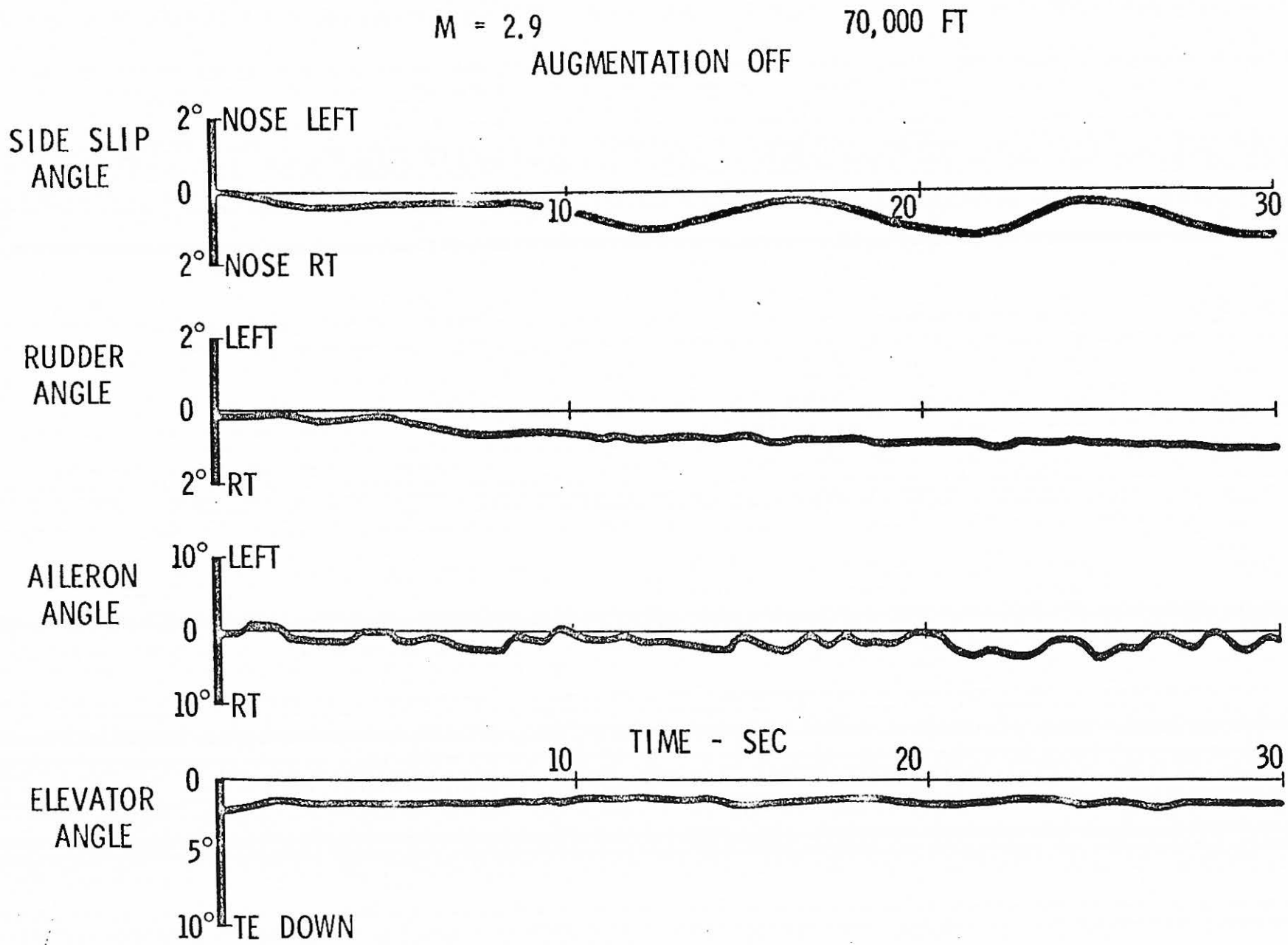


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Figure 12. Flight Map - Mach 3

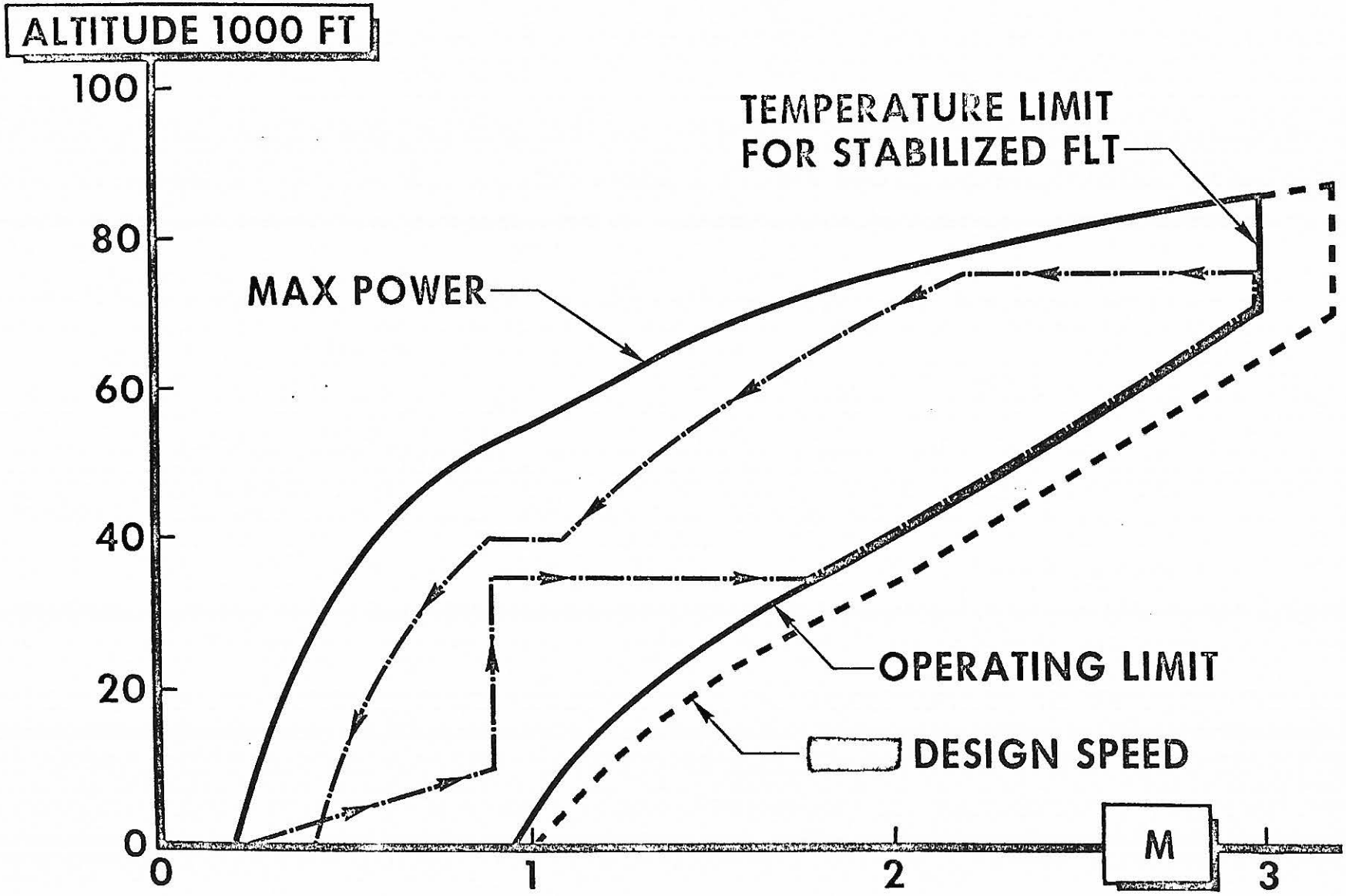


Figure 13. Speed-Altitude Envelope

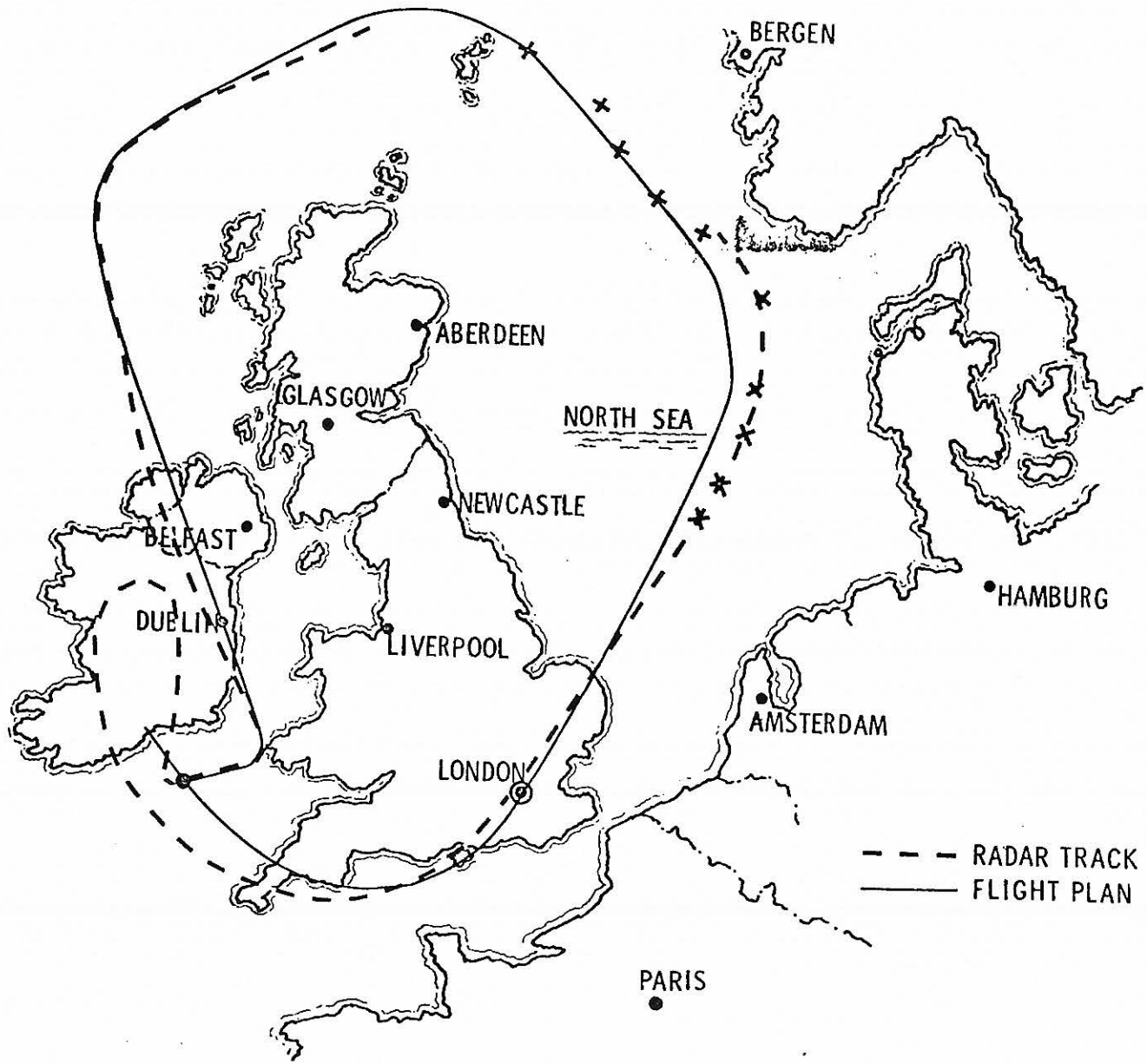


Figure 14. Flight Map - Superimposed on England

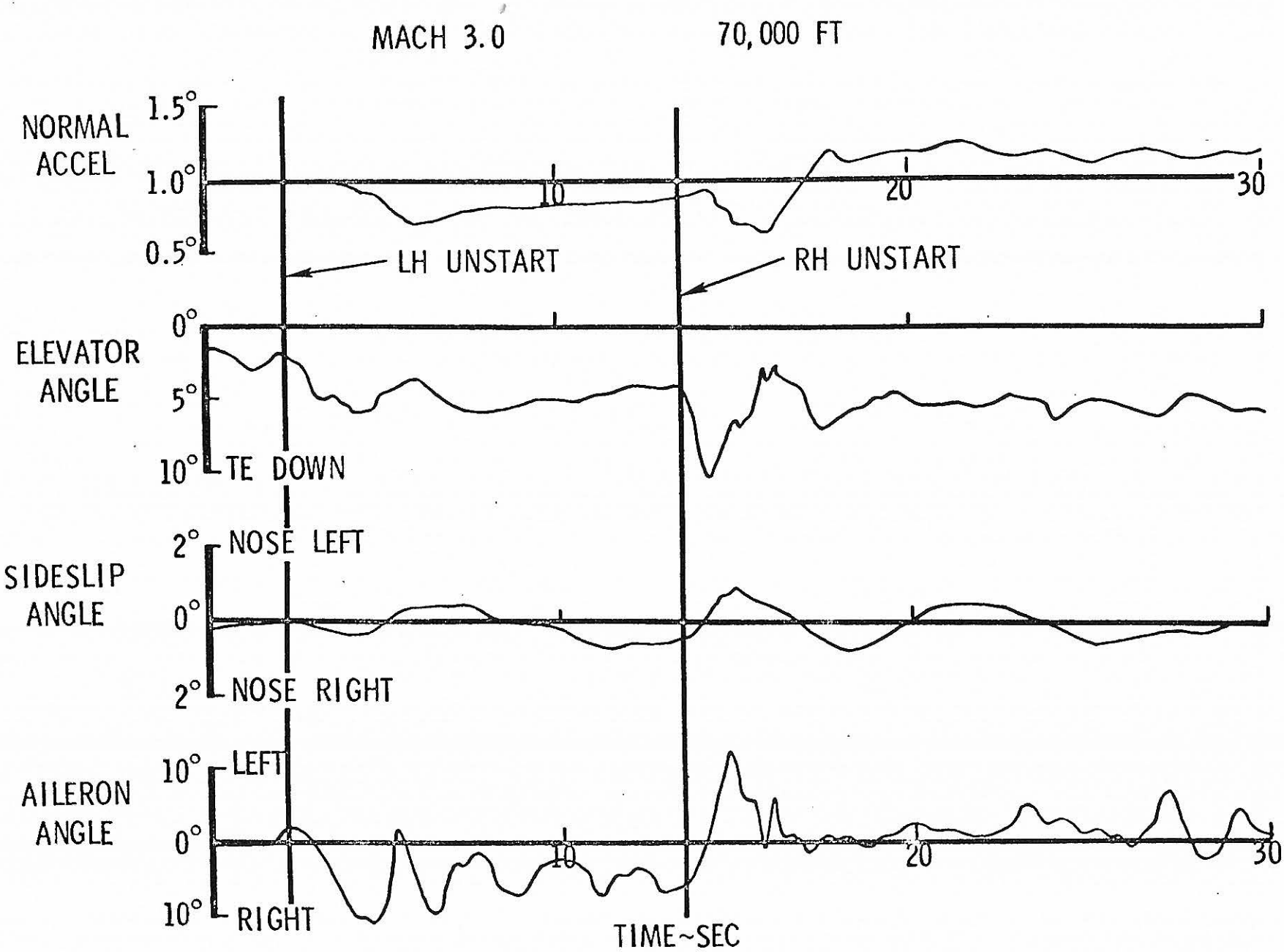


Figure 15. Transient Due to Unstart

G. H. BALZER
Historical Archives

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is a trial and error process which could be greatly enhanced by an instrument to guide the pilot back to the proper climb schedule in a manner similar to a flight director operation.

The airplane is not difficult to fly at high Mach number. Maneuvering forces are high and airplane response is relatively slow, but adequate. The dihedral effect is almost zero, so lateral-directional coupling is minimized. The augmentation has been turned off at speeds as high as 2.9 Mach number with an appreciable reduction in damping, as would be expected. Fig. 10 is a time-history of a sideslip to one-half rudder deflection at 2.9 Mach number at 70,000 feet with all augmentation on. Note that the sideslip follows rudder motion quite well, with the sideslip stabilizing when the rudder is held fixed. The effective dihedral is essentially zero, as evidenced by the small amount of aileron required to hold the roll rate zero. The very small elevator motions show that there was no difficulty in the pitch axis.

Fig. 11 is a time-history of a sideslip at the same flight condition with all augmentation turned off. In this case, the rudder is applied smoothly, but there is a pronounced oscillation of sideslip angle which is very lightly damped. The average aileron angle is small, but there is a noticeable motion required to damp the rolling tendency. Precise control still exists and flying qualities are acceptable, but the concentration required to manually damp the oscillations make unaugmented flight tiring, and most pilots would probably prefer to reduce speed if the augmentation failed.

Mach 3 was reached on this particular flight just over Rock Springs, Wyoming, and was maintained for 32 minutes, as shown in Fig. 12. It took

approximately 58 minutes to get to Rock Springs from Edwards, and 32 minutes to travel the 1035 miles back, including the long turn from Prescott, Arizona, to Edwards.

A random and unpredictable altitude excursion has frequently been experienced when attempting to maintain level flight at high speeds and altitudes. Careful examination of the flight test data has shown that, in many cases, there were no control surface motions or airplane attitude changes large enough to produce the altitude and rate of climb excursions. Locking the bypass doors had little or no effect on the pilot's ability to control the altitude, eliminating this as a possible cause. It appears that these altitude excursions are a result of pressure variations in the atmosphere, which are being encountered at high altitude, causing a change in altimeter reading even though the airplane is maintaining a constant geometric altitude. Later flights where the pilot has attempted to hold constant attitude without paying as much attention to variations in pressure altitude have resulted in better control, but this technique is not entirely satisfactory for two reasons. The attitude presentation in the airplane is not sensitive enough for accurate flight path control at high speed, and the desirability of flying close to the operating limits, typical of an SST type vehicle as shown in Fig. 13, means that decreased altitude, or increased pressure, can cause the airplane to inadvertently approach the inlet overpressure limits.

Forward visibility is restricted when the windshield is in the up position, so that high-speed flight is on instruments. Instrument flight in high Mach number is more demanding than at lower speeds because the high velocity

magnifies the effect of small deviations in attitude or heading, and response to small corrections is slow. Better instrument presentations would improve this situation, but there is no substitute for direct forward visibility at any altitude. The improved performance which may be achieved at the expense of direct forward visibility may be overbalanced by the deterioration in flying qualities which will result.

Turning at high speed is another characteristic which must be given consideration. The time to make a turn increases linearly with speed, and the turning radius increases with the square of the speed. Since banks must be shallow if the Mach number is to be kept high, times to turn and turning radius become very high. Referring again to Fig. 12, it was necessary to start turning at Prescott, Arizona, in order to fly over Edwards, and 17 minutes was spent in a 15-degree bank. It is perhaps pertinent to relate this flight to England. If the turn was started over London, it would have been completed west of Dublin, as shown in Fig. 14. It is obvious that the pilot is not going to hold force for 17 minutes, so almost all high-speed turns are accomplished by trimming into the turn, and high maneuvering forces and slow airplane responses are not a serious problem.

Another experience which will be common to all high Mach number airplanes, at least until more development is done, is the inlet "unstarts." As previously mentioned, the inlet is "started" slightly above Mach 2, when the external shock is swallowed and then maintained near the throat. However, under certain conditions, this shock can pop out of the inlet at higher Mach numbers; i.e., an "unstart." When this happens, the airplane is jarred

quite violently, pitches nose-up slightly, yaws away from the unstarted inlet, and rolls into the unstart. The pitch and yaw experienced on the XB-70 are mild, and about one-fourth aileron is required to overcome the rolling tendency, as shown in Fig. 15. The net thrust goes down and the drag increases, producing a sudden deceleration of about 0.2 g, causing the pilot to momentarily push the column forward. The automatic inlet control system causes a restart almost immediately, but during the short period before normal operation is resumed, the airplane can decelerate 0.1 to 0.2 Mach number.

Over 90 inlet unstarts, mostly deliberate, have been made. While they have been demonstrated to cause no structural damage or extreme airplane motions to the XB-70 because the inlets are located close to the centerline of the airplane, each unstart is startling, even to a crew experienced in flight testing.

After completing the high Mach number portion of the flight, the airplane is usually decelerated at constant altitude to 400 knots indicated airspeed, and then descended at constant airspeed to subsonic speed at 35,000 to 40,000 feet. The unstarts which occur just above Mach 2 while decelerating are mild. A normal jet penetration to the field is made subsonically. Approach and landing are not difficult, and visibility and depth perception are good. The technique used is normal and straightforward, and the response of the airplane is good. Rumor once had it that an airplane with a very long fuselage would be difficult to land due to the low response rate in pitch. This is definitely not the case with the XB-70A. The longitudinal control is excellent

and speed stability at approach speeds is good. In addition, the airplane enjoys good power response at low speeds, making it easy to control approach speeds accurately. The average rate of sink at touchdown has been approximately 3 feet per second, which is comparable to present day jet transports.

In summary, the pilots feel that the XB-70 is a very impressive airplane. While Mach 3 flight was not achieved without setbacks, and developmental problems, it is significant that sustained Mach 3 flight was attained with only two minor changes to the initial aerodynamic configuration.

1. The aileron feel bungee was replaced with a heavier spring to double the gradient because the pilots felt the aileron control forces were too low.
2. The operational procedures were modified to put the tips to the one-half position at 0.95 Mach number, instead of 1.4 Mach number, to improve the lateral-directional flying qualities at transonic speeds. This was later altered, by suggestion of the pilots, to put the tips to the one-half position at 300 knots.

It is important to point out, however, that to say that the XB-70 is not difficult to fly at Mach 3, is not the same as saying that Mach 3 flight is not difficult ---- it is!

First, the high true velocity means that small errors in heading soon produce large errors in ground track, and the long times to turn inherent in high-speed flight mean that these errors take a long time to correct. In the other plane, the high velocity is translated into very high rates of climb or descent by very small errors in pitch attitude. The desirability of flying

right on the airspeed, altitude, and temperature limit in order to maximize performance means that speed and altitude must be controlled very carefully. The rapidity with which ground navigational aids are passed causes the crew to continually seek a new station which is within range. When flying cross-country rather than within a test range, the airplane goes from one FAA control center to another very rapidly.

It should be recognized that while Mach 3 flight can be routinely programmed, with high expectations of accomplishing the mission on time as scheduled, this is yet a pioneering experience. Development in the areas of instrument presentation, navigational aids, automatic flight control systems, automatic inlet control systems, and others are required to make high Mach number transportation a relaxing experience rather than an exhilarating adventure.

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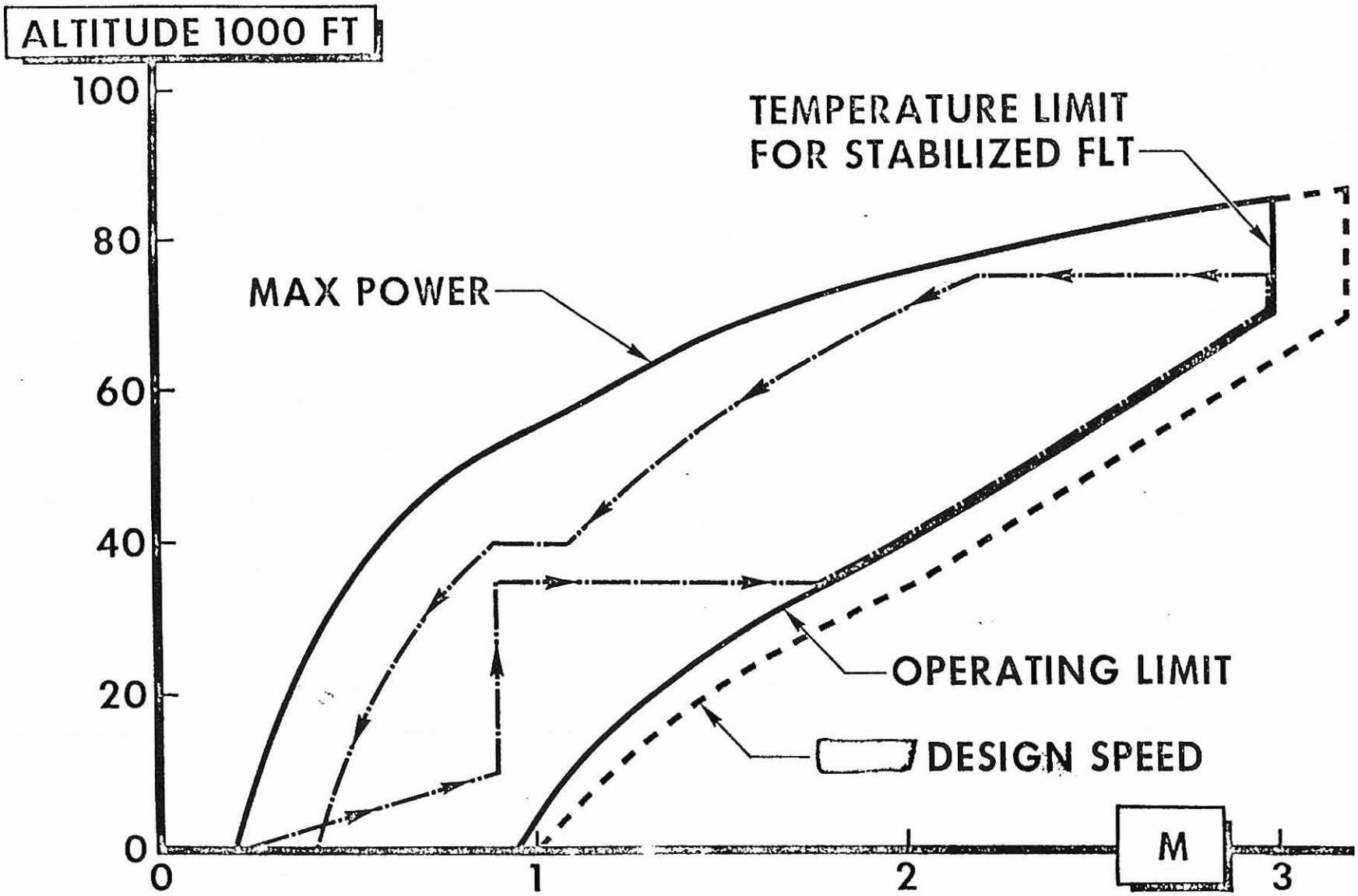


Figure 1. Typical Speed-Altitude Envelope for an SST Airplane

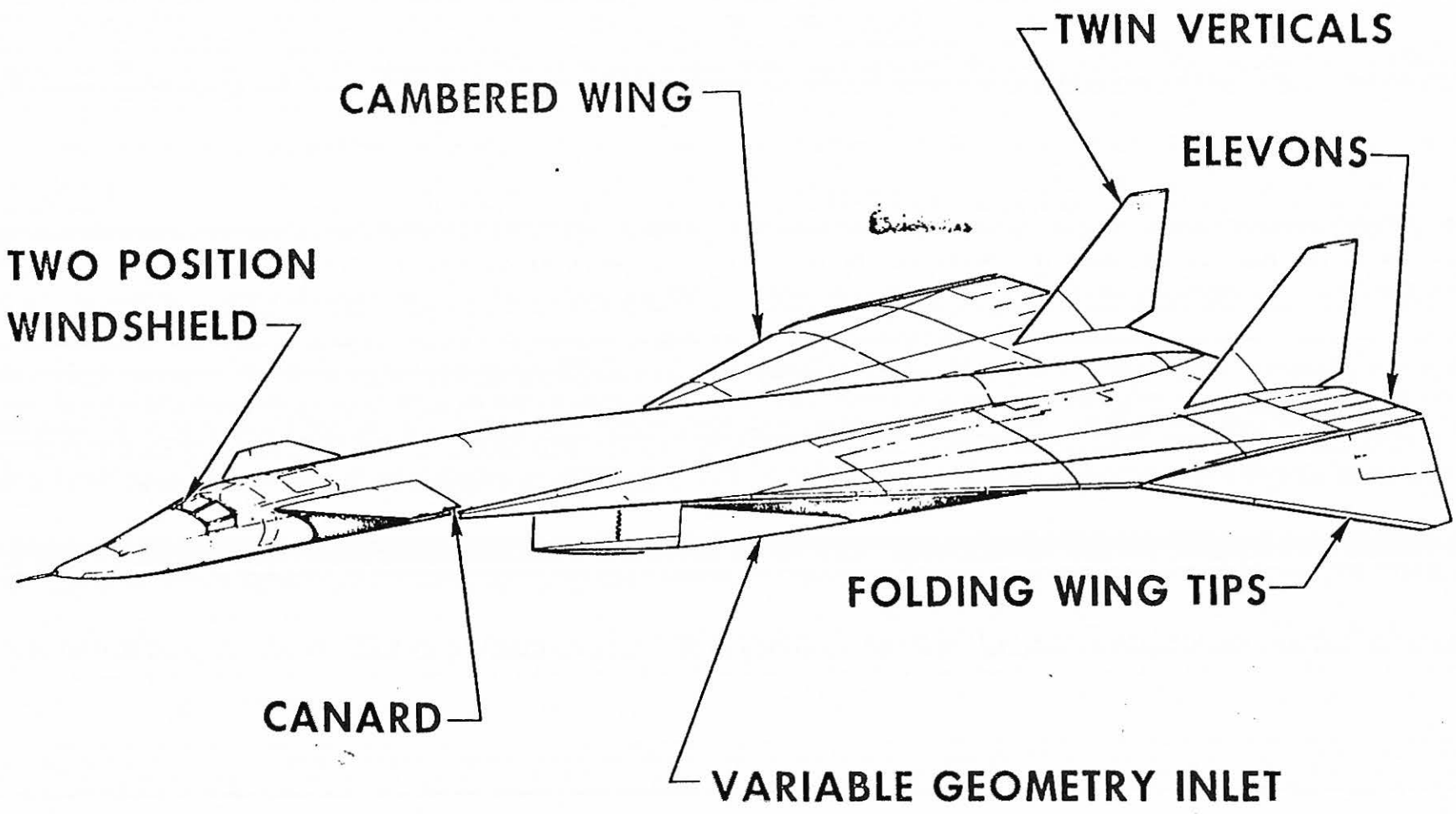


Figure 2. Aerodynamic Features

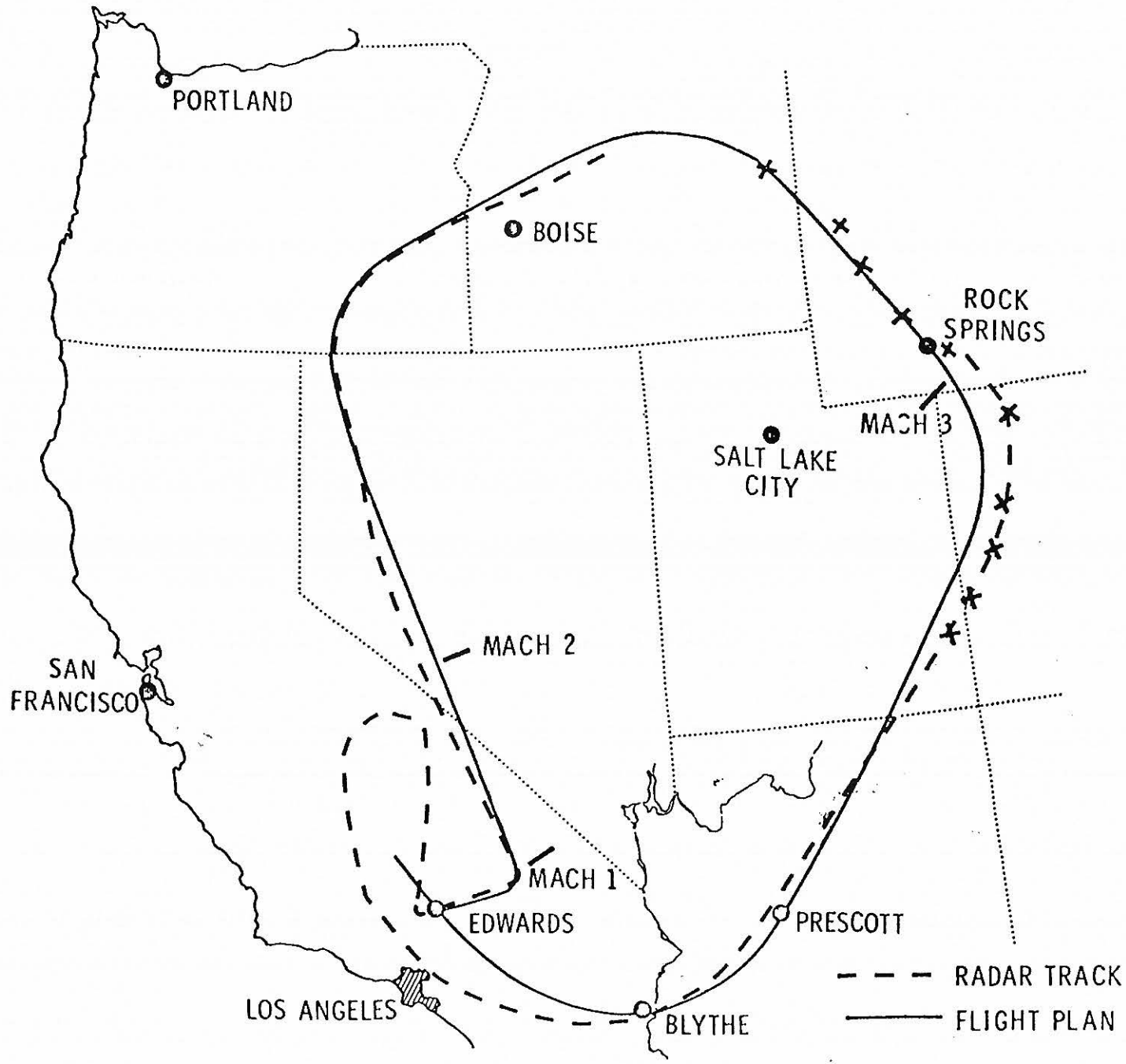


Figure 3. Flight Map

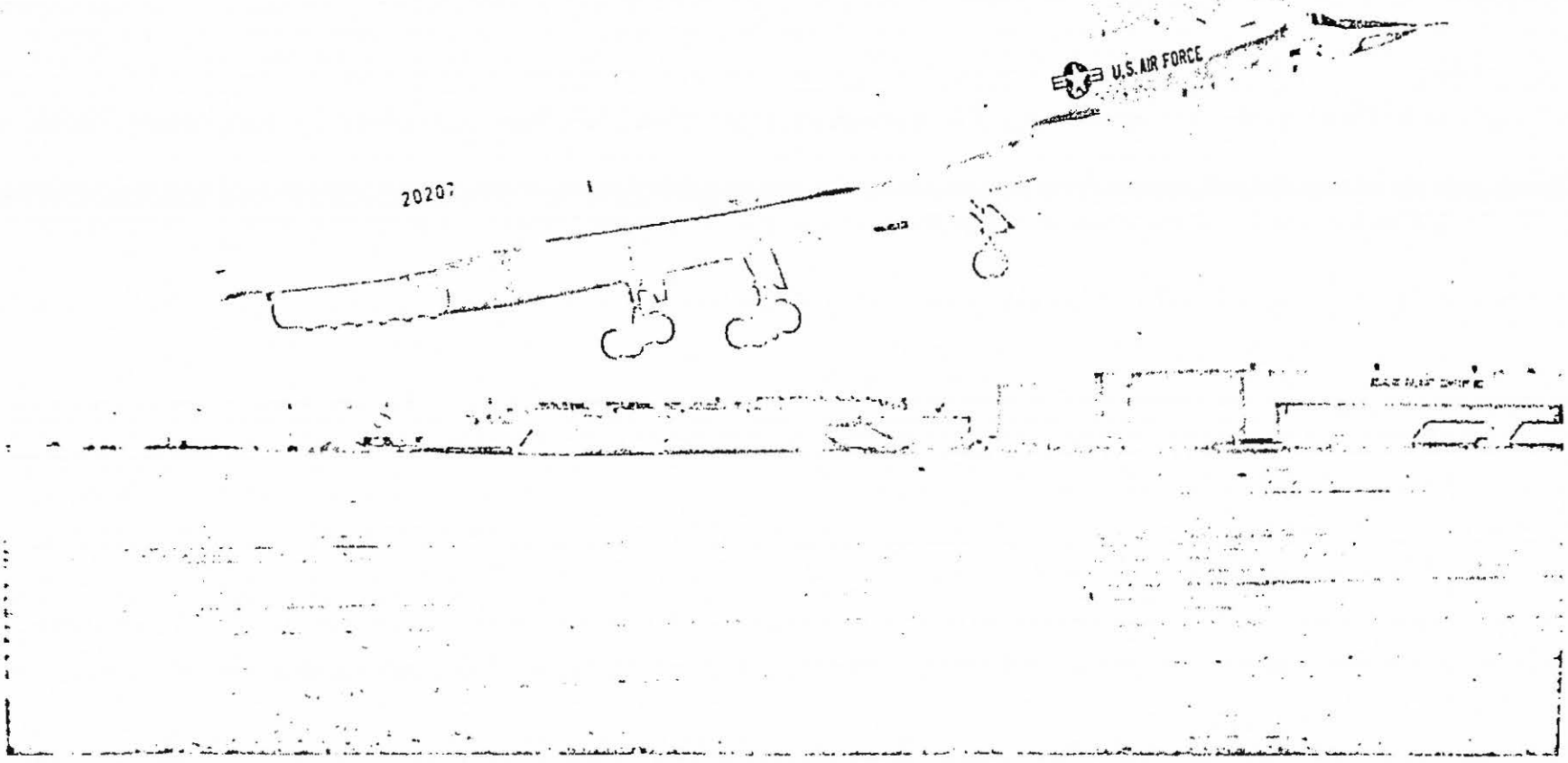


Figure 4. Takeoff

Figure 5. Subsonic Climb - Tips One-half Down

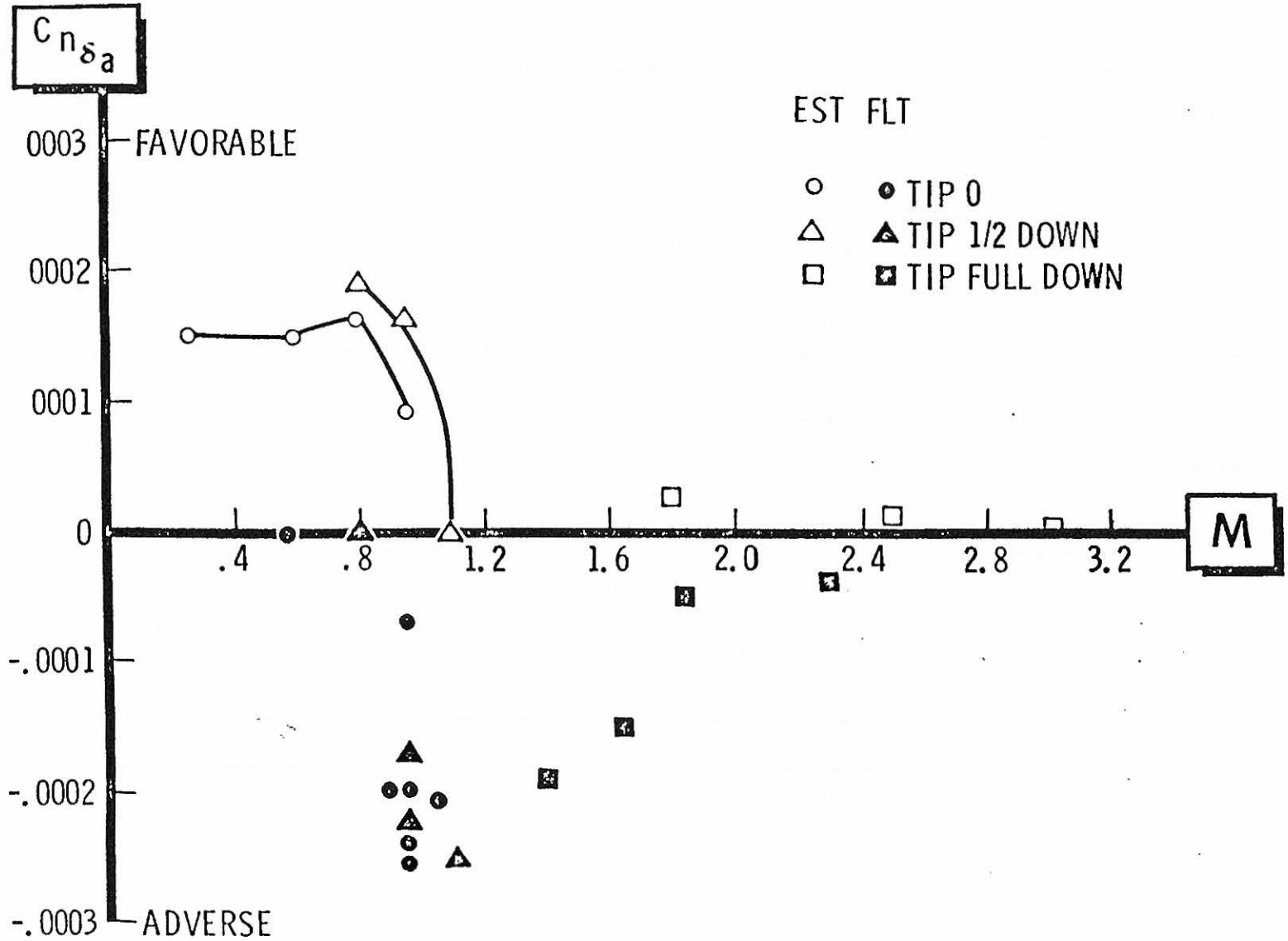


Figure 6. Yawing Movement Due to Aileron

Figure 7. Supersonic Flight - Tips Full Down

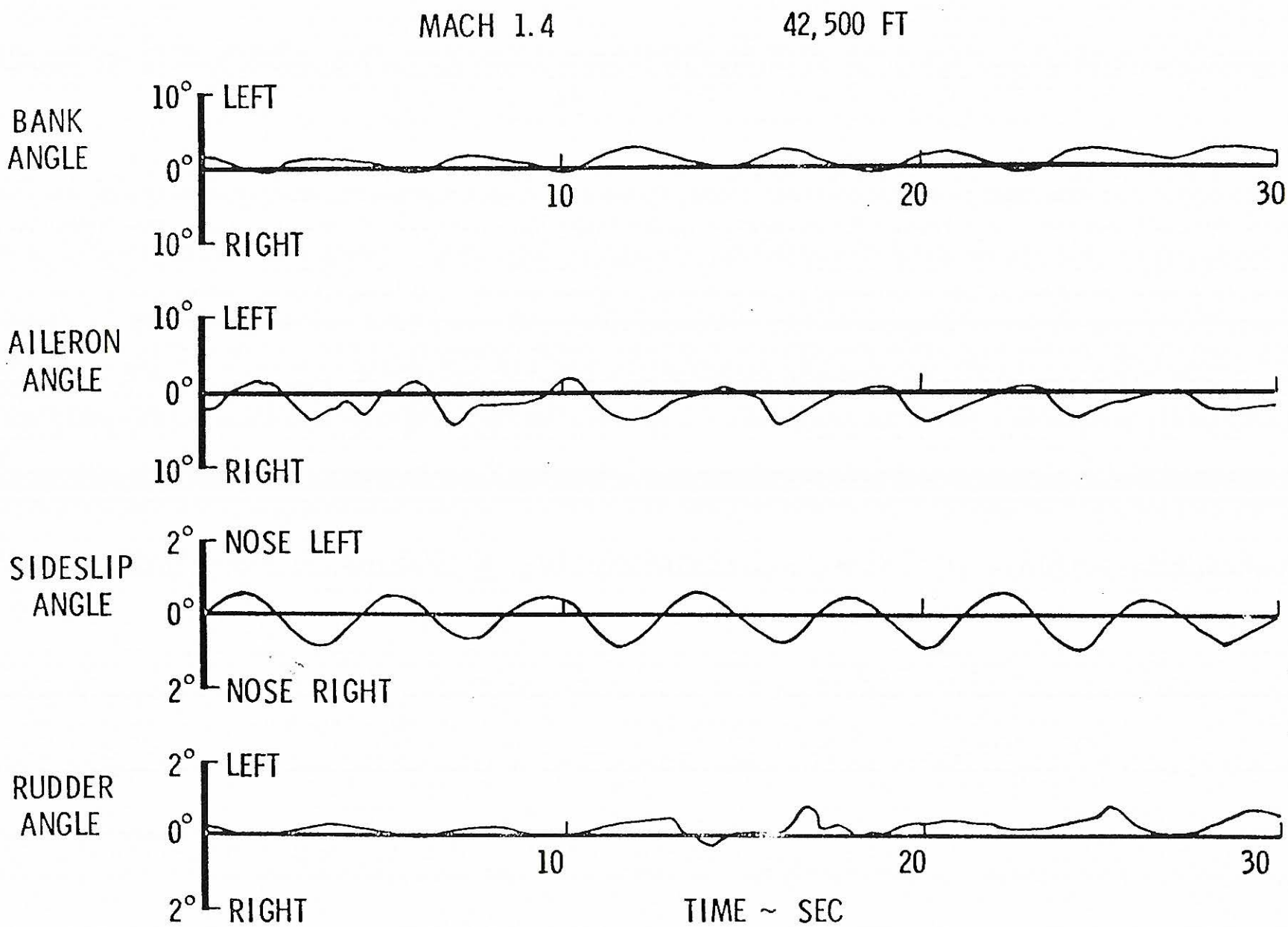


Figure 8. Lateral-directional Oscillation

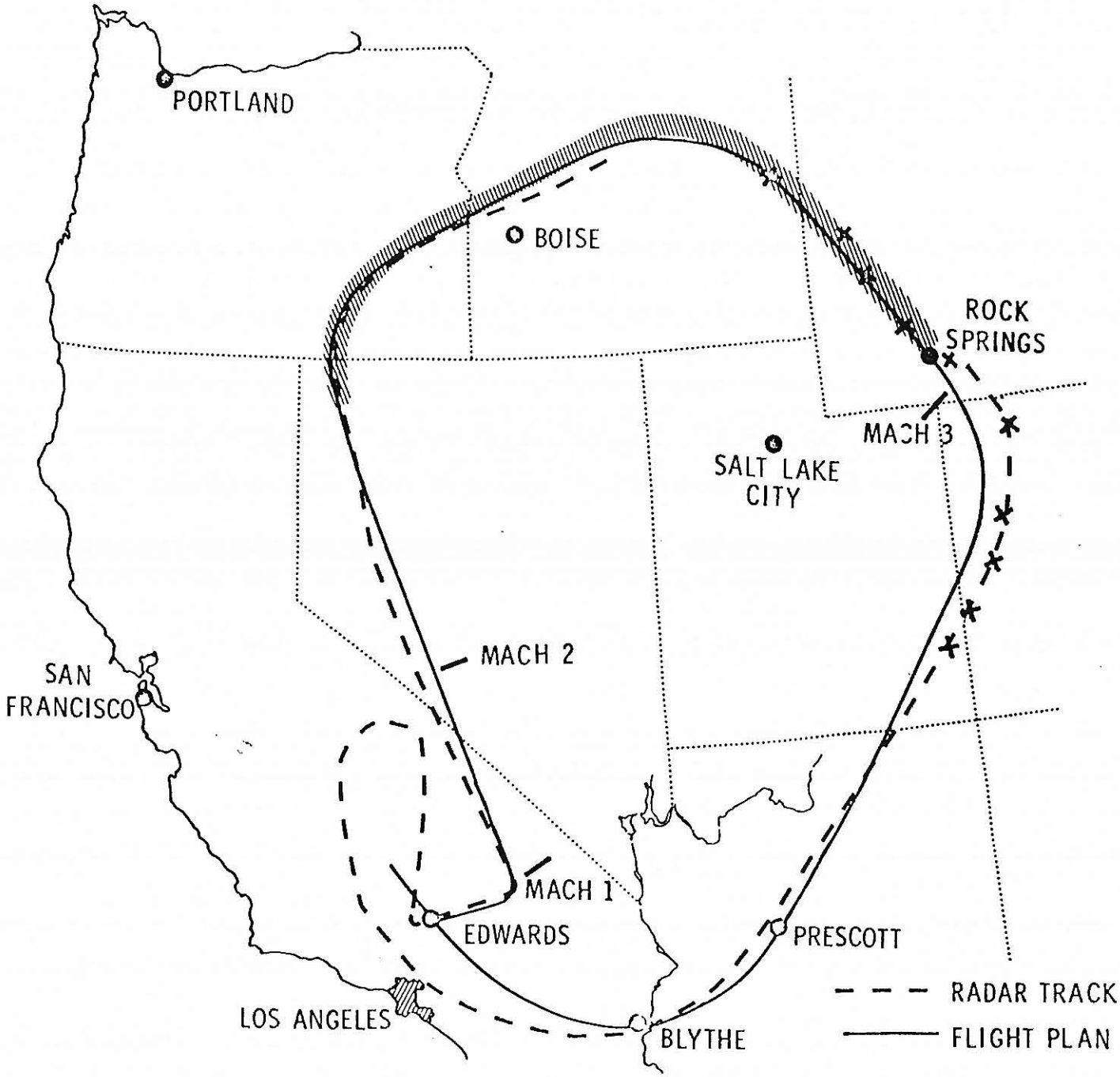


Figure 9. Flight Map - Supersonic Climb

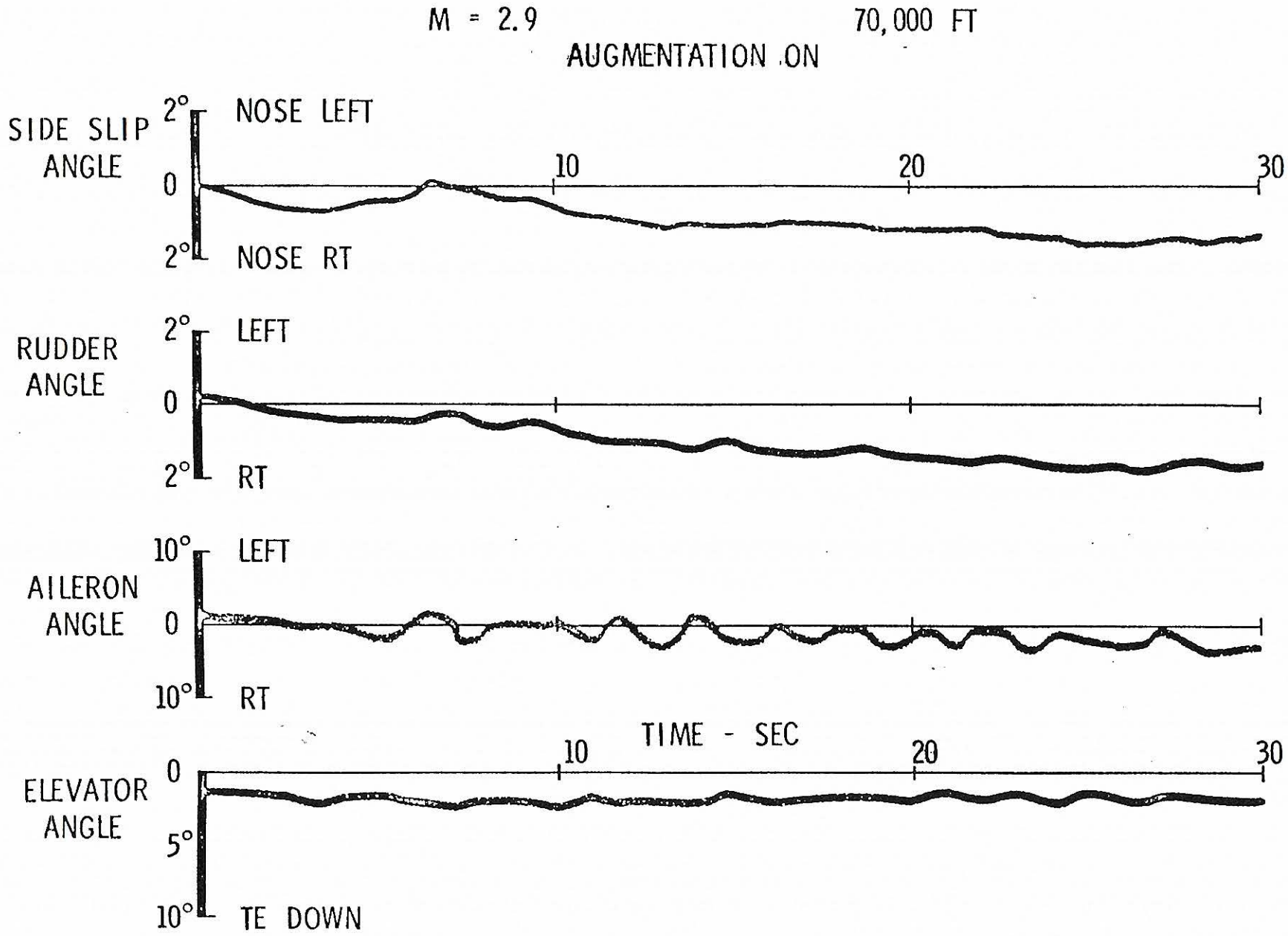


Figure 10. Time-History of a Sideslip Augmentation On

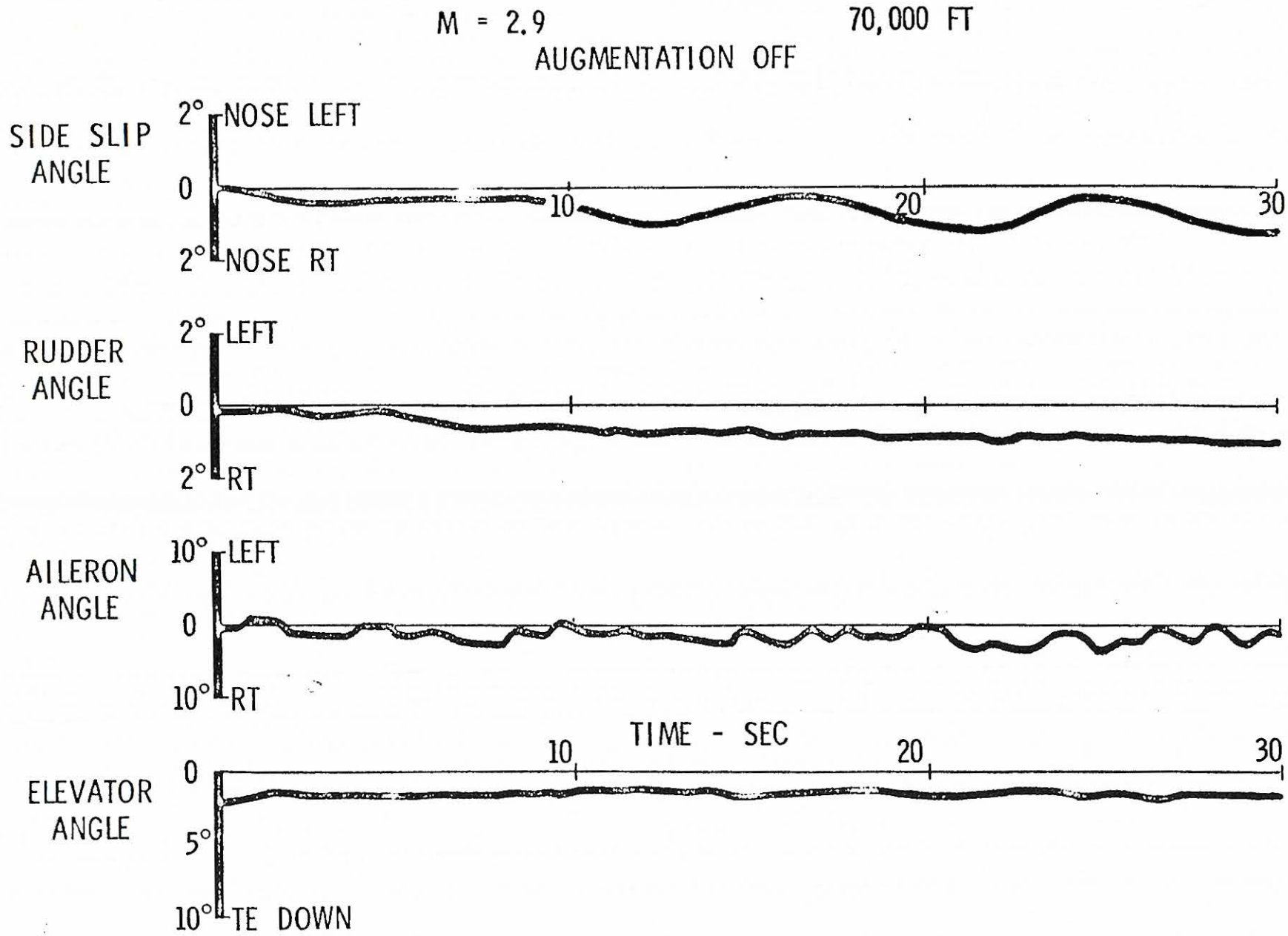


Figure 11. Time-History of a Sideslip Augmentation Off

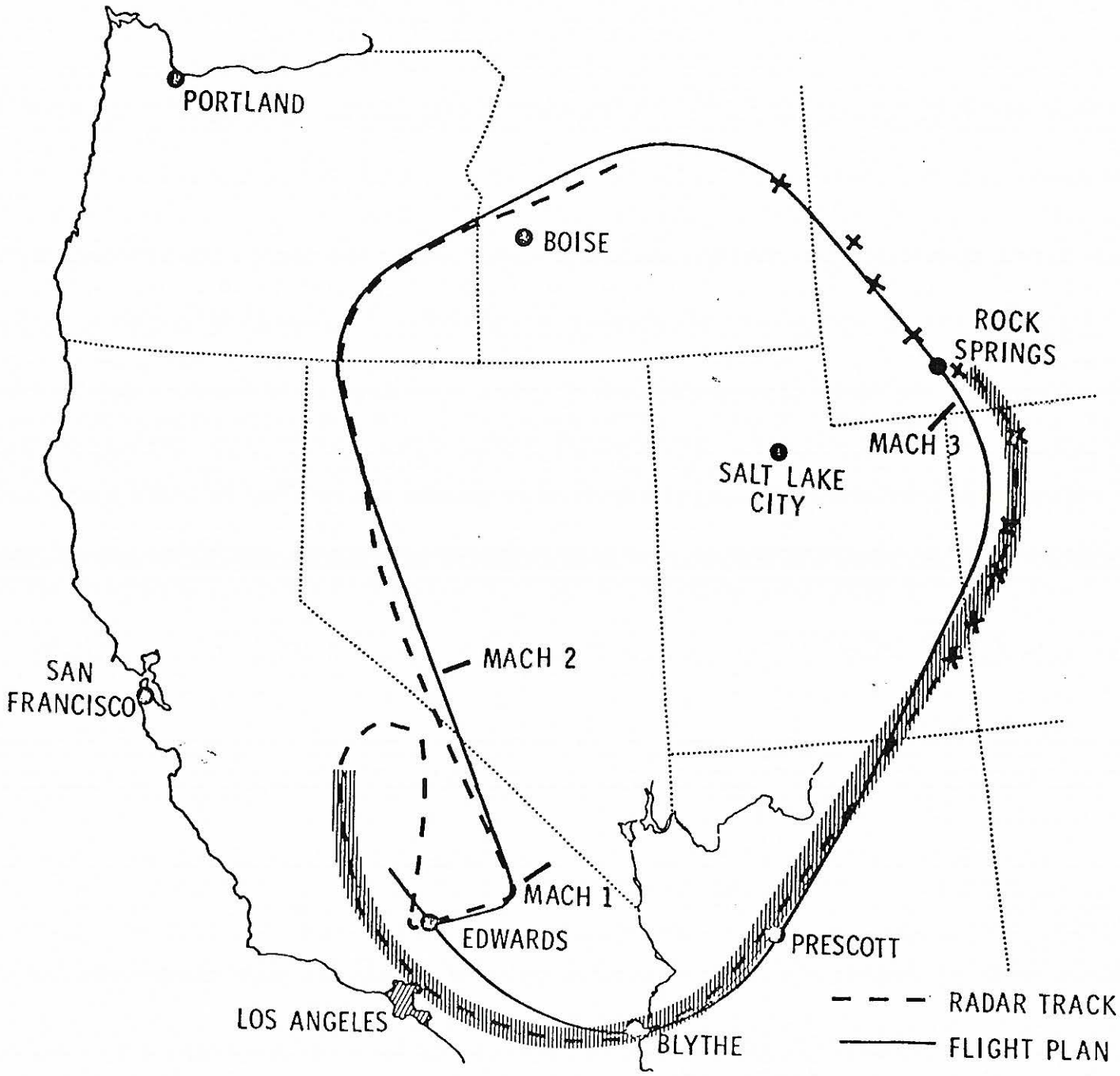


Figure 12. Flight Map - Mach 3

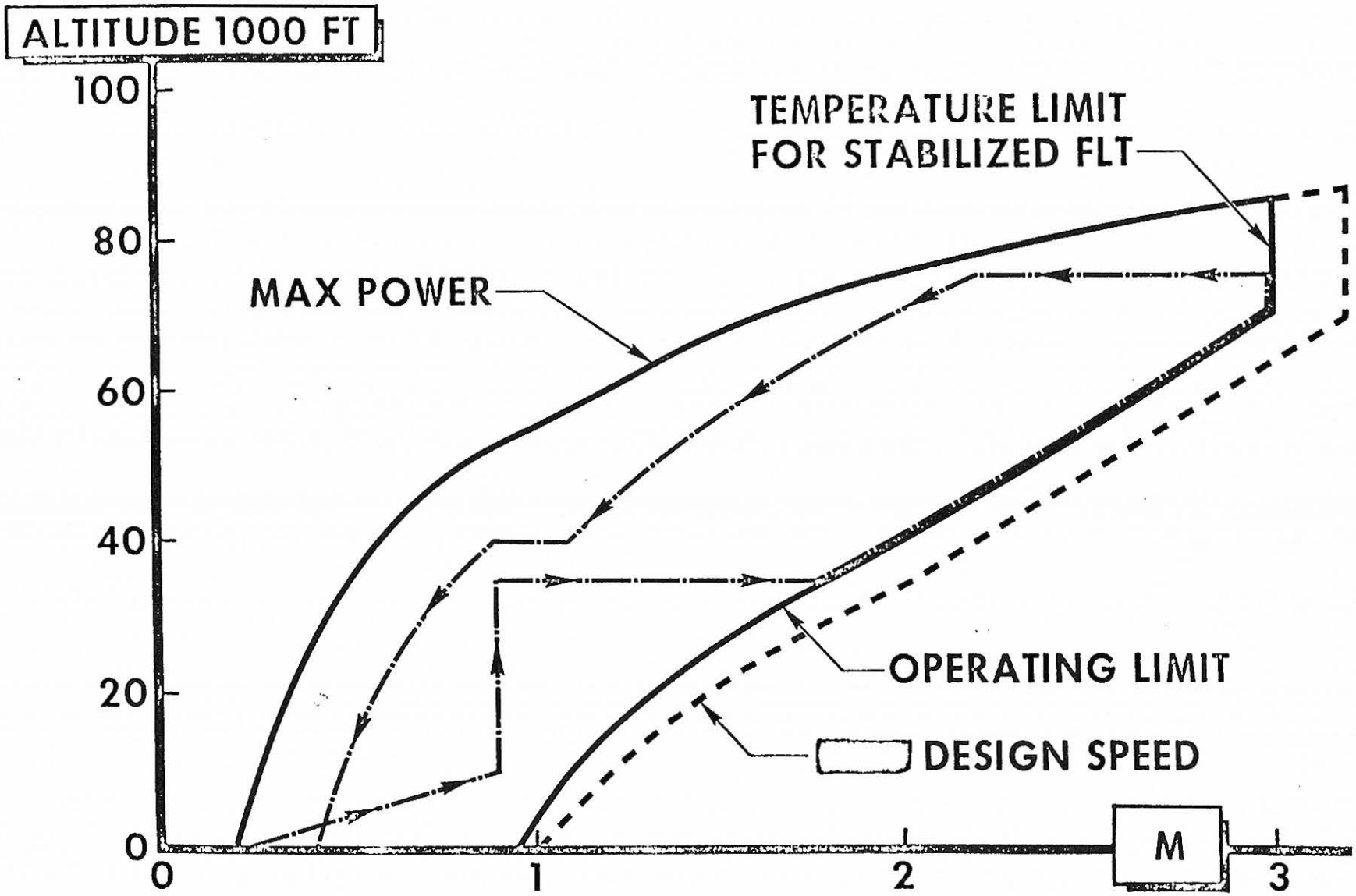


Figure 13. Speed-Altitude Envelope

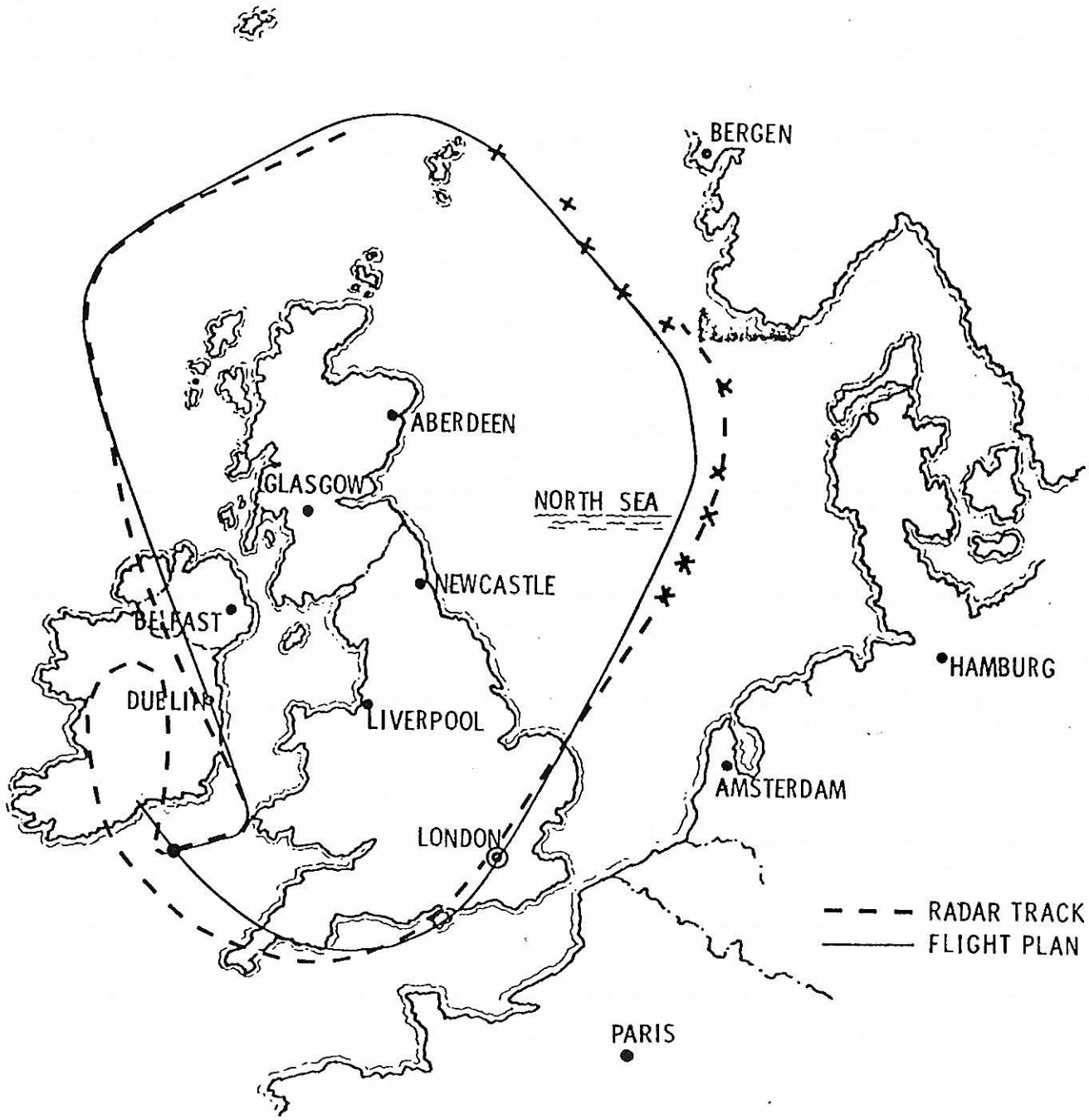


Figure 14. Flight Map - Superimposed on England

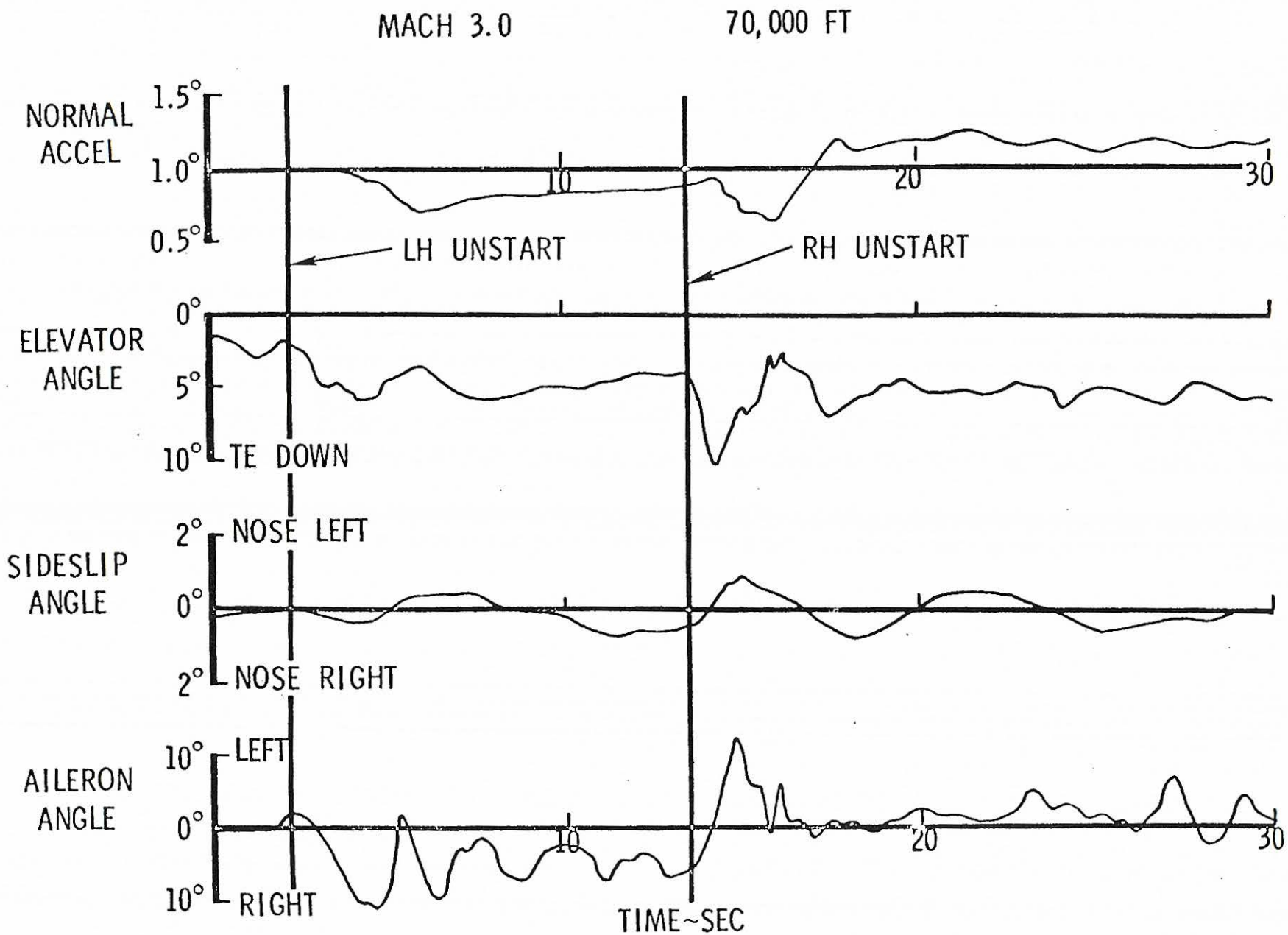


Figure 15. Transient Due to Unstart