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ABSTRACT

This report documents the location and extent of the impact corridor of the Skylab vehicle. Included in this discussion are summaries of the predicted breakup sequences and resulting footprint, methodology for reconstructing the actual breakup sequence and footprint, and an assessment of the overall impact footprint size.

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I. INTRODUCTION

When the Skylab vehicle reentered the earth's atmosphere on July 11, 1979, a great deal of attention was, quite naturally, focused on the question of where the surviving elements would impact. This report addresses that question.

Included in this report are brief descriptions of the predicted size of the impact area (footprint), the reconstruction of the actual impact area, and some pertinent conclusions.

II. PREDICTED FOOTPRINT

In studies performed in 1970 and 1973, personnel of the Lockheed Missiles and Space Company (LMSC) predicted that, assuming the Skylab vehicle began to break up at 400,000 feet (65 nmi or 120 km), debris from the Solar Arrays would begin to impact approximately 3600 nmi (6667 km) downrange from the breakup point (See References 1 and 2). This would define the "heel" of the impact footprint and all other debris would impact downrange of this point. The maximum distance any debris would travel, the "toe" of the footprint, would be 7400 nmi (13705 km) from the initial breakup point. Debris from the ATM was predicted to impact in this area. Figure 1 shows the predicted breakup sequence and associated altitudes, as forecast by LMSC. This figure is only included to illustrate the breakup sequence expected, and no significance should be attached to the relative positions of the traces after breakup, as it is not to scale.

← Breakup ALT

Shortly before Skylab reentered, in preparing for the footprint reconstruction activity, personnel from MSFC (EL25) performed a brief reentry study to assess the adequacy of our preparations. As a check, we compared our impact dispersions with those from the LMSC study (using the LMSC-predicted breakup sequence) and the results, with one exception, were in reasonable agreement. The one exception was the ATM case, with MSFC predicting impact some 2500 nmi (4630 km) farther downrange than LMSC. This difference could be accounted for by a difference in the Coefficient of Drag (C_D) used in the two studies. Although no detailed LMSC data are now available, one of the engineers involved in the LMSC study recalled using a C_D term no smaller than 0.3 for the intact ATM. The MSFC-determined C_D for the ATM was 0.1, a difference which could easily cause the downrange shift in the impact location. The results of the two studies are compared in Figure 2.

This study also served to provide us with a priori knowledge of the sensitivity of the footprint size to reentry parameters. The size of the footprint is a function of both the breakup altitude and the Ballistic Coefficient (BC) of the resulting pieces. The BC of any element is a function of its mass (M), area (A), and drag characteristics (C_D) and is calculated:

$$BC = \frac{M}{C_D A}$$

For breakup at any specified altitude, elements with greatly different BC's will produce a larger footprint than elements whose BC's are substantially the same. Also, given a set of BC's, breakup at higher altitudes will create a larger footprint than if these same elements break up at a lower altitude. The sketches in Figure 3 illustrate this relationship; however, this generality must be applied to Skylab with some caution. Due to the nature of the vehicle, the aerodynamic characteristics change markedly each time an element separates from the OWS. For example, when the OWS and ATM Solar Arrays separated, the mass loss was more than offset by the reduced area, with the result that the BC actually increased. This moved the impact point of the remaining elements farther downrange.

The problem of estimating impact location is complicated by the fact that each time a breakup event occurs, a new BC for the resulting elements must be determined. The general philosophy we used was to determine the trajectory of each major element (Solar Arrays, OWS, ATM, etc.) to a specified breakup altitude, then run only the resulting pieces with the smallest and largest BC's (taken from the LMSC reports) to impact. This defined the expected limits of each major element without requiring undue amounts of computer time or manpower. The same philosophy was used in the footprint reconstruction activity which is discussed in the succeeding paragraphs.

III. RECONSTRUCTION OF SKYLAB FOOTPRINT

As has already been pointed out, the length of the impact footprint is determined by the altitude at which an element breaks up and the Ballistic Coefficients of the resulting pieces. Since LMSC had previously estimated, in References 1 and 2, the BC's of the major assemblies (OWS, ATM, AM, IU), the prime concern was to define the altitude(s) at which these assemblies began to break up. It should be emphasized that this activity, while based on available data, is still somewhat of an art and not purely analytical, due to the lack of precise event timing, uncertainty about size and shape of elements after breakup, and the accuracy limits of observations. Essentially, the procedure was to adjust the breakup altitudes so that the predicted BC's resulted in reentry profiles which agreed with the available data.

Data used to reconstruct the reentry history came from several sources. They were:

- o Special perturbation vectors from NORAD
- o Tracking from the radars at Bermuda and Ascension Islands on the final revolution
- o Telemetry data while over Ascension and Bermuda Islands
- o Special altitude observations from NORAD
- o Locations of recovered debris

In addition to the above data, state vectors provided by NORAD, especially those received in the final 24 hours, were assessed to insure continuity of the trajectory. The following paragraphs describe in more detail the data used and how it affected the footprint determination.

During the 48 hours prior to reentry, a very important source of data was the special state vectors provided by NORAD. These vectors differed from the standard vectors in that they were determined from fewer sets of tracking data and thus were not as strongly influenced by the effects of long-term perturbations, such as solar activity. The importance of these vectors is that they were used to help determine the time at which any maneuver to shift the probable impact point should be initiated. This determination was made possible by analyzing the family of impact points resulting from these vectors. The initial reconstruction activity used these predicted impact points before other data was available to help assess the probability of a specific breakup sequence. These state vectors also proved valuable in helping determine the aerodynamic profile affecting the vehicle as it approached the reentry altitude. The altitude history derived from these vectors is shown in Figure 4. This altitude profile fit our reconstruction very well and increased our confidence that we had a good estimate of the altitude profile to begin the analysis which was based on the T-7 hrs NORAD vector.

Sets of tracking data were provided by the Bermuda and Ascension Island radars on the final revolution. Data from these trackers indicated an altitude of approximately 62 nmi (115 km) and 57 nmi (105 km) respectively, over these sites. Each of these trackers reported contact with a single target during their observation; this would indicate that separation of the ATM from the OWS had not occurred, at least down to 57 nmi (105 km). This is a significant point, since footprint predictions had been predicated on breakup beginning at 65 nmi (120.4 km).

KEY POINT

Further confidence in a later-than-expected breakup was provided by analyzing downlinked electronic data received while the vehicle was over Bermuda. This data indicated that the OWS and ATM solar arrays were still intact and functioning at that point. It appears that sometime after the Bermuda pass, and prior to Ascension acquisition, the OWS solar arrays, while still attached, may have folded back against the OWS. Analysis of the Ascension telemetry data supports this conclusion since, during this pass, downlinked electrical data indicated the OWS Array was still intact but no longer yielding expected currents and voltages.

Subsequent to the tracking data provided by the Ascension Island site, some special observations were received from NORAD. These observations consisted of the altitude and time at which various elements disintegrated. It is not possible to concretely establish a relationship between the observations and the specific element, but given other data (aerodynamic characteristics, predicted breakup sequence, and location of recovered pieces), it is possible to use this data to support a probable sequence of events. The procedure used was to construct theoretical breakup sequences based on available data and then determine a "most probable" sequence based on how well the altitude profile (vs. time) of each fit these special observations. Figure 5 shows how the ATM, OWS and AM debris envelopes from the most probable breakup sequence compared to these observations. It is clear from this data that nearly all of the observations are contained within the OWS/IU/AM debris envelope. This further supports the breakup sequence reconstruction.

The final set of data available was the actual location of recovered debris. While much of the debris impacted in the Indian Ocean, several pieces were recovered on land. These pieces were from the OWS and AM and were found in an area within the reconstructed reentry corridor and between Esperance and Rawlinna in Southwestern Australia. No debris from the ATM has been recovered, and it is assumed that, because of its higher BC, all this debris probably impacted northeast of Rawlinna (See Figure 6). This is a very sparsely settled area, practically inaccessible, and it is doubtful if any of the ATM debris will ever be found. Table 1 provides a list of the recovered pieces and their location.

IV. SUMMARY

Analysis of all available data leads us to believe that breakup of the Skylab assembly occurred at somewhat lower altitudes than predicted. While it is impossible to be precise concerning the breakup sequence, the one determined by this effort, summarized below, does fit well with all the data available to date.

The Solar Arrays, instead of breaking off cleanly, probably folded back against the main structure, and remained attached to a much lower altitude than expected before breaking off. This served to reduce the size of the footprint, since the minimum uprange point (the "heel") is determined by the Solar Arrays impact. The actual breakup process probably did not begin until approximately 54 nmi (100 km) altitude, when the ATM and Solar Arrays separated from the OWS assembly.

The ATM, which as a separate entity had a very high BC compared to the other elements, traveled the greatest distance downrange, probably impacting northeast of Rawlinna (dashed area on Figure 6). Failure to recover any ATM debris makes this a somewhat hypothetical conclusion, but the separation point is almost mandated by the better-known reentry histories of other elements, discussed below, and the resultant ATM trajectory is based on known aerodynamic data. The failure to recover any ATM debris could well be due to the probability that all of it impacted northeast of Rawlinna. The special NORAD observations, shown in Figure 5, do not fall within the ATM envelope resulting from this analysis, indicating that those observations were the result of OWS, IU, or AM debris. With the currently available data, it is not possible to determine the point at which the ATM itself began to break up and the length of the resulting footprint (Figure 6 represents a maximum dispersion).

The IU and AM probably separated from the OWS around 44 nmi (81.5 km). Locations of AM debris support this conclusion and also indicate that this element probably did not break up until near impact. Additional support is provided by the relationships of the OWS, AM, and IU debris envelopes to the special NORAD tracking observations, as shown in Figure 5. Separation at altitudes different than 44 nmi (81.5 km) do not fit these observations nearly so well. The location of recovered debris indicates the OWS probably began breaking up around 42 nmi (77.8 km), which caused much of this debris to impact in the Indian Ocean.

The following table compares the separation and breakup sequence developed by this analysis with the predicted sequence.

Element	Reconstructed Separation Altitude (nmi/km)	Reconstructed Breakup Altitude (nmi/km)	Predicted Separation Altitude (nmi/km)	Predicted Breakup Altitude (nmi/km)
Solar Arrays	54/100	54/100	65/120.4	65/120.4
ATM	54/100	(1)	58/107.4	45/83.3
IU, AM/MDA	44/81.5	(2)	48/88.9	48/88.9
OWS	-	42/77.8	45/83.3	45/83.3

(1) Insufficient data to estimate accurately.

(2) Debris of different BC's recovered in near proximity indicates breakup near impact.

V. CONCLUSIONS

The reconstructed Skylab footprint begins with the impact (theoretical) of the Solar Arrays' debris at 46.9S, 94.4E and extends to 26.0S, 131.2E, the maximum distance expected to be traveled by any of the surviving pieces. Figure 7 is included to illustrate the extent of the footprint, the length of which is approximately 2140 nmi (3963 km), 1660 nmi (3074 km) less than predicted. The difference is due to the lower-than-predicted occurrence of all the separation and breakup events. The reluctance of Skylab to break up not only reduced the size of the footprint, but moved the entire footprint farther downrange than expected. The absence of debris to pinpoint a "heel" (Solar Arrays) or "toe" (ATM debris) precludes any concrete determination of the footprint size, but the reentry sequence proposed here fits all available data quite well. Thus, it appears that the impact footprint described is a reasonable one.

TABLE 1

RECOVERED SKYLAB DEBRIS

ITEMS	PROBABLE SOURCE	LOCATION
Charred Fragments	OWS	33.9S, 121.9E (In Esperance)
Burned Material	OWS	33.9S, 121.9E (In Esperance)
Aluminum 356 Casting	OWS	33.7S, 122.1E (20 mi NE of Experance)
Foam Fiberglass Beam Section	OWS	33.9S, 122.0E (9 mi E of Esperance)
H_20 Tank Aft End	OWS	33.8S, 122.0E (9 mi NE of Esperance)
H_20 Tank	OWS	33.9S, 122.1E (10 mi E. of Esperance)
10' Steel Strip	OWS (H_20 Tank)	33.9S, 122.3E (25 mi E of Esperance)
Heat Exchanger	OWS (H_20 Cooler)	33.9S, 122.1E (12 mi E. of Esperance)
Segment of Fiberglass Sphere	OWS	33.9S, 122.1E (11 mi E of Esperance)
Insulation	OWS (Bulkhead)	33.9S, 122.1E (11 mi E of Esperance)
Aluminum Gear and Housing	OWS (Urine Separator)	33.7S, 122.5E (40 mi NE of Esperance)
N_2Tank	AM	33.2S, 122.6E (60 mi NE of Esperance)
Electronics Module	AM	33.5S, 122.3E (35 mi NE of Esperance)
N_2Sphere	AM	33.5S, 122.8E (49 mi ENE of Esperance in Neridup area)
Pressure Tank	IU	33.2S, 122.6E (60 mi NE of Esperance)

TABLE 1 (Continued)

RECOVERED SKYLAB DEBRIS

ITEMS	PROBABLE SOURCE	LOCATION
Film Vault Door	OWS	32.4S, 123.9E (5.5 mi NE of Balladonia)
O_2 Tank	AM	31.1S, 125.3E (5 mi S of Rawlinna)
O_2 Tank	AM	31.1S, 125.2E (15 mi SW of Rawlinna)
Steel Fragment	AM (Part of O_2 Tank)	31.1S, 125.4E (5 mi SE of Rawlinna)
Steel Dome	AM (O_2 Tank)	31.2S, 125.2E (15 mi SW of Rawlinna)

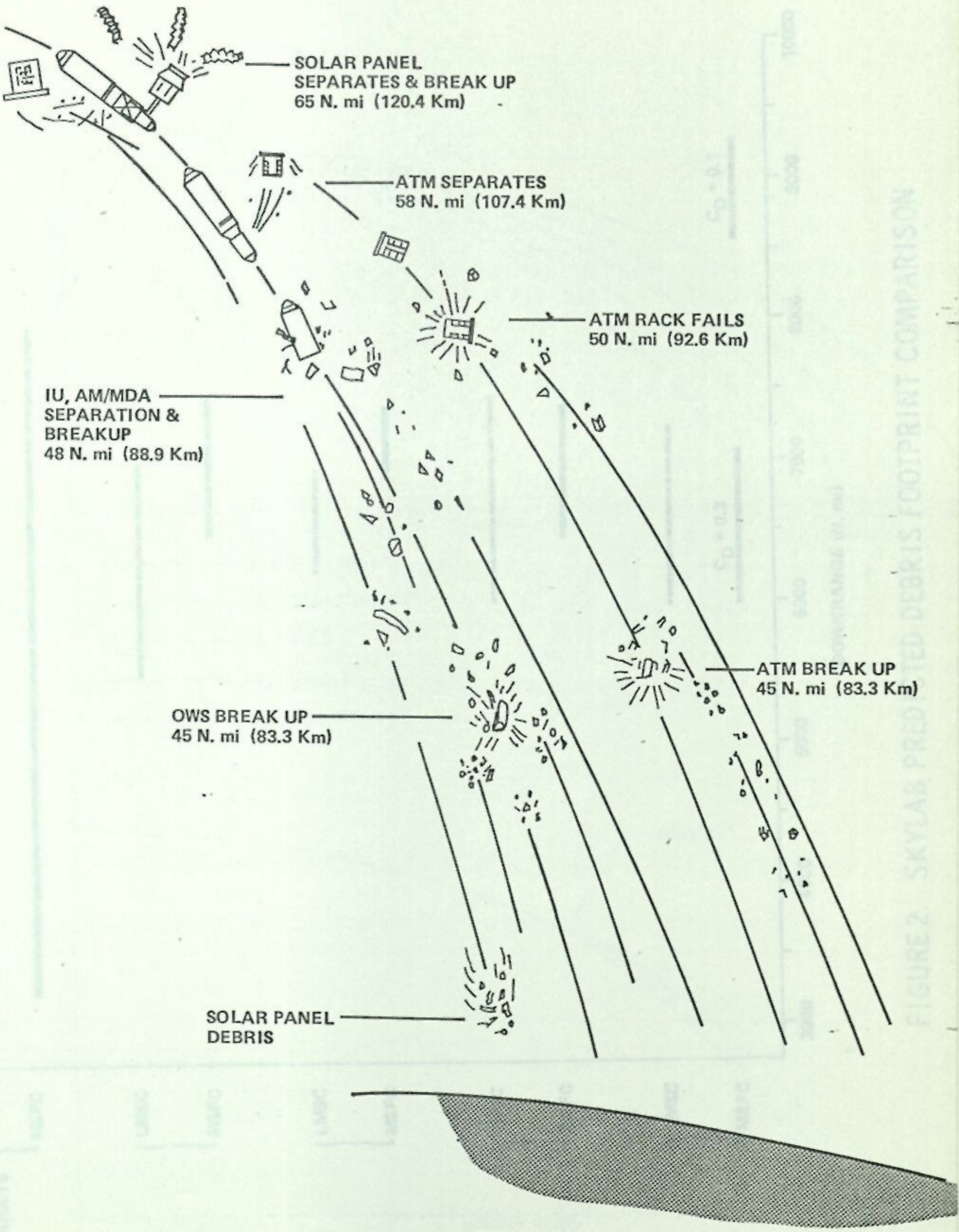


FIGURE 1 PREDICTED SKYLAB RE-ENTRY SCENARIO

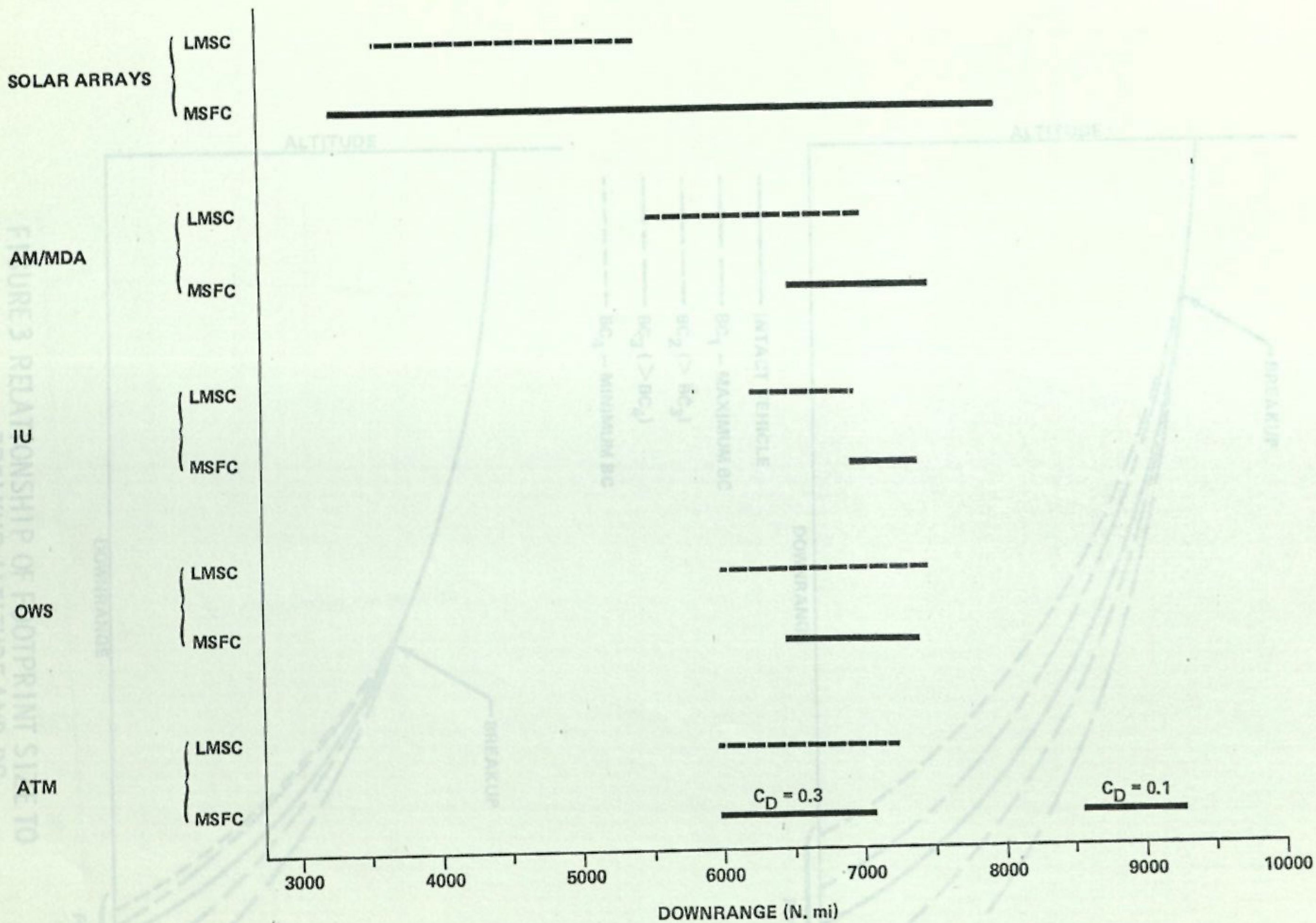


FIGURE 2. SKYLAB PREDICTED DEBRIS FOOTPRINT COMPARISON

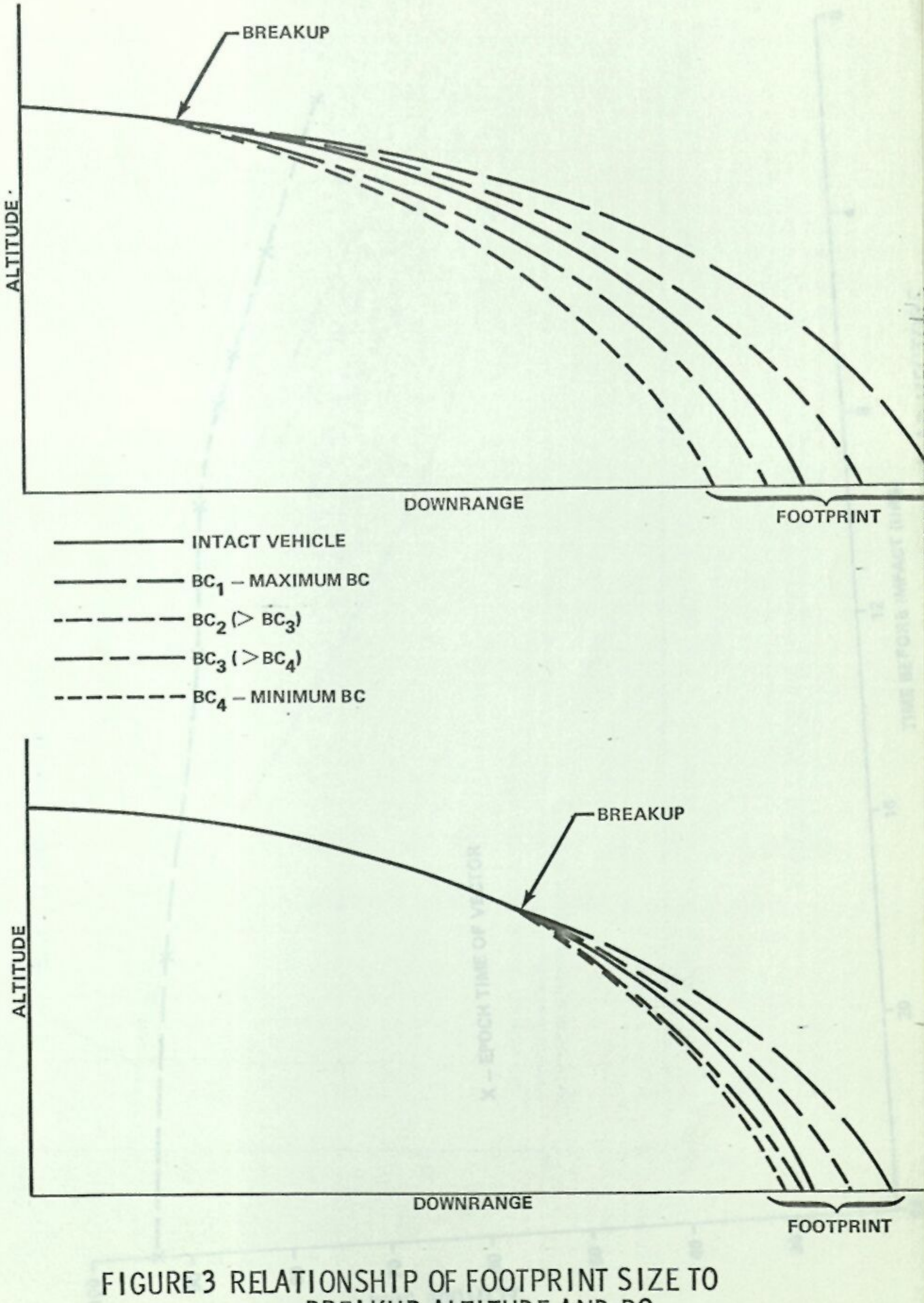
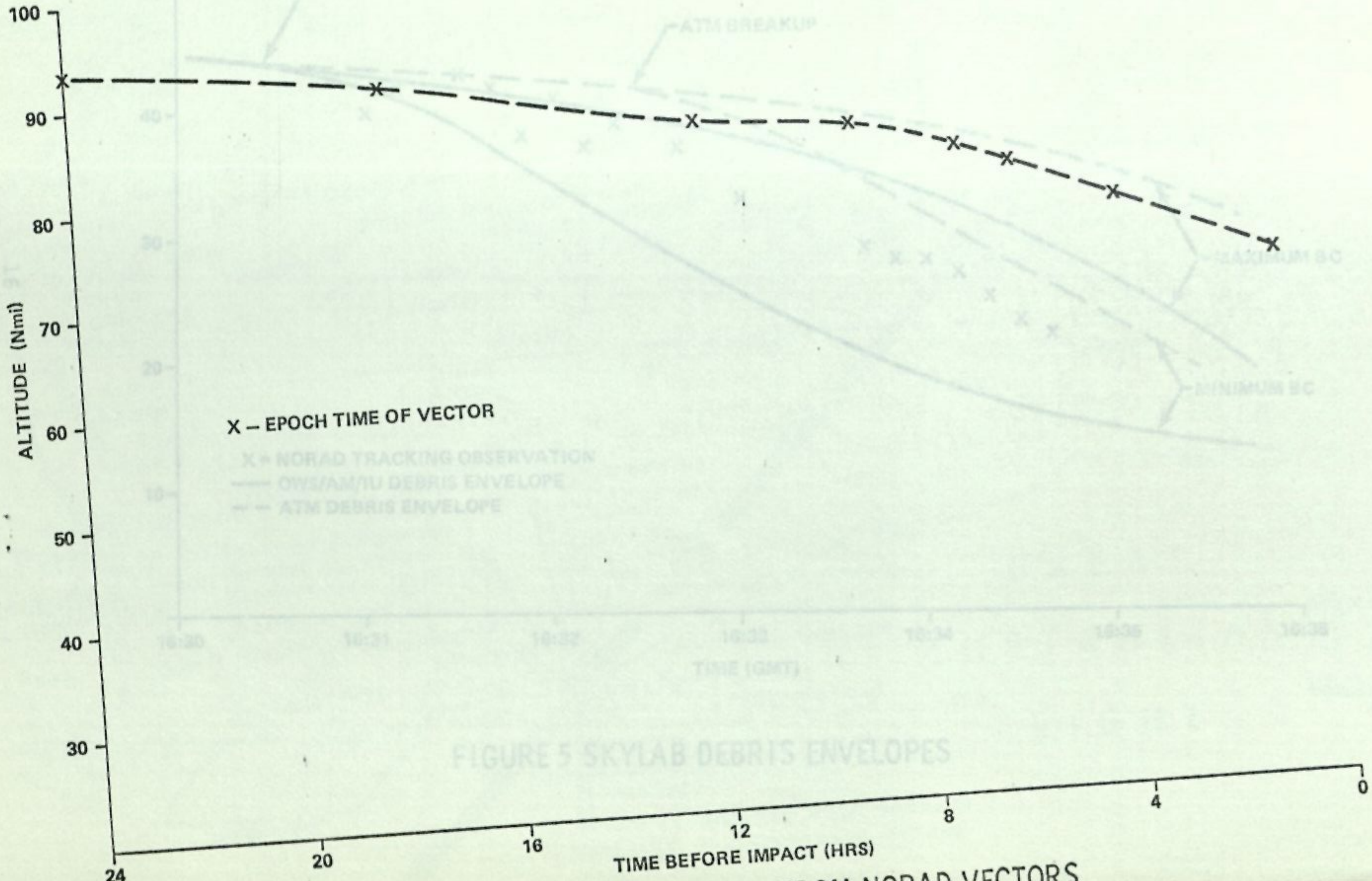


FIGURE 3 RELATIONSHIP OF FOOTPRINT SIZE TO BREAKUP ALTITUDE AND BC



... FROM NORAD VECTORS

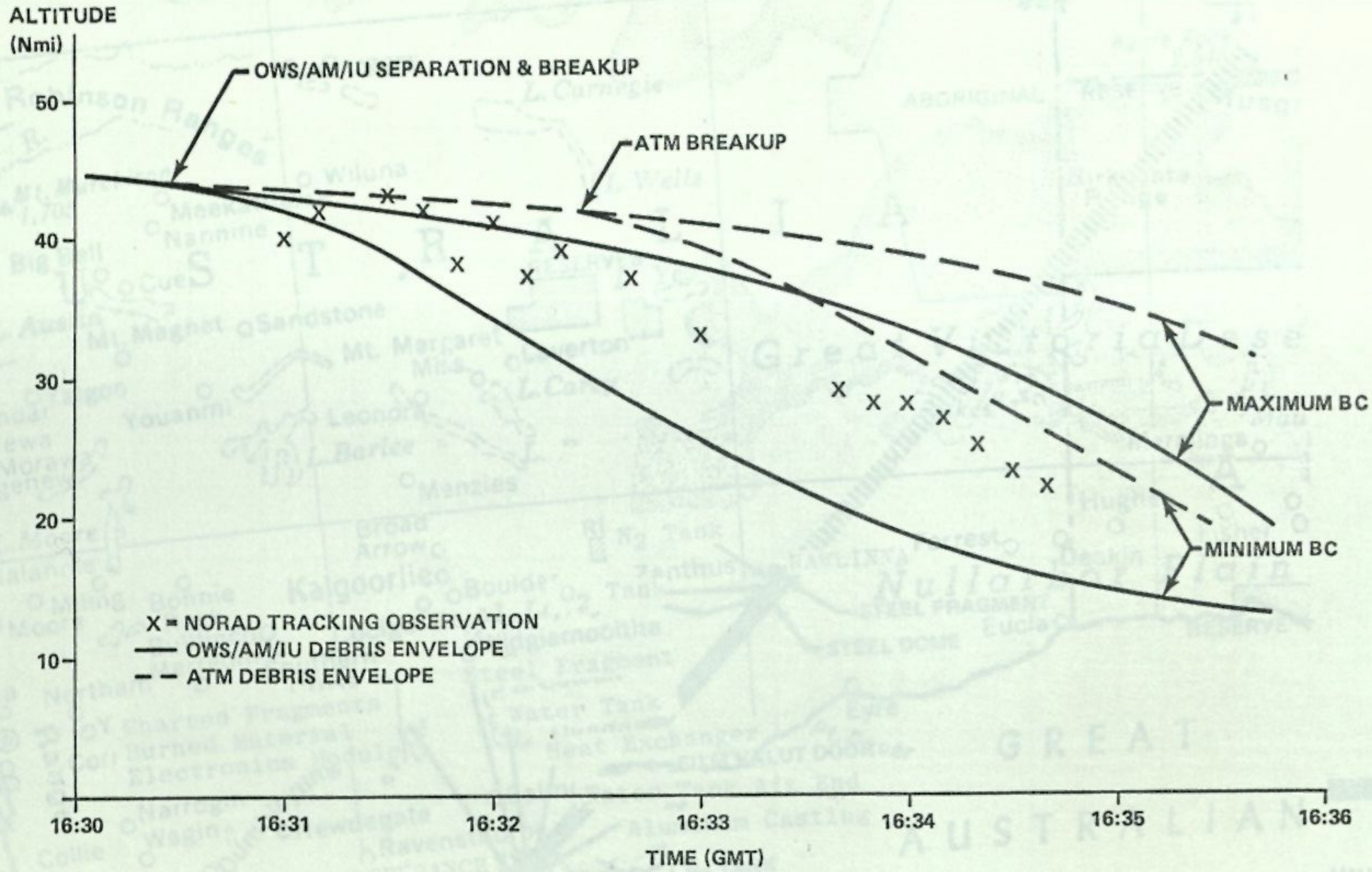


FIGURE 5 SKYLAB DEBRIS ENVELOPES

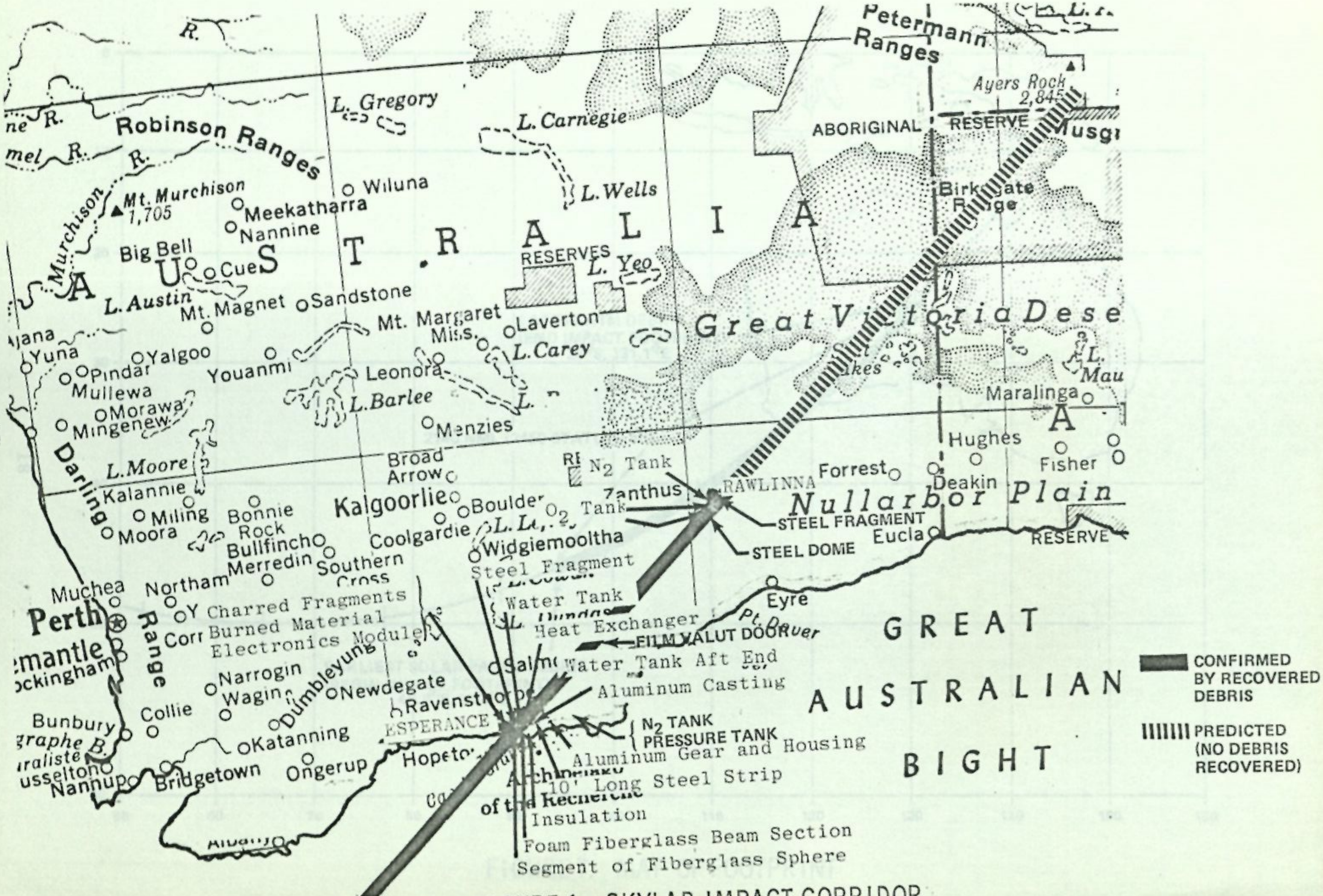


FIGURE 6 - SKYLAB IMPACT CORRIDOR

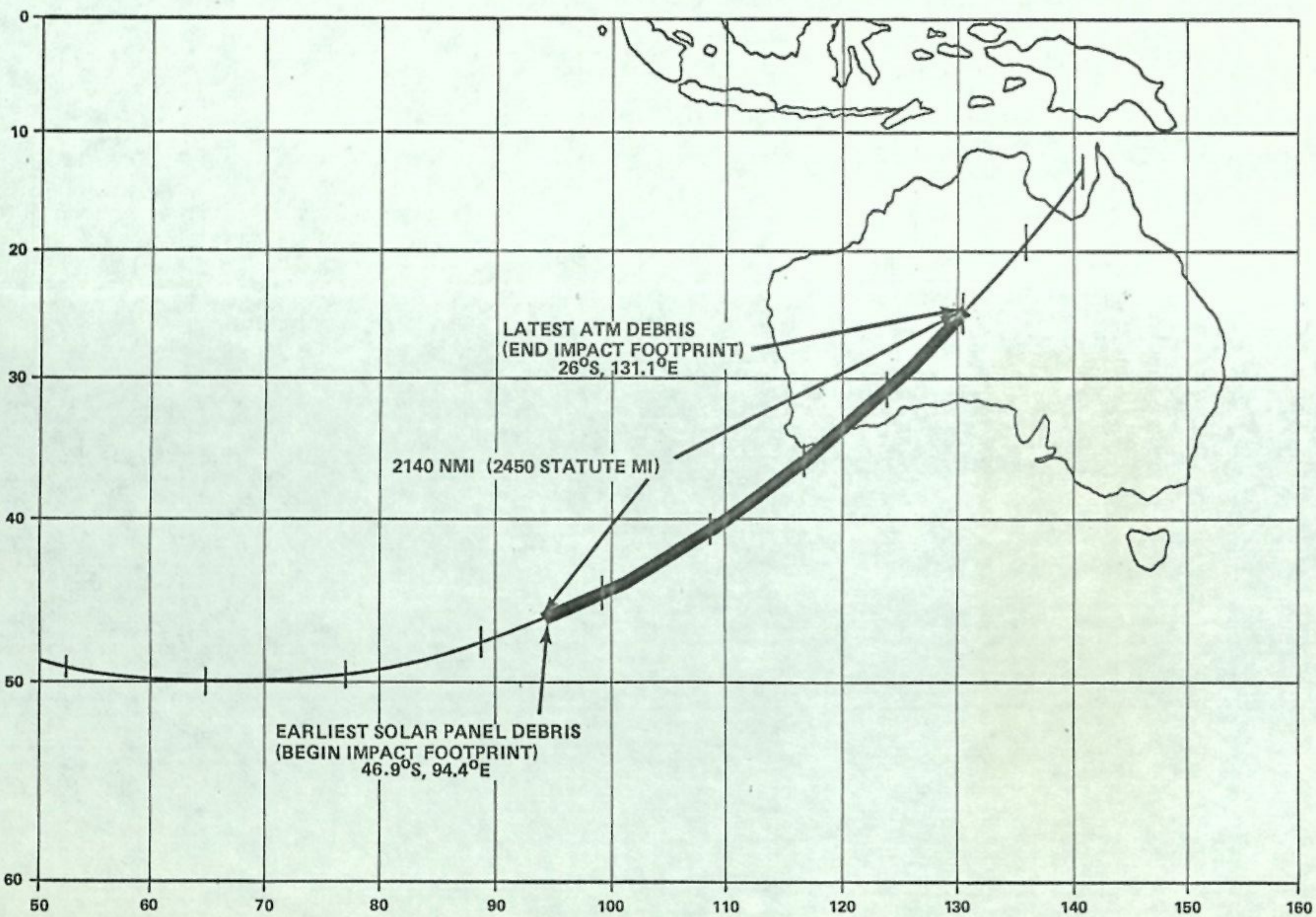


FIGURE 7. MAP OF FOOTPRINT