HAZARD ANALYSIS FOR THE BREAKUP OF SATELLITES 16937 AND 16938

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PREPARED BY

P. D. Anz-Meador
Scientist

D. L. Talent
Principal Scientist

R. H. Rast
Principal Scientist

APPROVED BY

R. C. Reynolds
Orbital Debris Project Leader

J. G. Carnes, Manager
Solar System Exploration Department

Prepared By

Space Systems Section
Solar System Exploration Department
Lockheed Engineering and Management Services Co., Inc.

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
LYNDON B. JOHNSON SPACE CENTER
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TABLE OF CONTENTS

Glossary of Acronyms and Abbreviations

Executive Summary

1.0 Introduction ........................................ 1-1
1.1 The Delta-180 Mission ............................. 1-2
1.2 The On-Orbit Safety Group ......................... 1-3
1.3 Summary of NASA Involvement .................... 1-3
   1.3.1 Goals. ....................................... 1-3
   1.3.1.1 Pre-mission Hazard Prediction .......... 1-3
   1.3.1.2 Post-mission Model Updates. .......... 1-4
1.3.2 Modeling ........................................ 1-4
   1.3.2.1 Scenarios ................................ 1-4
   1.3.2.2 Velocity Distributions ................. 1-5
   1.3.2.3 Linear Momentum Transfer ............. 1-5
1.3.3 Field Measurements ............................ 1-7
   1.3.3.1 DoD Radars. .............................. 1-7
   1.3.3.2 Meteor Radar. ............................ 1-7
   1.3.3.3 Ground-based Optical/IR ............... 1-7
   1.3.3.4 Airborne Optical. ....................... 1-8

2.0 Pre-mission Predictions ........................... 2-1
2.1 Flux in the LEO Environment ..................... 2-14
   2.1.1 Short-term Flux Predictions ............ 2-18
   2.1.2 Mid-term Flux Predictions ............... 2-20
   2.1.3 Long-term Flux Predictions ............. 2-20
2.2 Orbit Lifetimes .................................. 2-22
2.3 Summary of Predictions ......................... 2-22
3.0 The Measurement Campaign ............................................. 3-1
  3.1 DoD radars. .......................................................... 3-3
    3.1.1 Eglin. ............................................................. 3-3
    3.1.2 Kiernan Reentry Site (KREMS) Measurements. ........... 3-10
    3.1.3 Other DoD Radar Measurements .................................. 3-22
    3.1.4 NAVSPASUR. ...................................................... 3-27
  3.2 Meteor Radar Measurements ......................................... 3-30
  3.3 Optical/IR Ground-based Measurements. .......................... 3-33
    3.2.1 AMOS/MOTIF/GEODSS. ............................................ 3-33
  3.4 Airbourne Optical Measurements. .................................. 3-45
  3.5 Summary of Optical/IR Data. ...................................... 3-49

4.0 Comparison of Pre- and Post-mission Data .......................... 4-1
  4.1 Piece Count and Size Distribution ................................. 4-1
  4.2 Linear Momentum Transfer. .......................................... 4-13
  4.3 Velocity Distributions. ............................................ 4-13
  4.4 Size vs. Optical Magnitudes of Debris ............................ 4-15
  4.5 Object Lifetimes. ................................................... 4-22

5.0 Conclusions. ........................................................... 5-1

Appendix A. Pre-mission Modeling

Appendix B. Teledyne-Brown Report

Appendix C. Systems Planning Corporation/Remote Sensing Report

Appendix D. Primary Distribution List for Delta-180 Final Report
LIST OF FIGURES

Figure 1-1 Fragmentation Velocity vs. Size Distribution ........................................... 1-6
Figure 1-2 Facility Identification, Maui, HI ............................................................... 1-9
Figure 2-1 On-orbit Breakup Program Structure ......................................................... 2-2
Figure 2-2 Illustration of Overlap Area for Grazing Collision .................................... 2-4
Figure 2-3 Debris Velocity Distribution ............................................................................ 2-7
Figure 2-4 Gabbard Diagram: 100% Kinetic Energy Transfer Scenario ............................ 2-8
Figure 2-5 Gabbard Diagram: 50% Kinetic Energy Transfer Scenario ............................ 2-9
Figure 2-6 Number vs. Inclination: Head-on Collision ................................................. 2-11
Figure 2-7 Number vs. Inclination: Grazing Collision .................................................... 2-12
Figure 2-8 Number vs. Inclination: Explosion Scenario ................................................ 2-13
Figure 2-9 Flux vs. Altitude: head-on Collision post 1 year ........................................ 2-15
Figure 2-10 Flux vs. Altitude: Head-on Collision post 1 year Compared to Meteoroid Background .......................................................... 2-16
Figure 2-11 Flux vs. Altitude: Grazing Collision post 1 year Compared to Meteoroid Background .......................................................... 2-17
Figure 2-12 Flux vs. Altitude: Head-on Collision at Breakup ....................................... 2-21
Figure 3-1 World-wide Observation Network -- Radar, Optical, IR ................................ 3-4
Figure 3-2 Number vs. Detection time -- DOY 249 ......................................................... 3-5
Figure 3-3 Gabbard Diagram -- DOY 249 -- 23° Cloud ................................................. 3-6
Figure 3-4 Gabbard Diagram -- DOY 249 -- 38° Cloud ................................................ 3-7
Figure 3-5 Number vs. Inclination Distribution -- 23° Cloud ........................................ 3-9
Figure 3-6 Number vs. Inclination Distribution -- 39° Cloud ........................................ 3-11
Figure 3-7 Number vs. Period Distribution -- 23° Cloud .............................................. 3-12
Figure 3-8 Number vs. Period Distribution -- 39° Cloud .............................................. 3-13
Figure 3-9 Inclination vs. Period -- 39° Cloud .......... 3-14
Figure 3-10 Filtered ALTAIR Data -- DOY 249 .......... 3-19
Figure 3-11 ALTAIR Data -- DOY 249 .............. 3-20
Figure 3-11a Kaena Point dBsm vs. time .......... 3-26
Figure 3-12 Debris Decay -- 23° Cloud .......... 3-29
Figure 3-13 SRS Meteor Radar Array Deployment ....... 3-31
Figure 3-14 Ground Tracks Superimposed on SRS Radar
Radiation Pattern .......... 3-32
Figure 3-15 Typical Meteor Radar RTI .............. 3-34
Figure 3-16 Mass Distribution Observed by Meteor Radar .. 3-36
Figure 3-17 AMOS and MOTIF Instrument Plan Views .... 3-39
Figure 3-18 AATS Optical Diagram ............... 3-40
Figure 3-19 Typical Maui "Fence" -- DOY 256 ......... 3-43
Figure 3-20 Optical Window Installation on Aeromet Learjet .3-46
Figure 3-21 APS Equipment Layout on Aeromet Learjet .. 3-47
Figure 3-22 Learjet groundtracks DOY 249 and DOY 250 .... 3-50
Figure 3-23 Typical Optical Data Screening Form ........ 3-52
Figure 4-1 Number vs. Diameter Distribution -- DOY 249,
23° Cloud Compared to Theoretical Distribution ........ 4-3
Figure 4-2 Number vs. Diameter Distribution -- DOY 249,
39° Cloud Compared to Theoretical Distribution ....... 4-4
Figure 4-3 Number vs. Diameter Distribution -- DOY 250,
23° Cloud Compared to Theoretical Distribution ....... 4-5
Figure 4-4 Number vs. Diameter Distribution -- DOY 250,
39° Cloud Compared to Theoretical Distribution ....... 4-6
Figure 4-5 Number vs. Diameter Distribution -- DOY 251,
23° Cloud Compared to Theoretical Distribution ....... 4-7
Figure 4-6 Number vs. Diameter Distribution -- DOY 251,
39° Cloud Compared to Theoretical Distribution ....... 4-8
Figure 4-7 Number vs. Diameter Distribution -- DOY 318 NSSC
Catalogued Objects Compared to Theoretical
Distribution .......... 4-9
Figure 4-8 Number vs. Mass Distribution -- DOY 249 SRS
Meteor Radar Data Compared to Theoretical
Distribution .......... 4-12
# LIST OF TABLES

<table>
<thead>
<tr>
<th>Table 3-1</th>
<th>Detector/Time Matrix</th>
<th>3-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table 3-2</td>
<td>Summary of Surviving Objects</td>
<td>3-17</td>
</tr>
<tr>
<td>Table 3-3</td>
<td>Summary of ALTAIR post-EOM Data</td>
<td>3-21</td>
</tr>
<tr>
<td>Table 3-4</td>
<td>Summary of ALTAIR UHF Data</td>
<td>3-23</td>
</tr>
<tr>
<td>Table 3-5</td>
<td>NORAD's Delta-180 Related Objects</td>
<td>3-24</td>
</tr>
<tr>
<td>Table 3-6</td>
<td>Summary of NAVSPASUR Observations</td>
<td>3-28</td>
</tr>
<tr>
<td>Table 3-7</td>
<td>Debris Particle Mass Estimates</td>
<td>3-35</td>
</tr>
<tr>
<td>Table 3-8</td>
<td>AMOS/MOTIF/GEODSS Sensors</td>
<td>3-37</td>
</tr>
<tr>
<td>Table 3-9</td>
<td>Learjet Optical Observing Site Optical Systems Specifications</td>
<td>3-48</td>
</tr>
<tr>
<td>Table 3-10</td>
<td>Time-Ordered Event List -- Delta-180 Optical Observations</td>
<td>3-53</td>
</tr>
<tr>
<td>Table 3-11</td>
<td>Delta-180 Fragments Identified from Optical Data</td>
<td>3-58</td>
</tr>
<tr>
<td>Table 4-1</td>
<td>Observed Cloud Mass</td>
<td>4-11</td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
<td></td>
</tr>
<tr>
<td>---------</td>
<td>-------------</td>
<td></td>
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<td>AATS</td>
<td>AMOS Acquisition Television System</td>
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<td>ARPA Lincoln C-Band Observables Radar</td>
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<td>ARPA Long-Range Tracking and Instrumentation Radar</td>
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<td>DARPA Maui Optical Station</td>
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<td>APS</td>
<td>Airbourne Pointing System</td>
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<td>Advanced Research Projects Agency</td>
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<td>DoD</td>
<td>Department of Defense</td>
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<td>DOY</td>
<td>Day of year</td>
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<td>End of mission</td>
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<tr>
<td>FOV</td>
<td>Field of view</td>
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<td>GEODSS</td>
<td>Ground-based Electro-Optical Deep Space Surveillance</td>
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<td>Homing Overlay Experiment</td>
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<td>International Business Machines</td>
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<td>Intensified Silicon Intensifier Target</td>
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<td>Kwajalein Missile Range</td>
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<td>LBD</td>
<td>Laser Beam Director</td>
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<td>LEMSCO</td>
<td>Lockheed Engineering and Management Services Company</td>
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<td>LEO</td>
<td>Low earth orbit</td>
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<td>LLLTV</td>
<td>Low Light Level Television</td>
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<td>LOS</td>
<td>Learjet Optical System</td>
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<td>LWIR</td>
<td>Long-Wavelength Infrared</td>
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<td>MMWR</td>
<td>Millimeter Wave Radar</td>
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<td>MOTIF</td>
<td>Maui Optical Tracking and Identification Facility</td>
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<td>NASA</td>
<td>National Aeronautics and Space Administration</td>
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<td>NFOV</td>
<td>Narrow field of view</td>
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<td>NORAD</td>
<td>North American Aerospace Defense Command</td>
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<tr>
<td>PAS</td>
<td>Payload Assist System</td>
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<td>PARCS</td>
<td>Perimeter Acquisition Radar Characterization System</td>
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<td>RCS</td>
<td>Radar cross section</td>
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<tr>
<td>RTI</td>
<td>Range-Time-Intensity</td>
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<tr>
<td>SAO</td>
<td>Smithsonian Astrophysical Observatory</td>
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<tr>
<td>SDI</td>
<td>Strategic Defense Initiative</td>
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<td>SDIO</td>
<td>Strategic Defense Initiative Office</td>
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<tr>
<td>SIT</td>
<td>Silicon Intensifier Target</td>
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<tr>
<td>SLBM</td>
<td>Submarine-launched ballistic missile</td>
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<td>SRS</td>
<td>SPC Remote Sensing Company</td>
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<td>SSC</td>
<td>Space Surveillance Center</td>
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<td>SSN</td>
<td>Space Surveillance Network</td>
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<td>TBE</td>
<td>Teledyne Brown Engineering</td>
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<tr>
<td>TRADEX</td>
<td>Target Resolution and Discrimination Experiment</td>
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<tr>
<td>UHF</td>
<td>Ultra-High Frequency</td>
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<tr>
<td>USAF</td>
<td>United States Air Force</td>
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<td>USASDC</td>
<td>United States Army Strategic Defense Command</td>
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<td>USSC</td>
<td>United States Space Command</td>
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<tr>
<td>UT</td>
<td>Universal Time</td>
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<tr>
<td>VDAS</td>
<td>Video Digital Analysis System</td>
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<tr>
<td>VHF</td>
<td>Very High Frequency</td>
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EXECUTIVE SUMMARY

Satellites 16937 and 16938 were placed in orbit on September 5, 1986. Prior to the launch of these two satellites, the possibility was foreseen that a collision between them might occur. Consequently, the hazards to other spacecraft that might result from the orbital debris produced by such an event were assessed by modelling.

Because so little is known about the dynamics of collisions in space, three different collision scenarios were postulated and analyzed. These scenarios differed in the amount of momentum interchange between the colliding bodies. Results from the modelling efforts showed that in all cases, the debris resulting from a collision would reenter the atmosphere within a short time; within a few months the debris flux would be below background levels, and would not pose any significant hazard to other spacecraft.

Since so little is known about collisions in space, it was thought prudent to back up the modelling calculations with measurements, so that the predictions of the models could be verified if a collision occurred. For this purpose, DOD satellite tracking radars and telescopes were alerted to collect data, a sensitive airborne optical system was deployed to detect small debris, and a meteor radar was set up to detect debris that might reenter following a possible collision.

In fact, the satellites did collide on September 5 at 17:53 UT. An extensive array of radar and optical data was collected on the debris cloud resulting from the collision. The data were best fit by the model which postulated only a small amount of momentum transfer in the collision. The number of debris objects produced in the collision was in good
agreement with model predictions, but the rate of decay and reentry of the debris was slower by about 25% than predicted. The reflectivity of the debris was low, of the order of 10%, which hampered optical observations.

It was concluded that the models of the collision successfully predicted the potential hazard to other spacecraft, since the differences between the predicted and observed debris number, size distribution, and decay rate were not significant relative to the hazard assessment.
1.0 INTRODUCTION

On September 5, 1986 at 17:53 UT, satellites 16937 and 16938, the second stage and a scientific payload associated with Delta launch 180 (Delta-180) collided. The collision took place 217.5 km above a ground position of 14.82° N and 167.7° E. The impact speed was ~3 km/sec, and produced two clouds of debris, one at the 23° inclination of the second stage and one at the 39° inclination of the payload. This was the first known high velocity impact between comparably sized objects in orbit. The test provided an opportunity to observe a collisional breakup under controlled conditions. Since the role of collisions may be critical in determining future states of the man-made debris population, it was felt that as much information as possible should be extracted from the mission data.

The NASA/Johnson Space Center (JSC), as the lead NASA organization for studying orbital debris, was tasked to support range safety for any possible debris generated in the mission and for assisting in confirming that no severe long-term degradation of low Earth orbit (LEO) would result as a consequence of the proposed test. A conservative breakup model was agreed upon, and used to satisfy, to the extent possible, the requirement that any explosion or collision not pose a significant long-term hazard. These predictive calculations were made using the models available at JSC. A breakup model was developed based on laboratory tests, theoretical modeling, and the data extracted from the SOLWIND satellite breakup (P-78 test).

To verify the predictive calculations and to improve the breakup model, a coordinated observing campaign, consisting of optical, infrared (IR), and radar instruments was planned and executed by JSC. Data were taken for several weeks after the breakup.
This report documents all phases of the JSC activity, presenting the predictive modeling (Section 2), the observing campaign and the data acquired (Section 3), and the analysis of that data (Section 4). The conclusions of the project are presented in Section 5. The Space Science Branch of the Johnson Space Center was supported in this project by the on-site support contractor, Lockheed Engineering and Management Services Company (LEMSCO), and by three LEMSCO subcontractors, Teledyne-Brown Engineering (TBE) who analyzed the Eglin radar data and supported the end-of-mission radar data analysis, SPC Remote Sensing Company (SRS) who operated a modified meteor radar to detect reentry ionization trails, and the Aeromet Corporation who operated an aircraft used to observe the optical characteristics of the debris. Data from the TBE and SRS reports have been excerpted and included in the body of this report; the complete versions of their reports have been attached as Appendices B and C.

1.1 The Delta-180 Mission

Delta-180, a Delta 3920-class vehicle given the international designator 1986-069, lifted off from Cape Canaveral's Launch Pad 17B at 11:08 a.m. EST on September 5, 1986. Following a nominal flight, the Delta's second stage was placed in a near-circular orbit at an altitude of 220 km and an inclination of 28.5 degrees. Forty-five minutes later the 3rd stage separated from the 2nd stage while over the Indian Ocean. After a series of maneuvers, the two stages were in significantly different orbits: Delta 2nd stage, 210km x 550km, 23° inclination; Delta 3rd stage, 210km x 590km, 40° inclination. With these orbits, the two stages would cross one another with a relative velocity approaching 3 km/sec.

There was the possibility that the two stages would collide, generating a significant amount of orbiting debris. Since this debris could pose a hazard to other spacecraft, there were safety issues to address.
1.2 The On-Orbit Safety Group

To address any safety issues, the SDIO formed an on-orbit Safety Group. Membership in this group included the Johnson Space Center, The Aerospace Corporation, Johns Hopkins' Applied Physics Laboratory, the Eastern Test Range, Space Command, as well as operational and engineering elements associated with the Delta 180 mission. Members of the On-Orbit Safety Group were to predict and evaluate the potential hazard resulting from a possible Delta-180 breakup. The contributions JSC made were in the areas of computer modeling and data acquisition and analysis of any resulting debris.

1.3. JSC Involvement Summary

1.3.1 Goals

1.3.1.1 Pre-mission Hazard Prediction

Beginning in Spring, 1986, personnel of JSC's Space Science Branch began modeling orbital debris from various possible mission anomalies. These predictions were in the form of spatial densities and the cumulative flux of debris at altitudes up to 2500 km. Initial conditions were extracted from unclassified reports, while boundary conditions, such as debris velocity distribution, number vs. size distribution, and mass as a function of size, were established using published data from laboratory hypervelocity impact experiments, destructive testing of spacecraft components, and past on-orbit breakup events. Data produced by the modeling was presented at a series of meetings held in late Spring and early Summer.
1.3.1.2 Post-mission Model Update

Following the end-of-mission, the JSC tasks were to reduce selected data from various field sensors, analyze the data with respect to the pre-mission predictions, publish the findings, and update the on-orbit breakup event model. The latter goal included determining the number vs. size distribution of the breakup objects, and the correlation of object size (estimated from radar cross section) with the observed visual magnitude and albedo of the debris. Also to be examined were the velocity distribution of the debris resulting from the collision, an estimation of the debris lifetimes and, the question of linear momentum transfer. These quantities are of interest because of the unique nature of the Delta-180 mission.

Also, since the relative velocity of the collision was approximately 3 km/s, the extent of hypervelocity phenomenology was unknown. As regards the debris ejecta, parameters of interest were number, mass, and size distributions, velocity distributions, and other hypervelocity impact effects, such as albedo reduction.

1.3.2 Modeling

1.3.2.1 Scenarios

Three different impact scenarios were modeled: a head-on (or direct hit) collision, a grazing impact of the two satellites, and the proximity explosion of the satellites. In simulating a grazing impact, 10% of one object was used as a projectile on the second object; the roles were reversed and the debris produced in each event summed to give the total amount of debris generated. It was found that using this percentage of a satellite as a projectile, both satellites would be completely destroyed. Only in the case of a grazing
impact involving 2% or less of each satellite would a portion of the more massive satellite remain intact.

1.3.2.2 Velocity Distributions

Pre-mission generated data was most sensitive to the velocity distribution as a function of size of the debris. In early modeling efforts, several distributions were used. The curve derived from a hydro-code analysis of the 1984 Homing Overlay Experiment was considered but then discarded because it didn't accurately reflect the observed data from the P-78 test. Other curves were laboratory generated; these were functions of both size and kinetic energy transferred to target. The curve derived from observations of P-78 was also evaluated.

Characteristic of all velocity distribution functions was the small velocity perturbation given large objects and a velocity perturbation on the order of the impact velocity for small particles. This is depicted in Figure 1-1.

1.3.2.3 Linear Momentum Transfer

In previous work, the JSC breakup model had modeled a 100% transfer of linear momentum to the small debris, and no momentum transfer to the large fragments; this effect characterized the breakup of the SOLWIND satellite in the P-78 experiment. This resulted in the small objects being injected into one set of characteristic orbits, and the larger pieces remaining in the target's original orbit.

In the case of Delta-180, it was thought that three distinct debris clouds might be formed: one centered about the target's orbit, one centered about the projectile's orbit, and a third (the momentum exchange orbit) in a lower-energy orbit near an inclination equal to the mass-weighted mean of the
Velocity distribution (2.7 km/s impact)

velocity vs log10(diameter)
Top to bottom: 100%, 50%, and 10% KE transfer

Units of velocity are [m/s]
Units of diameter are [m]
target's and projectile's inclinations. For the Delta-180 predictions, the breakup model was modified in some scenarios to reflect the case in which not all the momentum was transferred to the small objects. This would allow some of the smaller particles to accompany the larger fragments in the target/projectile orbits.

1.3.3 Field Measurements

1.3.3.1 Department of Defense (DoD) Radars

Radars operationally controlled by or under contract with the North American Aerospace Defense Command (NORAD), the United States Space Command (USSPACECOM), and the United States Army Strategic Defense Command (USASDC) contributed both metric and signature observations of the Delta-180 objects. The metric observations (i.e., kinematic data only) defined the positions and velocities of the objects before, during, and after the breakup. Signature observations characterized the size, shape, and orientation of the fragments generated.

1.3.3.2 Meteor Radar

A very high frequency (VHF) backscatter radar system was erected in Hawaii to detect the ionization trails from Delta-180 objects entering the atmosphere after EOM. Both monostatic and interferometer radars were deployed to allow vector measurement of position and velocity. Operating at two frequencies allowed wavelength dependent studies of the return echo signatures.

1.3.3.3 Ground-based Optical/IR Instruments

The Defense Advanced Research Projects Agency (DARPA) operates the Maui Optical Station (AMOS) on the island of
Maui, Hawaii. The AMOS complex includes the Maui Optical Tracking and Identification Facility (MOTIF) which is operated as the primary sensor of the USAF SPACETRACK network. Also located at the Maui site is a complete Ground-based Electro-Optical Deep Space Surveillance (GEODSS) facility consisting of three primary instruments. Although GEODSS is operated by NORAD, it shares physical facilities with AMOS/MOTIF (Figure 1-2). All of these facilities were used during the Delta-180 measurement campaign.

The telescopes of AMOS/MOTIF employed during the Delta-180 effort were a 1.6m telescope, twin 1.2m telescopes and two acquisition telescopes systems -- one on each of the larger instruments. In addition, the three GEODSS instruments, two with apertures of 1.0m and one of 0.4m were also used.

The measurement effort extended from September 6, 1986 (DOY 249) through September 15, 1986 (DOY 258), and occupied about 1 hour each night. These ground-based optical efforts were conducted coincidentally with radar operations, in particular with the radar at Kaena Point.

1.3.3.4 Airborne Optical Instruments

On September 6, 1986 (DOY 249), and September 7, 1986 (DOY 250), a specially equipped Learjet was flown from the Kwajalein Atoll for the purposes of obtaining optical image data on the Delta-180 fragments. A Lenzar Low Light Level TV was positioned at a right side forward station, while a Wide Field of View (WFOV) and Narrow Field of View (NFOV) system shared a right aft platform. All three of these were SIT type video detectors.
Figure 1-2 Facility identification, Maui, HI.
2.0 PRE-MISSION PREDICTIONS

Predictive modeling of the debris generated by the Delta-180 test event was tasked to JSC by the Delta-180 program office. Given inputs of satellite (target) and projectile orbital elements and mass, the program EXPLOS/HAZARD was used to produce output data in the form of tables of resulting debris, reentering debris, Gabbard plots, and state vectors/orbital elements for several collision and explosion scenarios. These data were used to predict the environmental hazard arising from the Delta-180 mission, and to provide coordinates for planning radar and optical observations for the measurement campaign. Orbital lifetimes were also predicted.

A block diagram of the program is shown in Figure 2-1. Program module MASDIS calculates object mass as a function of size (diameter) and the delta-velocity distribution as a function of size. These power-law distributions have been developed from laboratory simulations and past on-orbit breakup events. Two extrapolations must be made with respect to hypervelocity impact data obtained in the laboratory: first, the data from the laboratory case of low mass projectiles/high mass targets must be scaled to the case of projectiles and targets of similar mass -- this scaling is not well-understood and there is a resulting uncertainty in the models; second, a flat plate or "semi-infinite" target composed of aluminum or basalt under 1g in a laboratory, may not react as would a typical spacecraft structure of similar dimensions. In particular, at distances far removed from the impact site, the breakup characteristics of a large laboratory test article may not mimic well the breakup of its on-orbit counterpart. Hence the breakup characteristics for the larger fragments must come primarily from on-orbit breakups.

The software module BREKUP determines whether the event was catastrophic (that is, whether the target fragments completely)
Figure 2-1 On-orbit breakup program structure.

On-Orbit Breakup Program Structure
or not, and computes the total mass (or number of objects) produced per size bin. An object (target) is subject to catastrophic breakup if the ejecta mass, defined as the projectile mass multiplied \((V_1/V_{\text{norm}})^2\) \((V_{\text{norm}}=1\ \text{km/sec})\), is greater than 10% of the object mass. For the Delta-180 experiment, the mass ratio of the second stage to the SDI/PAS payload was 0.6, so a head-on collision would have been catastrophic to both structures. If the impact was not head-on, only the overlap mass was considered as participating in the collision as shown in Figure 2-2, and in that case the collision would still be catastrophic if more than about 2% of the mass overlapped.

Superimposed on the number or mass per size bin for the Delta-180 experiment were a number of objects from the three scientific modules. Some of these objects could have remained intact after the event, resulting in a divergence from the power-law distributions of the explosion model. It was therefore expected that the observed fragment distribution might deviate from the predicted distribution by having more large fragments. In fact, the number of objects was observed to be much smaller per size bin than that predicted by the collisional breakup model.

Debris arising from a collision process is categorized in the model as either fragments or ejecta. Ejecta are those particles to which momentum is transferred and come from material near the impact site. Fragments will not be involved in the exchange of momentum, thus retaining the original orbital characteristics of the structure, and come from material farther away from the impact site. For a catastrophic event, in which both target and projectile are completely disrupted, both ejecta and fragments are produced. The number vs. mass distribution is given by:

\[
N = 1.7069 \times 10^{-4} \ m_T \ e^{-0.02056 \ m^{0.5}} \quad , \quad m > 1936\text{gm}
\]

\[
N = 8.6921 \times 10^{-4} \ m_T \ e^{-0.05756 \ m^{0.5}} \quad , \quad m < 1936\text{gm}
\]

2-3
Figure 2-2  Illustration of overlap area for grazing collision.
where \( N \) is the cumulative number of pieces produced with a mass greater than \( m \) [gm], and \( m_T \) [gm] is the mass of the target. These equations, from Time Evolution of the Near-Earth Man-Made Orbital Debris Environment by S.Y. Su and D.J. Kessler, may be expressed in terms of debris object diameter by making the substitution:

\[
m = 4.72 \times 10^4 \ d^{2.26},
\]

where \( m \) [gm] is object mass and \( d \) [m] is the object's diameter. This equation is based on measurements of payloads, rocket motors, and debris. In the case of non-catastrophic events, only ejecta are produced. Ejecta follow a power-law distribution given by:

\[
N = 0.4478 \left( \frac{m}{m_p v^2} \right)^{-0.7496},
\]

in which \( N \) is again the cumulative number of objects with mass greater than \( m \) [gm]. \( m_p \) is the projectile mass, in grams, and \( v \) is the projectile velocity, in km/sec. In some cases for the Delta-180 analysis, ejecta type material was distributed with little momentum transfer.

The driver program, EXPLOS, and later HAZARD, models a collision by distributing the objects evenly among 525 equal-area tiles on the surface of a sphere centered on the target. Thus, the objects are distributed isotropically by vectorally adding the delta-velocity given by the mass vs velocity distribution to the target's initial velocity vector. State vectors, and the classical orbital elements may then be calculated for each tile's contribution to the total number of objects. Mass is conserved.

Three different breakup scenarios were modeled to support the Delta-180 predictions: a direct hit (100% mass overlap), a grazing impact (10% mass overlap), and an explosion. Given spacecraft masses of 873kg for the Delta
stage and 1455kg for the SDI/PAS payload, no scenario examined would have left a substantial part of either structure intact. Some software modifications were developed to model the explosion case. The program output data, debris flux as a function of altitude and debris size, were sensitive to the velocity distribution used and the amount of linear momentum transferred.

The models were run utilizing several velocity distributions, as shown in Figure 2-3. The upper-most curve represents the results of a hydro-code analysis of the Homing Overlay Experiment (HOE) exoatmospheric interception tests carried out in 1984. The remaining curves represent the velocity distribution for different sizes and amount of kinetic energy transferred to the target. The Delta-180 experiment provided an opportunity to assess the kinetic energy transfer manifested in the delta-velocity delivered to the resultant pieces of debris. The effect of kinetic energy transfer may be seen by comparing Figure 2-4 and Figure 2-5; both are Gabbard plots of the objects greater than 10cm in diameter and were produced by HAZARD. The former utilizes the high velocity distribution (100% kinetic energy transfer) while the latter was run using the nominal distribution (50% kinetic energy transfer). The high energy curve deposits the larger, radar-observable debris over a substantially larger volume of space.

Linear momentum transfer between the Delta stage and the SDI satellite displays itself as a size vs. orbital plane distribution: those pieces undergoing momentum transfer will be injected into center-of-mass orbits, creating a debris cloud whose inclination lies at the mass-weighted mean of the original satellites inclinations.

The hypervelocity impact scenarios assuming 100% momentum transfer to the ejecta predicted that there would be

2-6
Figure 2-3  Debris velocity distributions.
Hazard Analysis Project

head-on (100%) scenario; diam. > 10cm

Figure 2-4 Gabbard diagram: 100% KE transfer scenario.
delta second stage

high velocity distribution
Hazard Analysis Project
head-on (100%) scenario; diam. > 10cm

Figure 2-5
Gabbard diagram:
50% KE transfer scenario.
delta second stage
nominal velocity distribution
three debris clouds: one composed of fragments at an inclination of 22.9° (Delta fragments), one composed of fragments at inclinations around 40.1° (satellite fragments), and the center-of-mass cloud composed entirely of ejecta around an inclination of 33.7°. The values used for the inclinations above are based on pre-mission planning. In accordance with observations, the Delta cloud shall be referred to as the 23° cloud, and the PAS/satellite cloud as the 39° cloud. An alternative scenario was defined which transferred only 50% of the momentum to the ejecta, so that the 23° and 39° clouds included ejecta as well as fragments.

The explosion case differed in that proximity explosions of both the Delta stage and the SDI/PAS spacecraft would transfer no momentum; hence, there would exist only two debris clouds, each conforming to the parent body's orbital characteristics. This scenario was interpreted as having the spacecraft fragment before collision and having the debris clouds pass through one another with little momentum transfer. Initial debris orbital characteristics for each case are given in Figures 2-6 through 2-8.

Perturbations on, and orbital decay of, the resulting objects were modeled using analytical King-Hele expressions for the decay of a satellite in an atmosphere. A modified version of the Jacchia 71 model atmosphere was used as the reference atmosphere. The exospheric temperature, a function of solar flux and geomagnetic index, was assumed to be constant over the lifetimes of the objects under investigation. All diurnal, seasonal, latitudinal, and semi-annual variations were neglected. In general, this program provides values within ~25% of the actual decay time.

For reporting purposes, the following nomenclature was adopted: short term effects refer to those effects occurring immediately post-EOM to several hours post-EOM; mid-
Figure 2-6 Number vs. inclination: head-on collision.
Figure 2-7 Number vs. inclination: grazing collision.
Figure 2-8 Number vs. inclination: explosion scenario.
term refers to several hours post-EOM to a week post-EOM, and long term refers to the ensuing debris cloud evolution. In most cases, analysis stopped at an elapsed time of 1 year; however, in some cases, the debris cloud evolution was followed for up to 5 years. Throughout the analysis, the natural meteoroid background was used as a point of reference. The natural background has never necessitated significant constraints on a space program.

2.1 Flux in the LEO Environment

From the number of objects in orbit at any time, one may calculate spatial densities and the cumulative object flux as a function of altitude and size. Figure 2-9 shows a typical plot of this cumulative flux, in this case the flux for a direct hit collision, with the debris receiving 50% of the kinetic energy, after an elapsed time of 1 year. Figure 2-10 shows the same case, but with the natural meteoroid background included. In the Figure 2-9, the cumulative flux for debris greater than 4cm in diameter is less than $10^{-9}$ impacts/m$^2$/yr after 1 year, while in the Figure 2-10, only the 1cm flux exceeds the natural background after 1 year. By contrast, Figure 2-11 displays the effect of the kinetic energy transfer to the debris. In this case, a glancing blow is modeled; the high energy velocity distribution curve is used, however, with the result that the cumulative flux for debris greater than 4cm in diameter exceeds the natural environment by over a factor of 2 around breakup altitude, and by a lesser extent out to an altitude of 1000km. Appendix A contains a catalog of debris flux evolution plots for various impact and explosion scenarios.

Caution must be applied in viewing plots such as these, for the spatial densities and attendant cumulative flux calculated and presented here are actually averaged over the entire volume of an altitude shell 50km thick. While this
100% impact
50% kinetic energy transfer
elapsed time = 1 yr

Figure 2-9
flux vs. altitude: head-on collision post 1 year.

$\log_{10}(flux [m^{-2} yr^{-1}])$

$\geq 1 \text{mm}$

$\geq 4 \text{mm}$

$\geq 1 \text{cm}$

altitude [km]
meteoroids excluded
Figure 2-10 Flux vs. altitude: head-on collision post 1 year compared to meteoroid background.
Figure 2-11
Flux vs. altitude: grazing collision post 1 year compared to meteoroid background.

10% impact
100% kinetic energy transfer
elapsed time = 1YR

\[\log_{10}(\text{flux} \left[ m^{-2} \text{yr}^{-1} \right])\]

-2
-3
-4
-5
-6
-7
-8
-9

0 500 1000 1500 2000 2500

altitude [km]

> 4mm

> 1cm

> 4cm
is adequate in gauging the environmental impact of the debris after it has evolved into a shell-like structure, the short term environment is much different.

Shortly after breakup, the debris will appear (as modeled) as a sphere in a co-moving reference frame; in an external inertial reference frame, it will appear as a double cone. As drag and perturbations alter the orbits of the debris pieces, their period will vary; thus, the cone-like structure will evolve into a torus girdling the Earth. Eventually, as the right ascensions of the ascending nodes precess, this torus will smear itself into a debris shell about the Earth.

2.1.1 Short Term Effects

Of considerable importance in an on-orbit test such as Delta 180 is the possible effect of the debris cloud on U.S. or foreign satellites in the path of the cloud. The United States Space Command and the Aerospace Corporation performed analyses of the cloud interaction with other space vehicles and the debris flux generated shortly after the event, especially during the first day when the debris flux was at its greatest. These analyses assured conditions in which the probability of damage to other spacecraft as a result of the on-orbit test was minimal.

The JSC debris model available at the time the Delta-180 predictions were made assumes the orbital planes of the debris objects are randomly distributed in calculating debris fluxes. Therefore, the fluxes produced must be viewed as "average" values. This average corresponds to actual fluxes once the debris cloud evolves to a shell configuration, which occurs in the long term, i.e. months post-EOM. Before that time, while the orbital planes have correlated position and the debris cloud is in a
pseudo-toroidal state, the average flux will be less than the true flux inside the debris cloud. However, the hazard to a spacecraft in the region of space spanned by the cloud is the product of the flux times the exposure time, and for all LEO orbits, the average flux times 100% exposure time will be essentially the same as the true flux times the transit time through the toroid. Therefore, while the average fluxes do not directly relate to the true fluxes inside the toroid, they do provide an accurate indicator of the hazard level relative to the meteoroid population and to the background orbital debris at all times post-EOM.

Due to the low altitude at which the test was conducted, a large portion of the debris produced was predicted to reenter immediately after breakup -- within the first day. The number distribution used predicted approximately 800 large (>10cm diameter) particles would be created; if half of these reentered shortly after EOM, as would be suggested by a symmetrical distribution of debris about the target, about 400 objects should have been seen by the Eglin radar. In fact, the Eglin AN/FPS-85 phased array radar observed 381 particles several days after breakup.

For each scenario, the cumulative flux for particles greater than 1cm and 4cm exceeded the natural meteoroid background over some portion of the volume of interest. For 4cm objects, the collision fragments dominated the meteoroid environment by up to a factor of 50. In some cases the total flux was increased over the background out to an altitude of over 2000km. The 1cm and larger objects also dominated the meteoroid background, but generally only by a factor of 10; however, the background was exceeded to higher altitudes, in most cases. The cumulative flux for objects greater than or equal to 4mm exceeded the meteoroids by only a factor of 2 to 3 at breakup altitude. Fragments as small as 1mm were produced in the collision, yet their contribution to the total

2-19
flux was negligible in all cases. A typical example of these data are provided in Figure 2-12.

2.1.2 Mid Term Effects

The mid-term period covers that time interval in which the debris clouds forms pseudo-toroids about the Earth. Thus, the actual flux rates will again be higher inside the toroids than that predicted be computer, and lower outside. As regards the graphics in Appendix A, the fluxes predicted for the mid-term period are typically about a factor of two less than the short term flux, and about a factor of two greater than the predicted flux after an elapsed time of one month.

2.1.3 Long Term Effects

The long-term consequences cover the time from the formation of the pseudo-toroid cloud a few days post-EOM until the reentry of all debris created during the Delta-180 mission. During this period, the pre-mission predictions most closely match the actual environment, since the impact of mission/model uncertainties become of decreasing importance with the passage of time. Although some long-life orbits, of up to five years, were populated in the breakup, the cumulative flux arising from this event began to fall below the meteoroid flux within three months to one year in every case investigated. This was primarily due to the perigee altitudes of the debris. Large objects, which receive small delta-velocities, remained in orbits similar to those of the parent body. Small objects which received large forward delta-velocities, began with perigee altitudes around breakup altitude (modeled as 217.5km altitude), but because of their larger area-to-mass ratio, these objects decayed quickly as drag forces decreased their orbital energy.
Figure 2-12: Flux vs. altitude: head-on collision at breakup.

100% impact
50% kinetic energy transfer
elapsed time = 0 wk

\[ \log_{10}(\text{flux [m}^{-2}\text{yr}^{-1}]) \]

-2
-3
-4
-5
-6
-7
-8
-9

0 500 1000 1500 2000 2500
altitude [km]

> 4mm
> 1cm
> 4cm
2.2 Object Lifetimes

Estimates of the average object lifetimes were made to support the assessment of long-term impacts of the test on space operations in LEO. These estimates were very sensitive to the velocity distribution and event scenario. In general the impact scenarios produced longer lived objects than the explosion scenario. In nearly all cases, objects larger than 4cm were removed from orbit in 1 year; smaller particles showed a persistence of up to several years, but not significantly contributing to the environment. The explosion case and the low kinetic energy transfer, grazing impact case deposited the debris objects in a smaller region of space. In these scenarios, large particles re-entered the atmosphere in approximately six months, with the smaller particles remaining in orbit up to several years. This is due chiefly to the high apogees of the particles; reentry did not occur until perturbations brought these apogees down to an altitude comparable to the perigee altitude, i.e., the altitude of the Delta-180 breakup.

2.3 Summary of Predictions

In summary of Appendix A, the cumulative flux for objects greater than or equal to 4cm were predicted to exceed the meteoroid background, albeit by only a factor of 10 or less at three months, decreasing to the background threshold in roughly 6 months. The 1cm flux curve displayed similar behavior, in all cases falling below the background at about 6 months elapsed time. The 4mm fluxes were predicted to fall below the background in, at most, 1 month post-EOM. No significant contribution was made to the total flux by the 1mm cumulative flux. Thus, in all cases surveyed, the potential hazard presented by the Delta-180 breakup event was predicted to be below that of the natural meteoroid background in 1 year or less.
3.0 THE MEASUREMENT CAMPAIGN

The measurement campaign involved a variety of radar and optical detectors in an effort to provide maximum coverage of the creation and subsequent evolution of the Delta-180 debris clouds.

At EOM, DoD radars with favorable passes were the Advanced Research Projects Agency (ARPA) Lincoln C-Band Observables Radar (ALCOR), the ARPA Long-Range Tracking and Instrumentation Radar (ALTAIR), the Millimeter Wave Radar (MMWR), and the Target Resolution and Discrimination Experiment radar (TRADEX). Additional post-EOM radars with good passes were Antigua, Kaena Point, Ascension, Beale, Eglin, Naval Space Surveillance (NAVSPASUR), and San Miguel. Other DoD radars were located at latitudes too high for good passes.

From one day before EOM to four days after, the JSC meteor radar on the island of Kauai collected metric observations of range and velocity, as well as signature observations to provide order-of-magnitude mass determinations. Details of all radar observations are included in this section.

Both ground-based and airborne optical observations were obtained for the post-EOM phase of the Delta-180 test. The airborne observations obtained data on two days, while the ground-based optical measurement campaign covered ten days with a variety of detectors. Specifics of both modes of data acquisition will be described in the following sections.

One objective of using multiple detectors was to obtain simultaneous observations using radar, IR, and optical systems to correlate radar cross-section, geometric size, and albedo. Table 3-1 presents the times of activity for all of the
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<th>MOTIF (AATS)</th>
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\(a\) ALTJAIR additional times (249): 00:21-01:10, 01:59-02:07, 03:35-04:11, 05:22-05:44, 22:50-23:43
\(b\) ALTJAIR additional times (250): 00:41-00:53, 03:00-03:25, 04:50-05:11, 22:50-23:22
\(c\) ALTJAIR additional times (251): 00:50-01:30, 02:25-03:15

X=No observations.
* = Time not available.
detectors. Figure 3-1 shows the location of these sensors on a world map.

3.1 DoD Radar Measurements

3.1.1 Eglin Radar

The electronically-steered phased-array radar located at Eglin Air Force Base was originally designed with a primary unclassified mission of space surveillance. With the emergence of a submarine-launched ballistic missile (SLBM) threat, however, Eglin is now a "collateral" sensor with a different primary mission. Lowering the SLBM fence allows Eglin to operate as a sensitive space surveillance radar. Since the inclinations of Delta-180 objects prevented detection by the north-facing Perimeter Acquisition Radar Characterization System (PARCS) in North Dakota, Eglin was chosen as the primary sensor for long-term debris data collection.

One day post-EOM, passes of both 23° and 39° inclination objects from Delta-180 occurred. Figure 3-2 shows the spread of the debris cloud on day 249 (September 6, 1986) as the number of debris objects tracked as a function of the time interval (90 minutes total observing time) during which Eglin acquired a particular object. Despite the low elevation for Eglin's 31° latitude, 190 objects were positively identified from the 23° cloud. From the higher pass elevation and larger mass SDI/PAS payload, one would have anticipated detecting more objects from the 39° inclination cloud. Eglin data, however, revealed only 191 objects. Gabbard plots for the 23° and 39° clouds during day 249 are shown in Figures 3-3 and 3-4 respectively. The 39° clouds lack of large objects could be explained by unknown additional Delta second stage mass which would have caused more fragmentation, differing fragment densities, unusual impact conditions, or increased

3-3
Figure 3-1 World wide observation network -- radar, optical, IR.
Figure 3-2: Number vs. detection time, DOY 249.

TIME INTERVAL (minutes) IN WHICH FRAGMENT WAS FIRST DETECTED, 6 September 1986

- 39° INCLINATION CLOUD
- 23° INCLINATION CLOUD
Figure 3-3 Gabbard diagram: DOY 249 -- 23° cloud.
Figure 3-4 Gabbard diagram: DOY 249 -- 38° cloud.
fragmentation caused by the range destruct package onboard the SDI/PAS.

As Figure 3-3 shows, the $23^\circ$ cloud periods range from 79 minutes to 116 minutes. Included in the objects plotted are several pieces in highly elliptical deorbit trajectories. About 20% were in fact in trajectories of this nature. A surprise in the data were several pieces of debris in very high apogee orbits; the data imply an increase in velocity of about 1km/s, which is a sizable fraction of the impact velocity. As was seen in the predictions (section 2), even for 100% kinetic energy transfer, a particle receiving this large a delta-velocity would be on the order of a centimeter in diameter. The Eglin sensors are not able to detect objects this small even at the perigee altitude of these pieces, so there is some inconsistency between the predictions and these observations.

The inclination distribution of the $23^\circ$ cloud ranged from $21.95^\circ$ to $25.25^\circ$. There was an inclination bias away from the initial inclination and towards higher inclination, as shown in Figure 3-5. This would imply some degree of momentum transfer to the large objects coming from the second stage.

The $39^\circ$ cloud Gabbard plot, shown in Figure 3-4, demonstrates many similarities to the $23^\circ$ cloud. Roughly 15% of the objects are in deorbit trajectories, and there are several anomalous objects with high apogee altitudes, including one with a period of 518 minutes. An orbit such as this would have been populated by an object experiencing a velocity change on the order of 2km/s, which would indicate an object of ~5mm diameter from the breakup model and is, of course, much too small to have been seen by the Eglin radar.

The inclination distribution exhibits a greater range than that of the $23^\circ$ cloud, $34.7^\circ$ to $41.4^\circ$, as would be expected
Figure 3-5 Number vs. inclination distribution: 23° cloud.
for similar plane change angles from a higher initial inclination. The inclination distribution is depicted in Figure 3-6, and shows a weighting toward higher inclinations, which is not the expected case.

A careful examination of the Gabbard plots presented thus far will disclose a clustering of objects in the 39° cloud between approximately 98 and 103 minutes of period. Plotting a number vs. period distribution for the 23° and 39° clouds yields Figures 3-7 and 3-8 respectively. Discounting "noise" due to reentering objects with 84 to 89 minute periods, each cloud is fairly symmetric about a period of 92 minutes. However, the 39° cloud shows a group of objects in long period orbits. Correlation with Figure 3-9, debris inclination vs. period, shows that between the periods of 98 and 104 minutes there is a general trend towards inclinations greater than the mean. The cause of this clustering is at present unknown, though it may be a residual effect of the maneuvers conducted immediately prior to EOM.

Efforts to obtain object size information from the Eglin data has been hampered by the use of default values for radar cross section in the NORAD two-line element sets derived from Intercept 205 of the Eglin "Log R" Intercepts 1, 15, and 224 also contain size information in the form of signal to noise ratios. Unfortunately, the calibration factors necessary to convert these ratios to radar cross sections are classified, and no action has at this time been taken to obtain them for direct or contracted processing. Eglin "Log S" tapes, currently undergoing analysis by Xontech, Inc., may include some further information concerning the size of the objects.

3.1.2 Kiernan Reentry Site (KREMS) Measurements

The KREMS at the Kwajalein Missile Range hosts ALCOR, ALTAIR, MMWR, and TRADEX and these were the only sites to
Figure 3-6 Number vs. inclination distribution: 39° cloud.
Figure 3-7 Number vs. period distribution: 23° cloud.
Figure 3-8  Number vs. period distribution: 39° cloud.
Figure 3-9  Inclination vs. period: 39° cloud.

39° DEBRIS CLOUD
collect EOM data. Each radar collected EOM data on the Delta-180 objects but only the post-EOM data are unclassified. A classified report on the EOM data will be published at a later date.

ALTAIR is a "contributing" sensor under contract to provide space surveillance data to the DoD. The mechanically-steered pencil-beam radar operates at both VHF and ultra high frequency (UHF) to provide range, azimuth, and elevation data, with additional capability for range rate in the coherent mode.

ALTAIR's normal mode of operation is to track a particular satellite for a period of time in order to determine the satellite's orbit. The amount of time necessary to acquire and track a debris object, however, would have severely limited the number of objects detected by ALTAIR. Therefore, a new procedure was developed in which the ALTAIR radar beam tracked the intersection of the two (23° and 39°) debris orbital planes and allowed the debris objects to pass through the beam.

Data were collected using this "beam park" operational mode for three passes during the period from approximately one to three days after the nominal end-of-mission. During this period, the debris from a breakup will remain in a toroidal shape with a focus or constriction of the torus near the latitude of the breakup. Although the intersection of the two toroids slowly drifts to the north of the interaction region due to slight differences in the nodal regressions of the two orbits, the drift is on the order of only a degree of latitude per day during the measurement period.

Therefore, by tracking the intersection of these two toroids, most of the measurable debris generated in the collision should pass through the radar beam. Rough orbits
may even be determined by knowing where the radar beam is pointed and by measuring the range and range rate of the object. Unfortunately, since the period of time that a debris object remains in the beam is short (10-40 secs.) coupled with uncertainties -- primarily in the range rate -- these orbits have large uncertainties.

Digital VHF (30-300 MHz) beam park data and paper Range-Time-Intensity plots (RTIs) were received at JSC in October, 1986. Film RTIs of the UHF (300 MHz - 3 GHz) observations were received in November, 1986. The digital data was processed using locally developed software implemented on a VAX 11/780 computer. The majority of the resulting element sets implied immediate reentry for the observed objects. Table 3-2 summarizes the number of those pieces (with perigees greater than -200km) and the number of those objects surviving one orbit (perigee greater than 100km). There could have been no objects with negative perigee altitude left in orbit after about an hour post-EOM, and objects with perigee altitude of less than 100km should have decayed within a couple of days. As the beam park data were collected on days 249, 250, and 251 (September 6, 7, and 8, respectively), the number of objects in these low perigee orbits more than a day after the breakup event reflects the large uncertainties associated with the measurements.

A sensitivity analysis of the data, including the propagation of the standard deviations from ALTAIR data to final element sets, demonstrated the sensitivity of the orbital elements to the range rate; in some cases, the standard deviation of this quantity was over a kilometer per second. As an example, one radar return, exhibiting one of the largest range rates, and a nominal standard deviation of 300 m/sec for that rate, was propagated through the transformation from topocentric coordinates to orbital elements. The resulting elements displayed only a 0.24° range
<table>
<thead>
<tr>
<th>DOY</th>
<th>Objects</th>
<th>Surviving</th>
<th>Percentage</th>
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</thead>
<tbody>
<tr>
<td>249</td>
<td>56</td>
<td>15</td>
<td>26.8 %</td>
</tr>
<tr>
<td>250</td>
<td>48</td>
<td>14</td>
<td>29.2 %</td>
</tr>
<tr>
<td>251</td>
<td>5</td>
<td>1</td>
<td>20.0 %</td>
</tr>
</tbody>
</table>
in inclination, but over a 30 minute difference in periods between a low range rate (mean rate minus one standard deviation unit) and a high range rate (mean rate plus one standard deviation unit). Other elements, such as mean motion, semimajor axis, and eccentricity, displayed exceptional variance.

A representative Gabbard plot of the data for day 249 is shown in Figure 3-10; the perigee height has been arbitrarily set at -200km, and no distinction has been made between the 23° and 39° clouds. For comparison, Figure 3-11 shows the same data, with all points plotted regardless of perigee. Note the points representing the highly elliptical data in the low-period area of the plot.

A further observation concerning the data is that there exists a discrepancy between the number of objects observed in the RTI format and the number of observations contained in the digital data. Table 3-3 records the number of objects observed as streaks in the paper RTIs, the number revealed by simply plotting the digital data, and the number of objects found by processing performed at JSC. Clearly, a great deal of useful debris data was lost between the RTI plots and the digital data.

A comparison of ALTAIR data with the Eglin data processed by Teledyne Brown is inconclusive beyond several specific observations. In particular, ALTAIR data is heavily biased toward the debris in the 23° cloud -- a fact for which there is no obvious operational reason since the radar was pointed at the intersection of the two orbits. In addition, a much greater percentage of the ALTAIR observations indicated debris objects about to deorbit than did the Eglin observations. This discrepancy is probably driven by uncertainties in the range rate data. If the suspect reentering objects are dropped, the ALTAIR and Eglin Gabbard plots are quite similar.

3-18
Figure 3-10 Filtered ALTAIR data -- DOY 249.
Figure 3-11 ALTAIR data -- DOY 249.
<table>
<thead>
<tr>
<th>DOY</th>
<th>RTI plots</th>
<th>Digital Tapes</th>
<th>JSC Processed</th>
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</thead>
<tbody>
<tr>
<td>249</td>
<td>N/A</td>
<td>212</td>
<td>56</td>
</tr>
<tr>
<td>250</td>
<td>175</td>
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<tr>
<td>251</td>
<td>162</td>
<td>99</td>
<td>5</td>
</tr>
</tbody>
</table>

TABLE 3-3
Summary of ALTAIR Post-EOM Data
Unfortunately, the ALTAIR data was the only unclassified data containing size information available for processing. This data, converted to radar cross sections, and data from the then current NORAD SATellite CATalog (derived from Eglin data), is presented in Section 4.

UHF beam park RTIs for days 249, 250, and 251 were analyzed by hand, as no digital data were available for this time period and only a piece count was performed. The results of this count, plus the normalized number of counts per minute of observation time is shown in Table 3-4. In all three cases the number of objects observed in the UHF spectrum was larger than the corresponding VHF observation set. This is to be expected, since more particles may be observed by utilizing observational wavelengths on the order of the characteristic size of the particles.

3.1.3 Other DoD Radar Measurements

Post-EOM observations made by Antigua, Ascension, Beale, and San Miguel were automatically routed to NORAD and used for producing element sets on the Delta-180 objects. Antigua and Ascension are mechanically-steered C-band low-gain radars. Beale is an electronically-steered phased-array radar similar to Eglin. San Miguel is a mechanically-steered UHF radar with long pulse widths and low pulse-repetition frequencies. These data are automatically incorporated into the NORAD catalog.

Recent NORAD Satellite Catalogs report 18 objects (international designators 1986-069A through -069T) related to the Delta-180 mission. Data from this catalog appears in Table 3-5. Thirteen of these objects were in the 39$^\circ$ cloud. Using those values for which RCS was reported, objects in the 23$^\circ$ cloud have an average diameter of 85.5cm, while those in the 39$^\circ$ cloud have an average diameter of 56.5cm.

3-22
### TABLE 3-4

**Summary of ALTAIR UHF Data**

<table>
<thead>
<tr>
<th>DOY</th>
<th>Number of objects</th>
<th>Elapsed Time (hh:mm:ss)</th>
<th>Frequency (min⁻¹)</th>
</tr>
</thead>
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<tr>
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<td>470</td>
<td>00:47:00</td>
<td>9.90</td>
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<td>250</td>
<td>498</td>
<td>01:46:00</td>
<td>4.69</td>
</tr>
<tr>
<td>251</td>
<td>228</td>
<td>01:30:16</td>
<td>2.53</td>
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</tbody>
</table>
# TABLE 3-5

NORAD's Delta-180 Related Objects

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<tr>
<th>International Designator</th>
<th>Catalog Number</th>
<th>Inclination (degrees)</th>
<th>RCS (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1986-069A</td>
<td>16937</td>
<td>39.1</td>
<td>N/A</td>
</tr>
<tr>
<td>B</td>
<td>16938</td>
<td>22.8</td>
<td>1.55</td>
</tr>
<tr>
<td>C</td>
<td>16940</td>
<td>38.8</td>
<td>0.36</td>
</tr>
<tr>
<td>D</td>
<td>16941</td>
<td>39.2</td>
<td>0.60</td>
</tr>
<tr>
<td>E</td>
<td>16942</td>
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<td>0.32</td>
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<td>F</td>
<td>16943</td>
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<td>16944</td>
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<td>0.37</td>
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<td>H</td>
<td>16945</td>
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<td>16946</td>
<td>22.9</td>
<td>0.19</td>
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<tr>
<td>K</td>
<td>16947</td>
<td>22.7</td>
<td>1.03</td>
</tr>
<tr>
<td>L</td>
<td>16948</td>
<td>22.7</td>
<td>0.09</td>
</tr>
<tr>
<td>M</td>
<td>16949</td>
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<td>0.01</td>
</tr>
<tr>
<td>N</td>
<td>16950</td>
<td>37.1</td>
<td>N/A</td>
</tr>
<tr>
<td>P</td>
<td>16951</td>
<td>39.0</td>
<td>0.04</td>
</tr>
<tr>
<td>Q</td>
<td>17019</td>
<td>39.5</td>
<td>0.22</td>
</tr>
<tr>
<td>R</td>
<td>17020</td>
<td>39.4</td>
<td>0.03</td>
</tr>
<tr>
<td>S</td>
<td>17021</td>
<td>39.4</td>
<td>0.26</td>
</tr>
<tr>
<td>T</td>
<td>17022</td>
<td>39.6</td>
<td>0.26</td>
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</table>

All values of RCS are supplied by Eglin.
Since most Delta-180 fragments remaining in orbit were expected to decay after a few weeks, it was important to learn as much about them as possible in a short time. The FPQ-14 radar at Kaena Point on Oahu, Hawaii was tasked to collect metric and Mission Payload Analysis data on the fragments.

Six IBM-compatible, 1/2-inch, 9-track, 800-BPI tapes were produced on site with a Xerox Sigma 5 computer running OASYS software. Upon arrival at the Johnson Space Center, one of the six tapes was unreadable, presumably from damage in transit. The other five were read for time, position, velocity, and acceleration data on each object recorded. Additionally, Word 139 of the four hundred 32-bit words was of particular interest because it contained a digital-to-analog output signal for the function recorder in dBsm.

Of the many objects observed, one was assigned a provisional number of 85301. Another was identified as the fragment now associated with Catalog Number 16938. Values of dBsm too small for maintaining tracking signal strength accuracy to within 5 dBsm were rejected. The resulting data were plotted as dBsm versus time (see Figure 3-11a). These data were also converted to radar cross sections (RCSs) and time-averaged to derive a mean RCS; for Object 16938 a value of 0.29 m² was obtained. RCS values from radars operating at different frequencies, or from a given radar on a single pass, must be compared carefully. Because of the large apparent size variations associated with spacecraft attitude, the availability of Kaena Point data for 16938 on only one pass, and the variance of RCS with radar frequency, the Kaena Point value of 0.29 is not inconsistent with USSPACECOM's Eglin RCS of 1.55 last reported in the Space Surveillance Center Catalog for Object 16938 before its decay on 25 November 1986.

Additional work is currently being done on interpretation of the Kaena Point data as well as for other radars.
Figure 3-11a  Kaena Point dBsm vs. time -- DOY 253

object 16938 data: 10 SEP 88

Kaena Point dBsm vs. time

UT hours

mdeg
3.1.4 NAVSPASUR

NAVSPASUR is not a radar in the typical sense. Transmitting at a VHF frequency of 217 MHz (1.38m), it combines the virtues of radar and radio interferometry into one system. A powerful transmitter in Texas produces a fan-shaped beam narrow in the north-south direction, but wide in the east-west direction. Receivers stationed across the southern United States detect any satellite with a large enough radar-cross section (RCS) passing less than 10,000 kilometers above latitude 33.5° North. This makes NAVSPASUR ideal for detecting objects from fragmentations, especially soon after the event, when orbits are poorly known.

NAVSPASUR was instrumental in monitoring the debris objects over a long period of time (September 30 - November 24), thus allowing an assessment of debris cloud evolution and the decay rate for debris objects. (Table 3-6 provides a summary of Space Surveillance Network (SSN) observations during this time period; note the short term rise in the number of objects in late October and early November.)

NAVSPASUR served to collect and analyze observations from several SSN sensors. Analysis allowed computation of provisional orbital elements for the objects so SSN sensors could be tasked to collect further observations. With the additional observations, objects could then be catalogued.

Twenty objects were analyzed for their decay characteristics. While necessarily incomplete, since not all objects have decayed to reentry, preliminary results of this study are shown in Figure 3-12. Differences in decay rates become more pronounced as pieces with higher apogee altitudes experience decay in apogee altitude. According to the predicted size vs. velocity relation, the smaller pieces should have received the larger delta-velocities and been in
TABLE 3-6

Summary of NAVSPASUR Observations

<table>
<thead>
<tr>
<th>Date</th>
<th>DOY</th>
<th>23° Cloud</th>
<th>39° Cloud</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>September 30</td>
<td>273</td>
<td>82</td>
<td>81</td>
<td>163</td>
</tr>
<tr>
<td>October 09</td>
<td>282</td>
<td>82</td>
<td>76</td>
<td>158</td>
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<td>October 19</td>
<td>292</td>
<td>48</td>
<td>71</td>
<td>119</td>
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<td>October 26</td>
<td>299</td>
<td>57</td>
<td>86</td>
<td>143</td>
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<td>November 02</td>
<td>306</td>
<td>51</td>
<td>91</td>
<td>142</td>
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<td>November 10</td>
<td>314</td>
<td>46</td>
<td>85</td>
<td>131</td>
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<td>November 17</td>
<td>321</td>
<td>40</td>
<td>71</td>
<td>111</td>
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<tr>
<td>November 24</td>
<td>328</td>
<td>37</td>
<td>59</td>
<td>96</td>
</tr>
</tbody>
</table>
Figure 3-12 Debris decay -- 23° cloud.
the higher apogee initial orbits. Therefore, the differences in drag coefficients should become more apparent as time in orbit increases. Thus, at later times, when the orbits of the large and small pieces become similar, this decay data can be inverted to provide a distribution in the area to mass ratio in the debris.

Over 60 objects were assigned provisional catalog numbers by NAVSPASUR and transmitted to the Space Surveillance Center at Cheyenne Mountain Complex. The orbital elements were used for the preliminary findings of this report.

3.2 Meteor Radar Measurements

Ionospheric radars deployed on Kauai, Hawaii operated at two frequencies: 27.66 MHz (10.84m) and 49.92 Mhz (6.01m), referred to for convenience as 28 and 50 MHz (see Figure 3-13). The 28 MHz monostatic radar transmitted and received from a single antenna aligned on an east-west baseline. The five 50 MHz radar interferometer antennas were arranged to provide three azimuthal baselines and three elevation baselines for vector measurements. Beam centers were directed at an elevation of 30°, with half-power beam widths of 40°. Figure 3-14 illustrates the geometry of the ground track intercepts and the areas of sensitivity in the radar's cardioid beam pattern. Signals were transmitted with a pulse width of 10 microseconds and an interpulse period of 2 milliseconds. Peak radiated powers for the pulses were 10 kilowatts for the 50-MHz and 6 kilowatts for the 28 Mhz transmitter.

A preliminary analysis of the returns from first-pass ionization trails shows an order of magnitude increase in echoes for a 2-minute period post-EOM at the time appropriate for the down-range location of the instrument. A sample Range-Time-Intensity (RTI) plot of returns from the 50 MHz
Figure 3-13  SRS Meteor radar array deployment.
Figure 3-14 Ground tracks superimposed on SRS Meteor Radar Radiation pattern.
radar is shown in Figure 3-15. Particle velocities of 7 kilometers per second distinguish the debris returns from meteor returns. Masses of between 5 and 1000 grams, with a strongly decreasing number distribution for increasing mass, have been calculated from the data (see Appendix C). Table 3-7 displays the data derived thus far from the calculations. A number vs. size distribution is shown in Figure 3-16. Work is underway to study data from the second pass and analyze the sensitivity of results to assumptions made.

3.3 Ground-based Optical/IR Measurements

3.3.1 AMOS/MOTIF/GEODSS

The AMOS, MOTIF, and GEODSS Electro-optical instruments are located on the island of Maui, Hawaii, just outside Haleakala Park at an altitude of 3.049km on the crest of Mount Haleakala. The latitude and longitude are 20.708472° N and 156.25797° W, respectively. The physical layout of the facilities is illustrated in Figure 1-2 -- the domes housing the various instruments are labeled. Each of these primary instruments will be briefly described and their specifications summarized in Table 3-8.

AMOS

AMOS is a telescope of 1.57m clear aperture with a focal length of 25m and an image scale of 8.25 arcseconds/mm at the Cassegrain focus. The telescope has instrument mounts at the rear of the telescope (classical Cassegrain focus) and on the side (folded Cassegrain focus). Focusing is achieved by driving the secondary mirror mount in and out; this function may be done automatically for non-infinite, changing target ranges. An AMOS Acquisition Telescope System (AATS) is mounted on the 1.6m telescope (Figure 3-17).
Figure 3-15 Typical meteor radar RTI.
<table>
<thead>
<tr>
<th>EVENT</th>
<th>50 MHz RADAR</th>
<th>28 MHz RADAR</th>
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</thead>
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<td>63</td>
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<tr>
<td>2</td>
<td>164</td>
<td>24</td>
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<tr>
<td>3a</td>
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<tr>
<td>3b</td>
<td>63</td>
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<td>4</td>
<td>51</td>
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<tr>
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<td>38</td>
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</table>
Figure 3-16  Mass distribution observed by meteor radar.
<table>
<thead>
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<th>INSTRUMENT</th>
<th>PRIMARY APERTURE</th>
<th>DETECTOR FIELD OF VIEW</th>
</tr>
</thead>
<tbody>
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<td>20.3</td>
<td>3.0°</td>
</tr>
<tr>
<td>AMOS/ASR</td>
<td>159.6</td>
<td>*</td>
</tr>
<tr>
<td>AMOS/IRCCD</td>
<td>159.6</td>
<td>3.3'</td>
</tr>
<tr>
<td>MOTIF/AATS</td>
<td>15.2</td>
<td>3.0°</td>
</tr>
<tr>
<td>MOTIF/L3TV (B37)</td>
<td>121.9</td>
<td>260&quot; X 130&quot;</td>
</tr>
<tr>
<td>GEODSS-1</td>
<td>101.6</td>
<td>2.1°</td>
</tr>
<tr>
<td>GEODSS-2</td>
<td>101.6</td>
<td>2.1°</td>
</tr>
<tr>
<td>GEODSS-3</td>
<td>38.1</td>
<td>6.0°</td>
</tr>
</tbody>
</table>

* Not available in AMOS facilities manual.
The AATS is primarily used for the acquisition of visible targets. However, during the Delta-180 measurement campaign it also served as a principal detector. The AATS combines good sensitivity with multiple field-of-view options -- these are 3°, 0.5°, and 0.1°. Fields-of-view can be changed as the target is centered in each to provide more precise tracking (Figure 3-18). Within the AATS, two optical systems provide the three fields-of-view which are fed to a common Intensified Silicon Intensifier Target (ISIT) television sensor. The 1.6m AATS has a 0.56m Richey-Chretian mirror which provides the 0.5° and 0.1° fields. The 3° field is provided by a 0.20m catadioptric system. The television sensor itself is a Quantex QX-11 ISIT vidicon having a 40mm cathode.

The AMOS telescope is mounted on a high performance three-axis mount. Each mount is a standard equatorial mount carried on an azimuth turntable. Tracking is done in the polar and declination axes with the azimuth turntable set to a fixed position optimized for the track. Mount capabilities include angular accelerations of 2 degrees/sec², angular tracking of 10 degrees/sec, and pointing to 2 to 3 arcseconds.

MOTIF

The MOTIF optical system consists of dual 1.2m telescopes mounted on opposite sides of a single polar axis; they are fixed to a common declination axis. The instrument is illustrated in Figure 3-17. Both telescopes are of classical Cassegrain design. One telescope, designated B29, has a 29-inch back focal distance; it has a focal length of 24.5m, a plate scale of 8.4 arcseconds/mm, and is used primarily for Long Wavelength Infrared (LWIR) and photometric data collection.

The other 1.2m telescope, designated B37, has a 37-inch back focal distance and two instrument mounting surfaces; it
Figure 3-17 AMOS and MOTIF instrument plan views.

DUAL 1.2m TELESCOPE

1.6m TELESCOPE
Figure 3-18 AATS optical diagram.
has a focal length of 19.8m and an image scale of 10.4 arcseconds/mm at the Cassegrain focus. The B37 telescope is normally used for low light level signal detection and imagery as it was for the Delta-180 campaign.

As for the AMOS 1.6m telescope, the MOTIF system has an AATS dual aperture instrument mounted piggy-back on the B29 telescope. The AATS on B29 is virtually identical to the AATS mounted on the 1.6m AMOS instrument, with one exception; the 3° field is provided by a 0.15m lens. The television sensor is the same.

GEODSS

The final group of ground-based electro-optical detectors used during the Delta-180 observations were the three telescopes comprising the GEODSS facility on Maui; these are designated simply as GEODSS 1, GEODSS 2, and GEODSS 3. The three domes housing the GEODSS instruments are shown in Figure 1-2.

Each of these three telescopes is of standard Cassegrain design. The diameters and focal lengths of GEODSS 1, GEODSS 2, and GEODSS 3 are: (D=1.02m, FL=2.18m), (D=1.02m, FL=2.18m) and, (D=0.38m, FL=0.76m), respectively. The fields of view associated with each are 2° for GEODSS 1 and 3, and 6° for GEODSS 2.

Because the GEODSS software was designed for "deep space" operations, new operational techniques had to be developed in order to observe objects in low earth orbit. The only procedure that would allow the telescopes to point to a particular spot in the sky, then follow that spot at the sidereal rate, was to input a satellite number whose orbital elements were in the GEODSS computer. When the satellite number was entered, the telescopes would move to the position
of the satellite at that time, and begin tracking the stars at the sidereal rate. However, the orbital period of the satellite had to be greater than 225 minutes in order to qualify as a "deep space" object, and computer software would only accept deep space objects. Since all of the Delta-180 objects had periods closer to 90 minutes, and because it was desired to detect objects whose exact orbital elements were not known, procedures to deceive the GEODSS computers programs had to be developed.

The procedure which was developed follows. Using known orbital elements, the AMOS/MOTIF computers were used to predict the path of objects across the sky as seen from Haleakala (i.e., azimuth and elevation as a function of time). This data was plotted in polar coordinates and used to approximately define the orbital plane of the fragments. Both theory and some experience had already suggested that the most sensitive position of the telescopes would be to point at the zenith to about thirty degrees away from the zenith in the direction away from the sun. However, in practice a given object, or its orbital plane may not be placed where lighting conditions are favorable. Therefore, these plots were used to determine when and where the most favorable conditions were approached.

Using the plots, azimuths and elevations were determined for each telescope such that each telescope became a picket in a "fence" which was perpendicular to the orbital plane (see Figure 3-19). The pointing information required to create this situation was given to Teledyne Brown Engineering, who then calculated "simulated" orbital element sets for each point in the sky that was to be observed with the telescopes. The chief characteristic of these fake orbital element sets is that the fake object would pass through the predetermined point in the sky at the time the observations with the telescopes were to begin. Typically, the fake objects had
Figure 3-19  Typical Maui "fence" -- DOY 256.

<table>
<thead>
<tr>
<th>Epoch 1986.7</th>
<th>RA 2h 30m 05 s</th>
<th>Dec 59d 00 m</th>
<th>Alt 50.70</th>
<th>Az 350.05</th>
<th>Long-156 Lat= 21</th>
<th>FOV 35.00 deg</th>
<th>Mag Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1 0 - 2 3 4</td>
</tr>
</tbody>
</table>

MAUI FENCE

G-2

G-3

MOTIF
near circular orbits slightly greater than geosynchronous altitudes. Using orbits of higher fake altitudes tended to reduce telescope pointing errors caused by not pointing at the object at exactly the right time.

The fake orbital element sets used in the fence generation were entered into NORAD computers with numbers beginning with 89391; these were then transferred to GEODSS computers. Instructions were sent from NORAD to set up a fence using these objects at a particular GMT, and to record data for a given amount of time. After the observing was completed, the fake objects were deleted from the NORAD and GEODSS computers to prevent confusion for observations on the next day.

The data obtained with the GEODSS telescopes were different from the AMOS, MOTIF, and Kwajalein data in that it was preprocessed. Whereas in all of the other detectors a simple video image was recorded with a full gray scale of pixel values, the images recorded with the GEODSS detectors were of a threshold type. If the signal strength at a certain location was less than a specified value, no response was indicated; however, if the signal was greater than that minimum, the value was set to a constant. In essence the detection mode was binary -- either on or off.

Further, instead of a 1/30th of a second framing rate, the data provided to JSC was updated every 12/30ths of a second. The chief advantage to this mode of data recording was that every satellite appeared as a short streak on the detector field as opposed to a dot that might be mistaken for noise.

In addition, the tapes could also be processed to remove the background starfield. However, using the JSC Video Digital Analysis System (VDAS) facility, it was found that the starfields were useful for registration of each image against the celestial coordinate system. The registration procedure will be described in Section 3.5.
Ground-based optical observations were obtained on eight out of ten days. Two days were completely lost to clouds -- September 9th and 10th. Partial cloudiness and/or haze were reported for September 8th, 11th, and 14th. Clear sky conditions prevailed on the 12th, 13th, and 15th.

3.4 Airborne Optical Measurements

During the post-EOM phase of the Delta-180 experiment, image data were obtained of fragments of satellites 16937 and 16938 using two optical systems flown on board an Aeromet Learjet. The base of airborne operations was the Kwajalein Atoll. The Learjet Optical System (LOS) integration and support was provided by Aeromet, Inc. A description of the instrumentation and mission mode follows.

The LOS consists of three optical windows installed in the right side of the Aeromet Learjet as shown in Figure 3-20. The LOS had two optical platforms, each with a stabilized mirror for tracking of targets at the forward and aft positions -- windows #1 and #2, respectively. Further, an Aeromet-developed Airborne Pointing System (APS) utilized the predicted satellite files combined with data from the on-board navigation system to generate pointing information for the stabilized mirrors. Data were recorded on videotape. Timing information was provided by an on-board timing system, which was synchronized to the Kwajalein Missile Range (KMR) timing system.

During the Delta-180 mission, only the forward and aft windows were used by the two optical systems. A Lenzar Low Light Level Television (LLLTV) was mounted on the forward platform while a dual wide field of view (WFOV)/narrow field of view (NFOV) video system was mounted on the aft platform. A diagram of the interior layout is shown in Figure 3-21. The pertinent characteristics of the optical systems are given in Table 3-9.
Figure 3-20 Optical window installation on Aeromet Learjet.
Figure 3-21 APS equipment layout on Aeromet Learjet.
<table>
<thead>
<tr>
<th>Instrument</th>
<th>Field-of-View</th>
<th>Focal Length</th>
<th>Camera Type</th>
<th>Frms./Sec.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lenzar</td>
<td>1.9° X 1.9°</td>
<td>220mm (f/1.35)</td>
<td>Video (SIT)</td>
<td>30</td>
</tr>
<tr>
<td>WFOV</td>
<td>7.3° X 5.5°</td>
<td>100mm (f/1.80)</td>
<td>Video (SIT)</td>
<td>30</td>
</tr>
<tr>
<td>NFOV</td>
<td>1.44° X 1.08°</td>
<td>508mm (f/5.70)</td>
<td>Video (SIT)</td>
<td>30</td>
</tr>
</tbody>
</table>
The mission plan called for two flights -- one on DOY 249 (September 6, 1986) and one on DOY 250 (September 7, 1986). During the first flight the Learjet arrived on station at 18:15:23 UT; its coordinates were Latitude: 18.7447° N, Longitude: 163.0124° E, and Altitude: 39,000 feet. The aircraft maintained a SSE heading, ending the data run at 18:34:09 UT; its coordinates were then Latitude: 16.6745° N, Longitude: 163.2432° E, and Altitude: 39,000 feet (Figure 3-22). The duration of the data gathering run was 00:18:24. No significant observations were obtained because the Learjet was located eastward (toward the sun) from the debris objects. Sunlight scattered by the atmosphere at the Learjet position was too intense to permit detection of debris objects west of the aircraft.

During the second flight a modified flight plan was used, such that the sensors looked northwards. This minimized the effects of scattered sunlight. The Learjet arrived on station at 17:05:00 UT; its coordinates were Latitude: 15.9349° N, Longitude: 173.6170 E, and Altitude: 43,000 feet. The aircraft maintained a WSW heading, ending the data run at 17:54:59 UT; its coordinates were then Latitude: 15.1082° N, Longitude: 167.8437 E, and Altitude: 43,000 feet (Figure 3-22). The duration of the data gathering run was 00:49:59. During that period of time a total of 18 "events" were recorded. The convention adopted here is that an "event" is any detection of any streak in any of the detectors.

3.5 Optical Data Reduction Procedures

Although the specific characteristics of each optical detector system were quite different from one another, the final form of the data delivered to JSC for reduction and analysis, was that of a video-tape record. The reduction and analysis procedures were similar for each data set regardless of source.
Figure 3-22 Learjet groundtracks DOY 249 and DOY 250.
A total of 98 video tapes were received at the JSC VDAS lab within several weeks of the end of mission. The tapes fell into two categories -- premission test tapes (25%) and post-EOM data tapes (75%). The tapes were logged in as they were received; each was assigned a serial number in the order of receipt.

The first task was to screen the data tapes for observable "events", which were defined as the appearance of an object passing through the field of view. To aid in this screening process, an optical data screening form was designed -- a sample is shown in Figure 3-23.

In depth screening of the tapes was restricted to those tapes designated as high priority. In coordination with the JSC Delta-180 field team, 23 tapes were identified as falling into this category. These tapes represented data from DOY 249, 250, 256, 257, and 258.

The screening was done using a video-tape replay unit and Inter-Range Instrumentation Group - B (IRIG-B) time decoder. Noted during the screening were time of the event, duration of the event, and apparent direction of travel. This information, was useful as a zeroth order discriminator in separating Delta-180 from non-Delta-180 events.

During the screening process a total of 80 casually identifiable events were recorded (Table 3-10). The phrase "casually identifiable" here means that the events were detected without any special enhancement. Of these, 21% were recorded using the airborne detectors, 29% with the AMOS/MOTIF instruments, and 50% with the three GEODSS telescopes.

Because some events were recorded simultaneously with more than one detector, the coincidence-corrected count is 64 unique events.
Figure 3-23  Typical optical data screening form.


<table>
<thead>
<tr>
<th>EVENT</th>
<th>DAY/TIME</th>
<th>DETECTOR</th>
<th>IDENTIFICATION / EVENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>249:14:51:11</td>
<td>1.6-M/AATS</td>
<td>METEOR</td>
</tr>
<tr>
<td>02</td>
<td>249:14:58:55</td>
<td>1.6-M/AATS</td>
<td>INTERLOPER SATELLITE</td>
</tr>
<tr>
<td>03</td>
<td>249:15:01:49</td>
<td>1.6-M/AATS</td>
<td>INTERLOPER SATELLITE</td>
</tr>
<tr>
<td>04</td>
<td>250:17:07:14</td>
<td>AIRBORNE/WFOV</td>
<td>METEOR</td>
</tr>
<tr>
<td>05</td>
<td>250:17:15:07</td>
<td>AIRBORNE/WFOV</td>
<td>METEOR</td>
</tr>
<tr>
<td>06</td>
<td>250:17:18:48</td>
<td>AIRBORNE/WFOV</td>
<td>INTERLOPER SAT./#7</td>
</tr>
<tr>
<td>07</td>
<td>250:17:18:48</td>
<td>AIRBORNE/LENZAR</td>
<td>INTERLOPER SAT./#6</td>
</tr>
<tr>
<td>08</td>
<td>250:17:20:22</td>
<td>AIRBORNE/WFOV</td>
<td>INTERLOPER SAT./#9,10</td>
</tr>
<tr>
<td>09</td>
<td>250:17:20:30</td>
<td>AIRBORNE/LENZAR</td>
<td>INTERLOPER SAT./#8,10</td>
</tr>
<tr>
<td>10</td>
<td>250:17:20:40</td>
<td>AIRBORNE/NFOV</td>
<td>INTERLOPER SAT./#8,9</td>
</tr>
<tr>
<td>11</td>
<td>250:17:24:31</td>
<td>AIRBORNE/NFOV</td>
<td>***** DELTA-180 *****</td>
</tr>
<tr>
<td>12</td>
<td>250:17:27:25</td>
<td>AIRBORNE/WFOV</td>
<td>INTERLOPER SAT./#13</td>
</tr>
<tr>
<td>13</td>
<td>250:17:27:34</td>
<td>AIRBORNE/NFOV</td>
<td>INTERLOPER SAT./#12</td>
</tr>
<tr>
<td>14</td>
<td>250:17:40:21</td>
<td>AIRBORNE/NFOV</td>
<td>INTERLOPER SAT./#16,17</td>
</tr>
<tr>
<td>15</td>
<td>250:17:40:33</td>
<td>AIRBORNE/WFOV</td>
<td>INTERLOPER SAT./#18,19</td>
</tr>
<tr>
<td>16</td>
<td>250:17:40:37</td>
<td>AIRBORNE/WFOV</td>
<td>INTERLOPER SAT./#14,17</td>
</tr>
<tr>
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<td>250:17:40:41</td>
<td>AIRBORNE/LENZAR</td>
<td>INTERLOPER SAT./#14,16</td>
</tr>
<tr>
<td>18</td>
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<td>INTERLOPER SAT./#15,19</td>
</tr>
<tr>
<td>19</td>
<td>250:17:40:56</td>
<td>AIRBORNE/NFOV</td>
<td>INTERLOPER SAT./#15,18</td>
</tr>
<tr>
<td>20</td>
<td>250:17:43:33</td>
<td>AIRBORNE/WFOV</td>
<td>INTERLOPER SAT./#21</td>
</tr>
<tr>
<td>21</td>
<td>250:17:43:38</td>
<td>AIRBORNE/NFOV</td>
<td>INTERLOPER SAT./#20</td>
</tr>
<tr>
<td>22</td>
<td>256:14:50:17</td>
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<td>INTERLOPER SATELLITE</td>
</tr>
<tr>
<td>23</td>
<td>256:14:50:30</td>
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<td>INTERLOPER SATELLITE</td>
</tr>
<tr>
<td>24</td>
<td>256:14:51:00</td>
<td>GEODSS-1</td>
<td>INTERLOPER SATELLITE</td>
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<tr>
<td>25</td>
<td>256:14:53:52</td>
<td>GEODSS-3</td>
<td>INTERLOPER SATELLITE</td>
</tr>
<tr>
<td>26</td>
<td>256:14:55:00</td>
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<td>INTERLOPER SATELLITE</td>
</tr>
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<td>27</td>
<td>256:14:55:43</td>
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</tr>
<tr>
<td>Time</td>
<td>Location</td>
<td>Satellite Name</td>
<td>Notes</td>
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</tr>
<tr>
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<td>256:15:04:20</td>
<td>GEODSS-1</td>
<td>METEOR</td>
</tr>
<tr>
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<td>256:15:09:16</td>
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<td>METEOR</td>
</tr>
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<td>1.2-M/AATS</td>
<td>INTERLOPER SATELLITE</td>
</tr>
<tr>
<td>31</td>
<td>256:15:10:17</td>
<td>GEODSS-1</td>
<td>INTERLOPER SATELLITE</td>
</tr>
<tr>
<td>* 32</td>
<td>256:15:12:22</td>
<td>1.2-M/AATS</td>
<td>***** DELTA-180 *****/#33</td>
</tr>
<tr>
<td>33</td>
<td>256:15:12:22</td>
<td>1.2-M/LLLTV</td>
<td>***** DELTA-180 *****/#32</td>
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<td>INTERLOPER SATELLITE</td>
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<tr>
<td>* 37</td>
<td>256:15:18:10</td>
<td>GEODSS-2</td>
<td>***** DELTA-180 *****</td>
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<td>38</td>
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<td>39</td>
<td>256:15:18:49</td>
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</tr>
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<td>40</td>
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<td>1.2-M/AATS</td>
<td>INTERLOPER SAT./#39</td>
</tr>
<tr>
<td>* 41</td>
<td>256:15:19:53</td>
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<td>***** DELTA-180 *****</td>
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<td>* 43</td>
<td>256:15:20:53</td>
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<td>***** DELTA-180 *****</td>
</tr>
<tr>
<td>* 44</td>
<td>256:15:23:30</td>
<td>1.6-M/AATS</td>
<td>***** DELTA-180 *****</td>
</tr>
<tr>
<td>* 45</td>
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<td>***** DELTA-180 *****</td>
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<tr>
<td>46</td>
<td>257:14:57:51</td>
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<td>METEOR</td>
</tr>
<tr>
<td>47</td>
<td>257:14:57:55</td>
<td>1.2-M/AATS</td>
<td>METEOR</td>
</tr>
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<td>48</td>
<td>257:14:58:07</td>
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<td>INTERLOPER SATELLITE</td>
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<tr>
<td>49</td>
<td>257:14:58:33</td>
<td>GEODSS-3</td>
<td>METEOR</td>
</tr>
<tr>
<td>50</td>
<td>257:15:03:46</td>
<td>GEODSS-2</td>
<td>METEOR</td>
</tr>
<tr>
<td>51</td>
<td>257:15:04:30</td>
<td>GEODSS-2</td>
<td>INTERLOPER SATELLITE</td>
</tr>
<tr>
<td>52</td>
<td>257:15:04:35</td>
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<td>METEOR</td>
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<tr>
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<td>257:15:07:00</td>
<td>1.6-M/AATS</td>
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<td>1.2-M/AATS</td>
<td>METEOR</td>
</tr>
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<td>1.2-M/AATS</td>
<td>METEOR</td>
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<tr>
<td>56</td>
<td>257:15:10:18</td>
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<td>INTERLOPER SATELLITE</td>
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<td>1.6-M/AATS</td>
<td>INTERLOPER SATELLITE</td>
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<td>58</td>
<td>257:15:13:01</td>
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<td>59</td>
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<td>INTERLOPER SATELLITE</td>
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<td>1.2-M/AATS</td>
<td>METEOR</td>
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<tr>
<td>63</td>
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<td>1.2-M/AATS</td>
<td>INTERLOPER SAT./#64</td>
</tr>
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<td>64</td>
<td>257:15:27:36</td>
<td>GEODSS-3</td>
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</tr>
<tr>
<td>---</td>
<td>----------</td>
<td>------------</td>
<td>---------------------</td>
</tr>
<tr>
<td>65</td>
<td>258:15:03:03</td>
<td>GEODSS-2</td>
<td>METEOR</td>
</tr>
<tr>
<td>66</td>
<td>258:15:03:08</td>
<td>GEODSS-3</td>
<td>METEOR</td>
</tr>
<tr>
<td>67</td>
<td>258:15:05:50</td>
<td>GEODSS-2</td>
<td>INTERLOPER SATELLITE</td>
</tr>
<tr>
<td>68</td>
<td>258:15:07:30</td>
<td>GEODSS-3</td>
<td>INTERLOPER SATELLITE</td>
</tr>
<tr>
<td>69</td>
<td>258:15:08:00</td>
<td>1.2-M/AATS</td>
<td>METEOR</td>
</tr>
<tr>
<td>70</td>
<td>258:15:08:46</td>
<td>GEODSS-1</td>
<td>INTERLOPER SAT./#71</td>
</tr>
<tr>
<td>71</td>
<td>258:15:08:54</td>
<td>GEODSS-3</td>
<td>INTERLOPER SAT./#70</td>
</tr>
<tr>
<td>72</td>
<td>258:15:10:09</td>
<td>GEODSS-1</td>
<td>METEOR</td>
</tr>
<tr>
<td>73</td>
<td>258:15:18:54</td>
<td>1.2-M/AATS</td>
<td>INTERLOPER SAT./#74,75</td>
</tr>
<tr>
<td>74</td>
<td>258:15:18:54</td>
<td>GEODSS-2</td>
<td>INTERLOPER SAT./#73,75</td>
</tr>
<tr>
<td>75</td>
<td>258:15:19:13</td>
<td>GEODSS-3</td>
<td>INTERLOPER SAT./#73,74</td>
</tr>
<tr>
<td>76</td>
<td>258:15:25:15</td>
<td>1.2-M/AATS</td>
<td>INTERLOPER SAT./#77</td>
</tr>
<tr>
<td>77</td>
<td>258:15:25:18</td>
<td>GEODSS-2</td>
<td>INTERLOPER SAT./#76</td>
</tr>
<tr>
<td>*78</td>
<td>258:15:28:25</td>
<td>GEODSS-3</td>
<td>**** DELTA-180 ****</td>
</tr>
<tr>
<td>79</td>
<td>258:15:33:16</td>
<td>GEODSS-1</td>
<td>INTERLOPER SATELLITE</td>
</tr>
<tr>
<td>80</td>
<td>258:15:33:20</td>
<td>GEODSS-3</td>
<td>INTERLOPER SATELLITE</td>
</tr>
</tbody>
</table>

† Asterisks in Column 1 identify principal observation of a Delta-180 fragment; redundant observations are noted in column 4.

‡ Total number of unique events: 64.

§ Totals by category:

- Delta-180 pieces: 10 (15.4%)
- Interloper satellites: 37 (56.9%)
- Meteors: 18 (27.7%)
Using the screening forms, individual events were identified as being worth more detailed investigation. Video frames for a given event were selected using the JSC VDAS Real Time Disk system. For any given event, the observation spanned a finite time ranging from a second to 45 seconds. The video frames for an event were selected with the maximum possible time base.

The two chosen frames were designated Event (X)/ Frame A, for the one near the beginning of the sequence, and Event (X)/ Frame B for the one at the end of the sequence. The IRIG-B time was noted for Frame A as well as the total number of frames between Frame A and Frame B. The framing rate provided the duration of the event.

A VDAS program, STARGEN, was used to overlay a Smithsonian Astrophysical Observatory (SAO) starfield on each frame. The program allowed correction for rotation and magnification of the SAO field to match the video frame field. Further, when distortions were a problem, the VDAS program TIE-POINT was used to allow for geometric distortion correction. Once the starfield had been registered, the R.A. and Dec. were measured for each of the frames in question. These values, along with the time (UT), were recorded. The procedure was repeated for the B frame.

With coordinates and time in hand an orbit was calculated for each event assuming eccentricity 0.0. This was satisfactory to determine inclination, which was used as the primary discriminant to cull Delta-180 objects from non-Delta-180 objects.

A total of 10 of these events were identified as Delta-180 debris fragments -- 2 tracked with AMOS (described in more detail below), 1 observed with the airborne platform, and 7 detected by the Maui fence. The Delta-180 fragment
observations are summarized in Table 3-11. Of all of the optical events 15% were Delta-180 related, 57% were unidentified satellite interlopers, and 28% were meteors. A more complete discussion of the information derived from these observations is presented in section 4.4.

With AMOS operating in the tracking mode two Delta-180 targets were acquired and tracked for extended periods of time. The first, acquired on DOY 256 at 15:23:30, was tracked for 80 seconds; the satellite object catalog number was 88290. From the NORAD data set of 01-OCT-86 this particular fragment had a period of 101.8 min, an eccentricity of 0.0867, perigee height of 216km, and inclination of 23.0495°. A magnitude could not be determined for the object in that it saturated the detector.

The second object, acquired on DOY 257 at 15:07:00, was tracked for 90 seconds; the object number was 16938 -- the Delta 2nd Stage. From the NORAD data set of 15-OCT-86 this particular fragment had a period of 91.8 min, an eccentricity of 0.0281, perigee of 217km, and inclination of 22.7915°. The RCS was 1.55m². At the time of culmination, 15:08:28 UT the object was at AZI=9°, EL=68°, and Range=290km. An estimate of the visual magnitude was obtained and is discussed in Section 4.4.

Examination of the remaining AMOS data consisted of screening the tapes at the times target acquisition was attempted to see if the target object was present. In the aforementioned two cases, identification was trivial; for each of 10 other tracking intervals, approximately 780 frames were co-averaged using routines available at the JSC VDAS facility. The purpose of the procedure was to enhance signal-to-noise and bring up out of the background any faint, but localized, target object. However, no additional target acquisitions were identified. The AATS 3° field was used in all cases including the detection of objects 88920 and 16938.
TABLE 3-11

Delta-180 Fragments Identified from Optical Data

<table>
<thead>
<tr>
<th>EVENT</th>
<th>PERIOD (MIN)</th>
<th>HT. AT OBS. (KM)</th>
<th>INCLINATION (°)</th>
<th>DOY/TIME (UT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>88.93</td>
<td>239</td>
<td>23.8</td>
<td>250:17:24:31</td>
</tr>
<tr>
<td>*27</td>
<td>108.00</td>
<td>1167</td>
<td>(42.1)</td>
<td>256:14:55:43</td>
</tr>
<tr>
<td>32</td>
<td>~ 80.00</td>
<td>reentry(?)</td>
<td>23.3</td>
<td>256:15:12:22</td>
</tr>
<tr>
<td>37</td>
<td>90.30</td>
<td>307</td>
<td>22.7</td>
<td>256:15:18:10</td>
</tr>
<tr>
<td>41</td>
<td>91.27</td>
<td>354</td>
<td>23.0</td>
<td>256:15:19:53</td>
</tr>
<tr>
<td>43</td>
<td>90.31</td>
<td>307</td>
<td>22.8</td>
<td>256:15:20:53</td>
</tr>
<tr>
<td>*45</td>
<td>98.55</td>
<td>707</td>
<td>(26.8)</td>
<td>256:15:24:44</td>
</tr>
<tr>
<td>78</td>
<td>133.30</td>
<td>2283</td>
<td>40.3</td>
<td>258:15:28:25</td>
</tr>
</tbody>
</table>

AMOS OBSERVATIONS . . .

<table>
<thead>
<tr>
<th>SAT. #</th>
<th>PERIOD (MIN)</th>
<th>PERIGEE (KM)</th>
<th>INCLINATION (°)</th>
<th>DOY/TIME (UT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>88290</td>
<td>101.8</td>
<td>216</td>
<td>23.1</td>
<td>256:15:23:30</td>
</tr>
<tr>
<td>16938</td>
<td>91.8</td>
<td>217</td>
<td>22.8</td>
<td>257:15:08:28</td>
</tr>
</tbody>
</table>

NOTES: * Orbits were calculated for 37 out of the observed 64 to obtain the above list. Many objects on the original list were eliminated by virtue of observed trajectory.

* Satellite numbers 88290 and 16938 correspond to event numbers #44 and #53 of Table 3-10, respectively.

* Events #27 and #45 are marked with an asterisk to indicate that they may be slightly out of the range appropriate to their respective Delta-180 debris clouds. Typical range for the 23° cloud: 21.95-25.25° and for the 39° cloud: 34.7-41.4°.

* Event #32 was at the right inclination for Delta-180 debris. Apparent angular speed indicates that it is de-orbiting.
4.0 A Comparison of Pre- and Post-Mission Data

This section describes the comparison of pre-mission modeling with the analysis of the post-EOM data. Foremost areas of interest include the number and size distributions of the particles, the linear momentum transfer, the velocity distribution of the debris, the optical correlation of size to magnitude, and the orbital lifetimes of the debris.

A comparison of the radar (Kaena Point) and optical/IR (AMOS, MOTIF, Maui GEODSS) simultaneous observations made on days 256 and 257 (September 13 and 14) will be included in the Appendices of the final report. Reduction and analysis of the end-of-mission data will appear as a separate classified report.

4.1 Piece Counts and Size Distributions

The primary source of data used in this section was the ALTAIR data of days 249, 250 and 251. Only these data contained values of the radar cross section. Subsequent sources were the NORAD satellite catalogs for October 15, 1986 (day 288) and November 14, 1986 (day 318), as well as data supplied by SRS Corp. from the modified meteor radar. (Appendix C of this report).

In modeling the breakup of the Delta-180 satellites, masses of 873kg and 1455kg were input for the masses of the Delta second stage and satellite/PAS combination, respectively. Using these masses, the Delta second stage would produce 300 objects greater than 10cm in diameter, i.e., objects observable by radar, while the SDI satellite would produce 501 objects greater than 10cm in diameter. Thus, a total of 801 pieces would be produced in the breakup.
Alternate values for the satellite mass involved are those contained in Appendix B of this report. In The Collision of Satellites 16937 and 16938: A Preliminary Report, Teledyne Brown states a dry mass of 350kg for the Delta stage, and a dry mass of approximately 1380kg for the SDI satellite. These values produce 120 objects and 475 objects from the Delta stage and satellite. The piece count here totals 595 radar observable pieces.

Unknown at this time are the actual masses of the Delta stage and satellite. Among the unknowns are the mass of any sensor packages attached to the Delta stage, and the amount of liquid propellant on board both vehicles at the time of collision. However, the two alternate sets of mass data above effectively establish an envelope of reasonable values for the number of large objects created in the breakup event.

Figures 4-1 through 4-6 show the number of pieces vs. the piece diameter observed by ALTAIR on days 250 and 251. The dotted line in each graph represents the number of pieces predicted to exist at breakup by the computer model. Figure 4-7 depicts the number of objects as a function of diameter for those pieces cataloged by NORAD approximately five weeks after the event. The unusually low values plotted in Figure 4-7 may simply reflect the limited number of pieces catalogued by NORAD.

Perhaps the most striking feature of any of these graphics is the preponderance of fragments in the size range 0.4-1.4m observed in the 23° cloud on day 249, as well as very large fragments (diameter > 1.0m) in the 23° cloud on day 250. This same cloud exhibits a large number of objects in the 0.7-0.8m diameter bin also. Apart from this deviance, number distributions fit the predicted values well. Unfortunately, too few objects were observed in the 39° cloud to form a distribution. However, this cloud, observed on day 251, also
Figure 4-1  Number vs. diameter distribution -- DOY 249, 23° cloud compared to theoretical distribution.
Figure 4-2 Number vs. diameter distribution -- DOY 249, 39° cloud compared to theoretical distribution.
Figure 4-3  Number vs. diameter distribution -- DOY 250, 23° cloud compared to theoretical distribution.
Hazard Analysis Project

ALTAIR data: day 250_39

Figure 4-4
Number vs. diameter distribution -- DOY 250, 390 cloud compared to theoretical distribution.
Hazard Analysis Project

ALTAIR data: day 251_23

![Graph showing number of objects vs. diameter (m)].

Figure 4-5

Number vs. diameter distribution -- DOY 251, 230 cloud compared to theoretical distribution.
Figure 4-6 Number vs. diameter distribution -- DOY 251, 39° cloud compared to theoretical distribution.
Figure 4-7 Number vs. diameter distribution -- DOY 318 NSSC catalogued objects compared to theoretical distribution.
possessed a large number (relatively) of objects in the 1.0-1.1m diameter bin.

The NORAD catalog set of pieces displayed too few observations to form a proper distribution. In the Delta stage cloud, there were 5 pieces; in the satellite cloud, there were 13 pieces, of which 11 had recorded radar cross sections. Once again, large pieces predominated in the 23⁰ cloud, as two pieces accounted for about 93% of the cloud's total mass. The mass was concentrated in the diameter range 0.5-0.7m in the 39⁰ cloud.

The total mass of each cloud on days 249 and 250 was calculated using the same formulae, relating diameter and mass, that were used in the computer model. These values are presented in Table 4-1. Pre-mission predictions yielded cloud (radar observable) masses of 740kg for the 23⁰ cloud (or about 85% of modeled mass of 837kg) and 1296kg for the 39⁰ cloud (about 89% of modeled mass). Derived from the measurement of the mass and the average cross section of various payloads, rocket motors, etc., the equations used by the computer model will not give accurate values for objects such as large flat plates. Such plates could have been produced (and considering the data, almost certainly were) in the fragmentation of the Delta second stage, which is basically a right circular cylinder composed of an outer skin and liquid fuel tanks.

Figure 4-8 demonstrates the results of the modified meteor radar established in Hawaii. The theoretical distribution here is based on that used in the computer model, and represents the summation of mass in the 23⁰ cloud and the 39⁰ cloud. This was done as there was no distinction between the two clouds in the reentry radar data. However, this should not make a great deal of difference in this case as the 39⁰ cloud was not close to Hawaii on this pass. Approximately 10% of the mass theoretically produced in the mass range 10-170gm by
### TABLE 4-1

**Observed Cloud Mass**

<table>
<thead>
<tr>
<th>Diameter (m)</th>
<th>Day 249⁹</th>
<th>Bin Mass (kg)</th>
<th>Day 250⁹</th>
<th>Day 251⁹</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>23⁰</td>
<td>39⁰</td>
<td>23⁰</td>
<td>39⁰</td>
</tr>
<tr>
<td>0.1-0.2</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>0.2-0.3</td>
<td>4</td>
<td>10</td>
<td>14</td>
<td>0</td>
</tr>
<tr>
<td>0.3-0.4</td>
<td>40</td>
<td>18</td>
<td>97</td>
<td>0</td>
</tr>
<tr>
<td>0.4-0.5</td>
<td>148</td>
<td>31</td>
<td>163</td>
<td>16</td>
</tr>
<tr>
<td>0.5-0.6</td>
<td>244</td>
<td>49</td>
<td>183</td>
<td>0</td>
</tr>
<tr>
<td>0.6-0.7</td>
<td>339</td>
<td>36</td>
<td>125</td>
<td>0</td>
</tr>
<tr>
<td>0.7-0.8</td>
<td>739</td>
<td>99</td>
<td>296</td>
<td>0</td>
</tr>
<tr>
<td>0.8-0.9</td>
<td>653</td>
<td>33</td>
<td>163</td>
<td>33</td>
</tr>
<tr>
<td>0.9-1.0</td>
<td>504</td>
<td>0</td>
<td>126</td>
<td>0</td>
</tr>
<tr>
<td>1.0-1.1</td>
<td>422</td>
<td>0</td>
<td>53</td>
<td>0</td>
</tr>
<tr>
<td>1.1-1.2</td>
<td>647</td>
<td>0</td>
<td>388</td>
<td>0</td>
</tr>
<tr>
<td>1.2-1.3</td>
<td>234</td>
<td>0</td>
<td>469</td>
<td>0</td>
</tr>
<tr>
<td>1.3-1.4</td>
<td>279</td>
<td>0</td>
<td>186</td>
<td>0</td>
</tr>
<tr>
<td>1.4-1.5</td>
<td>109</td>
<td>0</td>
<td>109</td>
<td>0</td>
</tr>
<tr>
<td>1.5-1.6</td>
<td>127</td>
<td>127</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1.6-1.7</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1.7-1.8</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1.8-1.9</td>
<td>190</td>
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</tr>
<tr>
<td>1.9-2.0</td>
<td>0</td>
<td>0</td>
<td>213</td>
<td>48</td>
</tr>
<tr>
<td>2.0-2.1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2.1-2.2</td>
<td>266</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2.2-2.3</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

**total:** 4945 403 2586 97 358 160

---

a assume mass given by m = 47.2 d².26 (m [kg], d [m])
b duration of observations = 1 hour, 45 minutes
c duration of observations = 1 hour, 52 minutes
d duration of observations = 1 hour, 47 minutes
Figure 4-8 Number vs. mass distribution -- DOY 249 SRS meteor radar data compared to theoretical distribution.
the breakup event was observed to reenter shortly after EOM by radar. This is in agreement with model estimates performed post-EOM at JSC.

4.2 Momentum Transfer

The transfer of linear momentum between the satellites involved in the breakup, like the velocity distribution of the various-sized fragments discussed in Section 4.3, awaits the calculation of relative velocities for the fragments observed by radar. However, a qualitative analysis of the momentum transfer may be made by noting the distribution of debris inclinations around the mean inclination of the parent body (see Figures 3-5 and 3-6).

While there is some skewing of the distributions towards an intermediate value, there exists no detectable debris cloud between those clouds formed of the Delta stage and the satellite. Thus, the distribution of debris inclinations suggests little momentum transfer between the impacting bodies. In terms of pre-mission modeling, this is consistent with on-orbit explosions, in which no momentum is transferred.

Unknown at this time, however, are the detailed impact mechanics of large objects of similar mass, and the effects of any residual propellants on board the spacecraft at the time of impact. Both of these factors could have affected the net forces, and hence, the change in momentum with respect to time, acting on the debris objects produced in the event.

4.3 Velocity Distributions

At the time of writing, the computation of the velocity distribution for the Eglin data awaits the processing by Teledyne Brown Engineering of the classified end-of-mission state vectors. In conversations with Mr. Ronn Kling of
Teledyne Brown, a Meirovitch-derived analysis, similar to that performed following the breakup of the P-78 (Solwind) satellite, is planned for the data. Also, methods involving the rotation of the orbit (hence, the "adjustment" of the orbital elements) so as to propagate from point of impact through observed position will be implemented as a check.

Unfortunately, these data contain no information concerning object size; pending further analysis of the Eglin "Log S" data tapes by Xontech such information will not be forthcoming. One method of alleviating this difficulty would be the identification of provisional numbers with the NORAD catalog numbers. The provisional pieces contain velocity information, while the cataloged pieces (in most cases) have RCS values. Thus, the nineteen cataloged pieces could be used to calibrate the velocity distribution curve.

Until finalization of action on this matter, no quantitative comparisons may be drawn. However, some qualitative estimates of the velocity distribution may be gleaned from a comparison of the Eglin Gabbard diagrams of day 249 with Gabbard diagrams produced pre-mission by computer modeling. Figures 2-4 and 2-5 depict the case of a direct hit (100% mass overlap) utilizing the high velocity (100% kinetic energy transfer) curve and the medium velocity (50% kinetic energy transfer) curve, respectively.

As shown in Figures 2-4 and 2-5, the "arms" of the Gabbard diagram are indicators of the amount of kinetic energy transfer and the velocity distribution involved in the event. For the medium velocity curve, the arms of the Gabbard plot will not meet so as to form a complete cross. Those of the high velocity curve shown in Figure 2-5 will, however. This is indicative of the higher velocity given larger pieces of debris, such as those observable by radar, by a large energy transfer. Smaller pieces will tend to receive proportionately
smaller velocity increments in all energy transfer scenarios. Thus, the spread of large objects about the original apogee and perigee of the target or projectile provides an excellent clue as to the velocity distribution as a function of debris size.

Comparison of pre-mission plots and the Gabbard diagram produced on day 249 from Eglin data suggests that the high velocity distribution used in pre-mission modeling is the most reasonable. Even this distribution fails to scatter objects to the apogees observed. Also unexplained is the clumping visible in the 39º cloud (Eglin, day 249) between 98 minutes and 104 minutes of period.

4.4 Size vs. Optical Magnitude of Debris

To describe an object size from either magnitude or radar cross section requires some knowledge of the albedo, or reflectivity, of the object, the geometry of the object, and its physical nature. For a given recorded event, such as many of the video events recorded during the Delta-180 measurement campaign, a video brightness is the direct observable. If their exists adequate calibration, the video brightness may be converted to an apparent visual magnitude. This magnitude, by itself, is insufficient for the determination of size or albedo. One or the other of these latter two quantities must be known before the the remaining one can be determined.

With supporting radar data, it is possible to get an idea of the size of an object. However, values of radar cross section (RCS) cannot be considered a true measure of the physical dimensions of an object because the shape of the object as well as its size and physical character influence the returned signal from which the RCS value is determined.
Radar cross section is defined as the projected area of a perfectly conducting sphere which, if placed in the same position as the real target, would scatter the same amount of energy to the observer. Obviously, if an observed object is not a perfect conductor and/or not spherical, an unambiguous interpretation of RCS is not possible. Usually, an irregular or rough object will reflect more signal toward the illumination source, or in the "backscatter" direction, than a conducting sphere. This difference becomes significant when radar and optical data are compared because RCS values are based on measurements made from backscattered radiation (phase angle=0°); optical measurements are usually made at a phase angle of about 70° to 90°. For radar data, the difference arising from different phase functions alone, can be as much as a factor of five in the amount of backscattered radiation. The "typical" difference between a debris target object and a metallic calibration sphere would be on the order of 2.5.

If the reported RCS for an object is used to calculate the radius of an equivalent sphere there will usually be a tendency to overestimate this radius by virtue of not properly taking the phase function into account. In the following paragraphs the phrases "corrected radius" or "corrected cross section" refer to employing the above factor of 2.5.

Examination of Table 3-11 betrays several interesting features -- one of which is that only 10 Delta-180 objects were observed. For the moment, ignore the two AMOS observations since they were obtained as a direct result of an attempt to track a target; further, ignore the observation made from the Learjet. The remaining set of observations consists only of those targets observed from Maui on DOY 256, 257, 258 using the optical detectors comprising the optical fence. Since there were only 7 objects observed, it is important to back-track and calculate retroactive "predictions" of the passage of all Delta-180 fragments during the 40 minute observing intervals on each day.
To examine the problem, a window was defined having a width roughly equal to the linear extent of the fence of optical detectors. The program SATRAK was run for each of the nights and was constrained to give look angles only for illuminated passes within the window. The number of look angles "predicted" were 60, 36, and 8 for DOY 256, 257, and 258, respectively. Thus 104 Delta-180 targets passed through the fence.

If, in fact, 104 debris pieces passed through the detector fields and only 7 were observed, then 93% were too faint to be seen. The principal reasons for not seeing a debris piece are (1) low albedo, (2) small size, and (3) lack of detector sensitivity.

ALTAIR radar data on the 104 Delta-180 pieces that passed through the window reveals that their average radar cross section was \( <\text{RCS}> = 0.64 \pm 0.27 \text{m}^2 \). Clearly objects as small as the average were not seen, otherwise the total number observed would be several times ten at least. If we assume that the objects observed were among the largest in the group, we may get some idea of the lower limit of detectability. An examination of the ALTAIR data shows that the seven largest objects had RCS values ranging between 1.14m\(^2\) and 1.26m\(^2\). This may now be interpreted in terms of a threshold of optical detectability. Using the "corrected" RCS as the cross-sectional area of an object that was barely above the detection threshold of the Maui detectors, a radius of 0.30m is obtained.

In addition to look angles, SATRAK also calculated the range to the satellites. Averaging these values for all of the satellites predicted to pass through the window, a value of 400km was obtained; this value is used here as a typical detector-object distance.
In what follows, two approaches to the data are examined. In the first, the detector threshold is assumed and the albedo of the debris will be calculated. In the second, the albedo will be drawn from a separate discussion of another Delta-180 piece on the following page, and used to determine the threshold level for the detectors of the Maui fence.

Extrapolating from experience with the NASA JSC Lenzar, a 10th magnitude piece of debris should be very near the threshold of detectability. Thus using this value of magnitude, a distance of 400km, a corrected radius of 0.30m, and a phase of 90°, an albedo of 0.02 is obtained. If the distance has been underestimated by a factor of two, the value of the albedo increases to 0.07. Further if the threshold magnitude is 9.0 (and using 400km for the range), the albedo is 0.04; for a range of 800km, the albedo increases to 0.16. A fainter value of threshold magnitude, such as 11 or 12, only diminishes the value of albedo below 0.01.

The albedo derived for the nominal case, 0.02, seems impossibly low. The key assumption is the threshold magnitude. If we have a separate observation from which we may derive albedo, we can work the problem the other way and ask if the small number of objects detected might have been due to a relatively high threshold (especially for the GEODSS instruments).

From the discussion on the following page, we have at least one Delta-180 debris object with an albedo of about 0.13. If we assume that this value is characteristic of all of the Delta-180 debris pieces and apply it to the above problem to determine the detection threshold for the principle detectors in the Maui fence, we obtain 8th magnitude -- two magnitudes brighter than the assumed value of 10.
In that albedos of 0.01 - 0.04 are unphysically low, it appears that the low number of detected events with most of the elements of the Maui fence is due to a detectability threshold of about 8th magnitude. This may have been due to the optical characteristics of the system or (more likely) the methods by which the data were recorded and/or processed at the telescopes.

The Maui fence consisted of two types of detectors -- three GEODSS instruments, and the MOTIF/AATS. The GEODSS instruments have diameters of 1.0m, 1.0m, and 0.16m; their fields of view are 2°, 6°, and 2°, respectively. The MOTIF/AATS has a diameter of 0.15m and a field of view of 2°. Of the seven objects observed with the Maui fence, one was seen with the AATS while six were seen with the GEODSS instruments. This means that the GEODSS instruments observed 0.6 Delta-180 pieces per 1° field of view while the MOTIF/AATS recorded 0.33 Delta-180 pieces per 1° field of view.

Since one of the GEODSS telescopes has a diameter comparable to the AATS and the other two each have diameters almost seven times as great, it would seem reasonable to expect more sensitivity from the GEODSS instruments than the indicated factor of two. Clearly the suitability of the GEODSS telescopes for the detection of LEO targets, as currently instrumented, must be questioned.

Returning now to the AMOS observations listed in Table 3-11, Event #44 is presented in the interest of completeness. It was not possible to measure a magnitude for this object due to lack of suitable calibration of the video data and lack of supporting radar data. Further, this object was bright enough to saturate the detector throughout much of the 90 seconds it was tracked.
The second object tracked with AMOS was identified as the remnant of the Delta 2\textsuperscript{nd} Stage -- object # 16938. It had an RCS of 1.55m\textsuperscript{2}, and culminated at 15:08:28 at a range of 290km. Due to a lack of calibration, it was not possible to make photometric measurements at a high confidence level. However, an image of this object at culmination, taken with the AMOS/AATS, was compared to an image of an identifiable starfield obtained previously with the MOTIF/AATS; both detectors use a Quantex QX-11 image system. Allowance was made for the slightly different apertures of these two telescopes. The comparison yielded an estimate of m\textsubscript{v}=7 \pm 1 for the magnitude of object #16938 at culmination.

Again using the model of a spherical reflector at phase=90\textdegree, and correcting the RCS to a more realistic value using the earlier assumptions, the albedo may be calculated using the range and magnitude values at the time of culmination. Using the nominal value of m\textsubscript{v}=7, the albedo is determined to be 0.13. For 8\textsuperscript{th} magnitude, the corresponding albedo is 0.05. For 6\textsuperscript{th} magnitude, the albedo is 0.32. Therefore, this observation is suggestive of generally moderate to low albedos for the Delta-180 debris.

Another individual observation that deserves some examination is the single 23\textdegree cloud object observed from the Learjet on DOY 250. Two questions arise when considering this observation: (1) what can be learned from this one observation about the debris piece that was observed, and (2) why was only one such piece observed?

Both questions can be examined by considering the ALTAIR radar data for DOY 250. During the flight of the Learjet the ALTAIR radar was on. During the overlapping period of observation, 17:00 to 18:00 UT, ALTAIR recorded 11 Delta-180 debris pieces in the 23\textdegree cloud, and 7 in the 39\textdegree cloud. None of the objects recorded by ALTAIR match the optical
observation. There are two reasons that the one optically
detected object might not have been observed by the radar --
either it was not in the beam, or it was too small to give a
detectable return.

By virtue of a negative detection, there is no way to know
if the object was in the ALTAIR beam or not. However, since
ALTAIR is a pencil-beam radar, there is a significant chance
that it was not in the beam. On the other hand, if it was in
the beam but not detected, an estimate of its size may be
obtained. This line of reasoning will be explored bearing in
mind that there is no more reason to believe that the object
was in the beam undetected than outside of the beam.

Over 100 Delta-180 debris pieces were detected by ALTAIR
in the 23° and 39° clouds -- the average range at the time of
detection was 1300km and 1500km, respectively. The smallest
RCS observed was 0.18m² for an object in the 23° cloud. If we
assume that the observed object was not detected because it
was too small, we may use 0.18m² as a means for estimating an
upper limit to the radius of the object. This upper limit
value would be r=0.24m.

The observed magnitude, mᵥ=10.6 does not include
correction for the fact movement of the object relative to the
background. In limited field tests at JSC, with the Lenzar
optical system, it has been determined that a 2.5 correction
in magnitude is appropriate for an object moving at the rate
of 1° per second. Therefore, the corrected magnitude for this
object is about mᵥ=8.1. At the time of observation the range
was 465km. Again assuming the spherical reflector model, a
phase angle of 90°, and radius of 0.24m, an albedo of 0.20 is
determined.

This calculation assumes that the object is just below the
threshold for detection by the ALTAIR radar. It is also
possible that the object is smaller and has a higher albedo. Of course, since the albedo cannot exceed 1, this allows for the calculation of a lower limit to the size of the object. This calculation yields a radius of 0.11m. Thus, within the assumptions, the radius of the object lies between 11 and 24cm with an albedo between 1.00 and 0.20. If the conjecture that the object was in the beam, yet undetected, is correct this one object, although small, had a high enough albedo to be recorded optically, and a small enough RCS not to be observed by the ALTAIR radar.

Regarding the second question as to why more Delta-180 debris objects weren't observed optically, it is first noted that a total of 18 debris pieces were observed by ALTAIR coincident with the optical observations. Of these 18 pieces only 5 had values of RCS greater than 0.70m² and none were greater than 1.15m². Again, if the typical Delta-180 debris fragment has an albedo of 0.05 to 0.15 as suggested earlier, the lack of data from the Learjet is consistent with such relatively dark debris pieces.

In summary, the Delta-180 optical observations tend to support the suggestion that debris fragments created during a collision between two spacecraft are somehow darkened. The typical albedo implied by the Delta-180 data is on the order of 0.15 with some individual exceptions. Further, the actual optical piece count compared to the expected count, indicates that the GEODSS telescopes are not suitable for this type of LEO work with their present instrumentation.

4.5 Object Lifetimes

The full analysis of orbital lifetimes for the objects produced in the Delta-180 mission awaits further observations of the decay rate of cataloged pieces by Eglin and other radars. Nevertheless, estimates may be extracted from data
taken over the months following the breakup event. The sources of these data are Eglin and the NAVSPASUR network, as well as the contributing sensors of the NORAD system. Information concerning actual observations may be found in Appendix B, Section 5.

To summarize, approximately half of the original number of objects observed by Eglin and NAVSPASUR were still in orbit 58 days after the event. Observational selection effects and sensitivity effects (such as solar activity, which degraded the performance of NAVSPASUR during a portion of the observations) introduced some uncertainty into the data. For example, the number of objects in the 39° cloud actually increased during late-October and early-November. Unfortunately, several high-interest objects, such as the very high apogee objects, could not be correlated from observation to observation.

The NORAD cataloged objects exhibited an even more gradual decay rate. After 2 months in orbit, only 28% of the objects had decayed. While one should be wary of problems associated with the statistics of small sample sets, it is interesting to note that 4 out of the 5 decayed objects were fairly small (0.67m in diameter and less). This would, in general, tend to support the theory that the less massive, or smaller objects would decay at a faster rate than larger objects.

Pre-mission modeling indicates a decrease in the flux at breakup altitude and the number of particles by a factor of 2 after an elapsed time of 1 week, a further reduction by a factor of 2 after 1 month, and a reduction by a factor of 5 in the ensuing 2 months. Thus, after an elapsed time of 3 months, the spatial flux and the number of radar observable objects would be reduced by a factor of 20 below the levels present at breakup.
Such a rate would be faster than that observed by Eglin and the NAVSPASUR network, or by the associated NORAD sensors. The solar activity during this period cannot account for this discrepancy, since the solar minimum was modeled (average solar flux $F_{10.7}$ calculated was $81 \times 10^4$ Jy, a typical value during solar min.) in the decay routines. Any increase in the average solar flux would tend to shorten the lifetimes of objects in low earth orbit. While only those bodies surviving their first few hours in orbit will be detected by NORAD/NAVSPASUR sensors, those objects reentering immediately after breakup were not included in calculations of number in orbit, spatial density, or cumulative spatial flux. This negates a possible error by counting some debris as decayed (even though HAZARD does declare newly-created debris with perigees and/or apogees less than 100 km in altitude to be decayed, these were not included in the number of objects used in the calculation of the spatial densities or cumulative flux) before the sensors have an opportunity to observe them. At present, an investigation of the decay processes acting on the satellite objects, and the routines which model this decay, is continuing.
5.0 CONCLUSIONS

Pre-mission modelling of the collision produced three scenarios, differing by the amount of momentum transferred in the collision. Debris size distribution, orbital elements, momentum transfer, and energy transfer from these models were compared with data on the debris cloud gathered in the days and weeks following the event.

For this comparison, the most useful data were those obtained from the Eglin, NAVSPASUR, and ALT AIR radars. These radars followed the evolution of the debris cloud up to three weeks after the collision, and provided essential information on the number and size of debris particles and their decay and reentry.

The reentry radar located on Kauai provided a useful check on the early reentry of debris from the collision. Objects in the size range from 10 to 1000 grams were detected by the ionization trails produced upon reentry. The number and size distribution of particles reentering during the first pass of the debris cloud over Kauai was in approximate agreement with model predictions.

The optical data from the Kwajalein airborne effort and the Maui ground-based effort was less successful than the radar data. The total number of debris pieces detected by the optical system was 10 -- 8 associated with the 23° cloud and 2 associated with the 39° cloud. From an analysis of the optical image data, an estimate of the reflectivity of the debris pieces can be made. As a group, the Delta 180 debris fragments appear to be relatively dark, having albedos equal to or less than 0.15. The low albedo was the cause of difficulty in observing these fragments by optical techniques. Future efforts to observe debris by optical techniques should use more sensitive sensors. The GEODSS systems were found to
be sensitive to only 8th magnitude stars, although similar instrumentation at the MIT experimental site at Socorro, N.M. is sensitive to 16th magnitude stars at the angular velocities exhibited by the Delta-180 debris. The Lenzar camera system aboard the Learjet was sensitive to only 9th magnitude stars at the angular velocities of the debris. An increase of sensitivity of at least 3 magnitudes would be required for any future optical observations of debris.

The piece counts predicted pre-mission overestimate the number of detectable debris objects arising from the breakup event, even allowing for decay immediately after breakup. Subsequent modeling, using smaller masses for the Delta stage and satellite predicts a post-EOM environment similar to that actually observed during subsequent days. Size distributions based on the ALTAIR data suggest that many more large objects were observed than were predicted in the 23° inclination cloud (Delta rocket body). Estimates of the mass of these objects imply that many consisted of large (diameter > 0.5 m) plates, such as might be found in the fuel tanks and skin of a spacecraft. The number of objects observed in the 39° inclination cloud was consistently smaller than the predicted number-size distribution. This infers that while many pieces may have been produced, the number-size distribution is biased towards small pieces.

A great deal of information concerning the transfer of linear momentum between colliding bodies is conveyed in the Gabbard diagrams of the debris resulting from the breakup. The data examined reveals two distinct debris clouds spread about inclinations of 23° and 39°. Though the mean of the PAS/satellite's debris cloud is below that predicted by pre-mission modeling, conclusions drawn concerning the transfer of momentum during the collision are tenuous at best, since end-of-mission state vectors are at present classified. However, the gross structure of the clouds indicated very
little momentum exchange between the larger fragments since no cloud near the center-of-mass inclination of 33° has been detected.

The velocity distribution of the debris tends toward the 100% kinetic energy transfer curve used in pre-mission modeling performed at JSC. This indicates that the kinetic energy of the two parent satellites was transferred almost intact to the debris, i.e., little kinetic energy was spent in actually fragmenting the structure of the satellites. Unknown are the effects of chemical energies (the range safety packages and remaining fuels on board) liberated during the end-of-mission.

The orbital lifetimes of the debris appear to be in excess of that predicted by the model. This is arrived at by ratioing the number of objects observed and predicted at selected intervals of time. In general, the lighter pieces tend to decay more quickly than more massive pieces; this agrees with current theory.

Overall, the model performed adequately in predicting the number of pieces produced in the Delta 180 mission; the anomalous results in predicting the size distribution of the objects may be an artifact of processes occurring at EOM. Velocity distributions and linear momentum exchange scenarios also performed well in predicting the deposition of fragments post-EOM. However, the observed rates of decay appear to be slower than that predicted by the model. Thus, while fewer pieces appear to have been produced, the lifetimes experienced by these objects are longer by approximately a factor of two or three. Using the data derived from the Delta 180 mission, the model will be improved so as to be able to better predict hazards of on-orbit breakups.
For the longer term, dedicated space-based or more sophisticated ground-based instruments to monitor small orbital debris will be required to adequately support planning and safety activity.
Appendix A

Pre-Mission Modeling

The contents of this appendix comprise plotted results of the pre-mission modeling performed during March and April, 1986, by NASA/JSC's Solar System Exploration Division. These graphics are in a format such that they describe the evolution of the cumulative flux arising from several scenarios over the elapsed time of 1 year. Several sets of data also include the natural meteoroid background flux, to serve as an indication of the relative magnitude of the debris flux.

As discussed previously, the three scenarios encompassed a head-on collision (or 100% collision), a grazing collision (or 10% collision), and proximity explosions of the two satellites. The other parameter of interest was the velocity distribution of the debris. High velocity (100% kinetic energy transfer), nominal velocity (50% kinetic energy transfer), and low velocity (10% kinetic energy transfer) distribution curves were utilized. In each case, the percentages refer to the amount of kinetic energy actually manifesting itself as a change in velocity of the debris objects (energy "sinks" potentially include material deformation, melting of material, light flash, etc.). For each case examined, the environment was sampled at elapsed times of 0 weeks (i.e., end-of-mission), 1 week, 1 month, 3 months, 6 months, and 1 year.
Meteoroids Excluded

Altitude [km]

Elapsed Time = 1 wk
50% Kinetic Energy Transfer
10% Impact

\( \log_{10} \left( \frac{\text{dN}}{\text{d}m_{\text{E}} \text{yr}^{-1}} \right) \)
meteorooids exciuded

altitude [km]

\[ \log_{10} (\text{flux} \, \text{m}^{-2} \text{yr}^{-1}) \]

Elapsed time = T0

50% Kinetic Energy Transfer

10% Impact

FIGURE A-3
\[ \log_{10} (\text{flux [m}^{-2}\text{yr}^{-1}]) \]

**50% kinetic energy transfer**

**10% impact energy**

elapsed time = 3mo

meteoroids excluded
Figure A-5
Figure A-7

Meteoroids Excluded

 altitude [km]

Log 10 (flux [m^{-2} yr^{-1}])

Elapsed time = 0 yr

10% Kinetic Energy Transfer

10% Impact

> 4 cm

> 2 cm

> 1 cm
Figure A-11

Meteoroids exceeded

Altitude [km]

Elapsed time = 5000

10% Kinetic Energy Transfer

10% Impact

log10 (flux [m^-2 yr^-1])

< 4 cm

< 1 cm
Figure A-12: Meteors Excluded from Orbit [km] vs. Log10 (Flux [m^-2 yr^-1]).
Figure A-13

100% Kinetic Energy Transfer

Km

Log (Flux [m^-2 yr^-1])

Elapsed Time = 0 yr

< 4 mm

< 4 cm

< 1 cm

< 4 cm

Meteoroids excluded

Altitude [Km]
$\log_{10}(\text{flux \ [m^{-2} yr^{-1}]})$

---

**FIGURE A-14**

100% kinetic energy transfer elapsed time = 1 wk

---

Meteoroids excluded

Altitude [km]

-log

0 500 1000 1500 2000 2500

4 cm

1 cm

4 mm

1 mm
Figure A-17

Meteoroids excited at altitude [km]

100% Kinetic Energy Transfer

10% Impact
log_{10}(\text{flux \ [m^{-2}\text{yr}^{-1}]})

50\% \text{ kinetic energy transfer elapsed time} = \text{OWK}

10\% \text{ impact energy transfer}
\[ \log_{10}(\text{flux} \ [m^{-2}yr^{-1}]) \]

50\% kinetic energy transfer

elapsed time = 1 \times 10^6 years

10\% impact transfer

V

4cm

V

1cm

V

4mm

A-21
Figure A-22
\log_{10}(\text{flux [m}^{-2}\text{yr}^{-1}])

50\% \text{ kinetic energy transfer elapsed time} = 6\text{mo}

\begin{align*}
\text{V} & \quad 4\text{cm} \\
\text{V} & \quad 1\text{cm} \\
\text{V} & \quad 4\text{mm}
\end{align*}

A-23
Figure A-26: 

Elapsed time = TJKK
50% Kinetic energy transfer
100% Impact

Log10 (flux [m^2 yr^-1]) vs. Altitude [km]
Figure A-28
\log_{10} (\text{flux } [\text{m}^{-2} \text{yr}^{-1}])

50\% \text{ kinetic energy transfer elapsed time } = 6 \text{mo}

V
4cm
V
1cm
V
4mm

A-29
altitude (km)

log10 (flux / m^-2 yr^-1)

\[ \text{elapsed time} = \text{yr} \]

50% kinetic energy transfer

100% impact

Figure A-30
The figure shows a plot of altitude (km) against log flux (m^-2 yr^-1). The x-axis represents altitude in kilometers, ranging from 0 to 6,000 km. The y-axis represents the log flux, ranging from 10^-10 to 10^-2.

The graph includes several horizontal lines indicating different levels of flux. The lines are labeled as follows:

- > 4 cm
- > 2 cm
- > 1 cm
- > 4 mm
- > 4 mm

The labels on the x-axis indicate time in years, with 1,000 km representing a specific time point. The text at the bottom of the graph reads: "50% kinetic energy transfer exposure elapsed time = 1,000."
\[ \log_{10}(\text{flux \ [m^{-2}yr^{-1}]}) \]

50% kinetic energy transfer elapsed time = 3 mo

explosion

altitude [km]

500
1000
1500
2000
2500

1 cm
1 cm
4 mm
4 mm

V
V
V

A-34
Figure A-38
$\log_{10}(\text{flux [m}^{-2}\text{yr}^{-1}])$

10% kinetic energy transfer elapsed time = 300

V 4cm

V 1cm

V 4mm

2500 2000 1500 1000 500

altitude [km]
Figure A-41

10% Impact
10% Kinetic Energy Transfer
Elapsed time = 65.0

Y axis: Log 10 (flux [m^-2 yr^-1])
X axis: Altitude [km]

> 4 cm
> 2 cm
> 1 mm
Figure A-44
Figure A-46

Atitude [km]

log10 (flux [m^-2 yr^-1])

> 4 cm

> 1 cm

> 4 mm

Elapsed time = 3.0 G

100% Kinetic energy transfer
10% Impact
Figure A-47

Elapsed time = 6500
100% Kinetic Energy Transfer
10% Impact

Log flux (m^-2 yr^-1)

Altitude (km)
Appendix B

The Teledyne-Brown Report

This appendix contains the complete text, with figures and tables, of Teledyne-Brown Engineering's report on the Delta-180 mission. Topics include an analysis of the data derived from Elgin AFB observations of the debris clouds produced in the breakup event.
TECHNICAL REPORT CS87-LKD-001
THE COLLISION OF SATELLITES 16937 AND 16938:
A PRELIMINARY REPORT

NICHOLAS L. JOHNSON
ADVISORY SCIENTIST

15 NOVEMBER 1986

PREPARED FOR:

LOCKHEED ENSCO, INC.
HOUSTON, TEXAS 77258-8561

PURCHASE ORDER NUMBER 0200113094

PREPARED BY:

TELEDYNE BROWN ENGINEERING
1250 ACADEMY PARK LOOP, SUITE 240
COLORADO SPRINGS, COLORADO 80910-3799
THE COLLISION OF SATELLITES
16937 AND 16938:
A PRELIMINARY REPORT

NOVEMBER 15, 1986

TELEDYNE
BROWN ENGINEERING
1250 Academy Park Loop, Suite 240
Colorado Springs, Colorado 80910
TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0 Executive Summary.</td>
<td>1</td>
</tr>
<tr>
<td>2.0 Experiment Background.</td>
<td>3</td>
</tr>
<tr>
<td>3.0 Data Collection.</td>
<td>5</td>
</tr>
<tr>
<td>4.0 Characterization of the Initial Debris Clouds.</td>
<td>7</td>
</tr>
<tr>
<td>4.1 23° Debris Cloud.</td>
<td>7</td>
</tr>
<tr>
<td>4.2 39° Debris Cloud.</td>
<td>10</td>
</tr>
<tr>
<td>5.0 Evolution of the Debris Clouds</td>
<td>13</td>
</tr>
<tr>
<td>5.1 23° Debris Cloud.</td>
<td>13</td>
</tr>
<tr>
<td>5.1.1 Eglin Data</td>
<td>13</td>
</tr>
<tr>
<td>5.1.2 SSN Data</td>
<td>13</td>
</tr>
<tr>
<td>5.2 39° Debris Cloud.</td>
<td>14</td>
</tr>
<tr>
<td>5.2.1 Eglin Data</td>
<td>14</td>
</tr>
<tr>
<td>5.2.2 SSN Data</td>
<td>14</td>
</tr>
<tr>
<td>References</td>
<td>15</td>
</tr>
<tr>
<td>Appendix A1 - Eglin 23° Debris Cloud, 6 September</td>
<td>45</td>
</tr>
<tr>
<td>Appendix A2 - Eglin 39° Debris Cloud, 5 September</td>
<td>61</td>
</tr>
<tr>
<td>Appendix A3 - Eglin 39° Debris Cloud, 6 September</td>
<td>67</td>
</tr>
</tbody>
</table>
1. Executive Summary

On 5 September 1986 two satellites of approximately the same order of mass collided at a relative velocity of about 3 km/s in a planned experiment. Instead of a single, diffuse cloud of debris spread between the orbital inclinations of the two parent satellites, two distinct debris clouds centered on the parents' orbits were found. Sixteen hours after the event more than 380 fragments had been detected by ground-based radars. An equal number of moderately sized objects are believed to have reentered the Earth's atmosphere within an hour of the event, while many times this number of very small debris were probably still in orbit.

Periodic assessments of the status of both debris clouds were made during the two months following the collision. Natural orbital decay removed approximately two-thirds of the known debris from near Earth space during this time. No long term space environment degradation nor hazard to artificial satellite operations will likely result from this experiment.

The nature of the initial debris clouds was not noticeably different than those originating from conventional explosions or higher velocity collisions and conformed to pre-experiment simulations. The number of particles detected soon after the event approximated the number expected for particles 5 cm in diameter or more. The two debris clouds were slightly asymmetric, with the greatest inclination deviations tending toward a regime between the two parent orbits. On-going analyses into the debris decay characteristics will prove useful in enhancing collision fragmentation models, particularly with respect to assessing the near- and far-term space debris hazards. Detailed analyses of component ejection velocities must await release by appropriate authorities of orbital parameters of the two parent satellites at the time of the impact.
### TABLE 1-1. DEBRIS ASSESSMENT SUMMARY

<table>
<thead>
<tr>
<th>DATE</th>
<th>DAYS AFTER THE EVENT</th>
<th>DATA SOURCE</th>
<th>NUMBER OF OBJECTS UNDER SURVEILLANCE</th>
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<tr>
<td></td>
<td></td>
<td></td>
<td>23° CLOUD</td>
</tr>
<tr>
<td>5 SEPT 86</td>
<td>0</td>
<td>EGLIN</td>
<td>0</td>
</tr>
<tr>
<td>6 SEPT 86</td>
<td>1</td>
<td>EGLIN</td>
<td>190</td>
</tr>
<tr>
<td>30 SEPT 86</td>
<td>25</td>
<td>SSN*</td>
<td>82</td>
</tr>
<tr>
<td>9 OCT 86</td>
<td>34</td>
<td>SSN</td>
<td>82</td>
</tr>
<tr>
<td>12 OCT 86</td>
<td>37</td>
<td>EGLIN</td>
<td>132</td>
</tr>
<tr>
<td>19 OCT 86</td>
<td>44</td>
<td>SSN</td>
<td>48</td>
</tr>
<tr>
<td>26 OCT 86</td>
<td>51</td>
<td>SSN</td>
<td>57</td>
</tr>
<tr>
<td>2 NOV 86</td>
<td>58</td>
<td>SSN</td>
<td>51</td>
</tr>
</tbody>
</table>

* SSN = Space Surveillance Network, from NAVSPASUR
2. Experiment Background

At 11:08 EDT on 5 September 1986, a Delta 3920 launch vehicle lifted-off a pad at Cape Canaveral, minutes later placing a mated second stage and special payload into an orbit of 220 km by 222 km with an inclination of 28.5° (References 1 and 2). Approximately 45 minutes after launch, the Delta second stage and payload separated. After another two hours and a series of maneuvers, the two vehicles collided at a relative velocity of about 3 km/s (References 3 and 4), creating two distinct clouds of space debris.

The payload, which was based on a Payload Assist System (PAS) framework, was designated USA-19 and received an international designator of 1986-69A and a Space Surveillance Center (SSC) catalog number of 16937. Following the collision, the fragment assigned the 16937 identity was found in an orbit of 213 km by 748 km at an inclination of 39.1°. The mass of the payload at launch was about 2300 kg, 60% of which was propellants (Reference 5).

The Delta second stage was designated USA-19 R/B (rocket body) and received an international designator of 1986-69B and SSC catalog number of 16938. Following the collision, the fragment identified as satellite 16398 was left in an orbit of 221 km by 561 km at an inclination of 22.8°. The Delta second stage approximates a right cylinder 2.4 m in diameter and 6 m in length with an empty mass on the order of 350 kg (References 2 and 6).

A collision velocity of only 3 km/s is below that usually associated with the natural collisions of objects in space. Consequently, the extent of hypervelocity impact phenomenology exhibited in the resulting debris was uncertain prior to the test and represented an area of investigation for post-flight analysis. The debris characterization objective was potentially complicated by the reported activation of an explosive device on one of the vehicles (the Delta second stage) at the time of the impact (Reference 7). Also unknown is the effect on the debris of the energy contribution of the residual propellants on board the vehicles at the moment of the collision.

If 5 cm diameter objects are considered the lower sensitivity threshold of the Space Surveillance Network (SSN) at the subsequent observation altitudes of only a few hundred kilometers, equations developed by Kessler and Cour-Palais (Reference 8) and Kessler and Su (Reference 9) can be applied to estimate the number of detectable objects created during the

B-3
collision of satellites 16937 and 16938. Assuming hypervelocity impact relationships are applicable in this case, the reported total dry mass of almost 1300 kg should have produced on the order of 850 pieces of debris visible to the SSN. However, due to the very low altitude of the collision and the assumed symmetric distribution of fragments, approximately half of these objects should have decayed within a few hours of the event. Therefore, only 400-500 observable pieces of debris might be expected in the first days following the experiment.
3. Data Collection

Prior to the experiment Teledyne Brown Engineering (TBE) assisted NASA Johnson Space Center (JSC) and the U.S. Air Force Space Command (AFSPACECOM) in the definition of space surveillance data collection requirements for the purpose of assessing the consequent space debris environment. TBE furnished NASA JSC a set of preliminary recommendations for support from the SSN in December, 1985. A Fragment Working group meeting was held at NASA JSC on 7 March 1986 and attended by TBE representative Mr. Ronn Kling.

Due to the low inclinations of the colliding objects, the AN/FPS-85 phased-array radar at Eglin AFB, Florida, was chosen as the primary sensor for debris data collection. On 18 July 1986 Mr. David Nauer of TBE and Mr. John Stanley of NASA JSC met with Eglin radar personnel on site to discuss the operational impacts and needs of the forthcoming experiment. Among the items discussed were the lowering of the SLEM detection fence during the early passes of the expected debris cloud(s) through Eglin coverage and the special tasking of each identified piece of debris.

The ALTAIR and Kaena Point mechanical tracking radars were also selected to obtain specific data on the debris cloud(s) shortly after the test. These latter radars, however, are limited in the number of objects which can be tracked in a specified time interval and are unable to produce orbital data of the quality provided by Eglin. On 5 August 1986, Mr. Ronn Kling of TBE and Mr. Gene Stansbury of Lockheed (on behalf of NASA JSC) met with ALTAIR program personnel at Lincoln Laboratory. At that meeting three data collection modes were adopted: multiple object (short) tracking, single object (long) tracking, and beam park.

A meeting was then held at the TBE facility in Colorado Springs on 7 August 1986 to finalize data collection plans. Attendees included representatives from TBE, NASA JSC, USSPACECOM, AFSPACECOM, PRC/Kentron, and AVCO/Textron. A recommendation of the attendees called for a "dry-run" exercise of the appropriate space surveillance sensors during the week of 18 August to verify the feasibility of non-standard data collection tasking and techniques. Also at this meeting, NASA JSC recommended the establishment of an optical fence using the AMOS, MOTIF, and Maui GEODSS sensors to obtain piece counts of very small debris (below the sensitivity threshold of ground-based radars). TBE was tasked to develop the software and procedures to erect said fence and to act as an interface between the SSC and NASA personnel at Maui. The subsequent exercises conducted in the second half of August confirmed the data collection procedures required to meet debris assessment objectives.
4. Characterization of the Initial Debris Clouds

Debris from the collision of satellites 16937 and 16938 was initially found in orbital inclinations ranging from 21° to 42°. However, the debris was distributed in two distinct "clouds", one centered near an inclination of 22.8° and one centered near an inclination of 39.6°. These inclinations correspond to the inclinations of the remnants of satellites 16938 and 16937, respectively. For the remainder of this preliminary report, the collision debris is denoted as part of the 23° debris cloud or as part of the 39° debris cloud, which are herewith discussed separately.

To characterize the 23° debris cloud and the 39° debris cloud, TBE reduced and analyzed data collected by the Eglin and ALTAIR radars on the day of the event and the following day. Data from ALTAIR were received by TBE in late October. Attempts to reduce the observations into orbital parameters of acceptable quality in time for inclusion into this report were unsuccessful. The inherent accuracy and utility of the ALTAIR data are currently under investigation. Further analysis of these data may be performed at a later date.

The Eglin radar observations, on the other hand, permitted a detailed assessment of the structure of the two clouds soon after the event. The following two subsections highlight the predominant initial characteristics of the two debris clouds as reconstructed from the Eglin data.

4.1 23° Debris Cloud

Selected data tapes recorded by Eglin on 5 September within hours of the event and examined by TBE revealed no debris associated with the 23° debris cloud. This lack of data was a consequence of pass geometry and the time interval available and not indicative of the nature of the cloud.

On 6 September, a 90-minute observation interval was selected during which the orbital plane of 16938 passed through Eglin coverage (Figure 1). Although the elevation angle of each fragment to Eglin was less than normally desired, the low inclination of the 23° debris cloud did not allow high elevation passes. Despite this limitation a total of 190 pieces of debris were positively identified with the 23° debris cloud. Figure 2 indicates the general time of first detection of each piece of debris and provides some insight into the dispersion of the cloud some 16 hours after the event.
Appendix A1 is a listing of all orbital element sets generated by TBE on this cloud. Even though the data span an interval greater than 90 minutes, those objects outside of the selected interval are not included in the piece count quoted above. Note that Eglin performed a pass-to-pass correlation for some objects. However, the consistency of this pass-to-pass correlation was uncertain and the 90-minute time window was selected to avoid duplicate counting. A deficiency of this technique is that an object with an orbital period greater than 90 minutes could be omitted. However, Figure 2 suggests that in this case the cloud was not yet uniformly distributed around the orbital plane and therefore the number of objects missed is likely to be very small. Finally, in a few cases an assigned 9X,XXX number appears to be cross-tagged during the track interval. No attempt has yet been made to examine exhaustively all element sets to determine the frequency with which this might have occurred. The total number of trackable objects in the 23° debris cloud less than one day after the experiment can be estimated to be on the order of 200.

The distribution of the debris in inclination was not fully symmetric. The range of inclinations was 21.95° to 25.25° with a higher deviation from the mean toward the higher inclinations (Figure 3). The potential significance of this characteristic is discussed further in Section 4.2.

The nominal variation in orbital periods for the 23° debris cloud was 79 minutes to 116 minutes. The Gabbard diagram of Figure 4 clearly demonstrates that several pieces appear to be on reentry trajectories. In fact, about 20% of the fragments were determined to be on their last orbit about the Earth. The horizontal arm of Figure 4 is at an altitude of 210–220 km, consistent with the initial orbit of satellites 16937 and 16938 and with their subsequent periapses. Unfortunately, the exact orbital parameters of 16937 and 16938 at the time of the impact were not yet available when this report was prepared. Reference 7 did report that both vehicles were accelerating at a rate of 5 g's (50 m/s²) when the collision occurred. Consequently, the proportion of fragments tracked on 6 September which were ejected in retrograde and prograde directions is unknown. Certainly the majority of pieces are in higher energy orbits than the primary remnant of 16938 (orbital period about 92 minutes). However, if the distribution of ejecta was symmetric about the parent object as suggested by theory, a significant portion of the debris imparted with retrograde velocities would have reentered the atmosphere very shortly after the event before the Eglin pass that was analyzed.
The highest energy fragment (satellite 94998 in Appendix A1) associated with the 23° debris cloud had an apogee of about 5500 km and an orbital period of over 146 minutes. This represents an increase in velocity of about 1 km/s from the stated orbit of satellite 16938. This magnitude of ejection velocity is compatible in hypervelocity impact ground tests with a particle 1 mm in diameter or less. Although no radar cross-section (RCS) estimate on this object was available to TBE, the Eglin radar is incapable of detecting such a small object at the range of the observation. (In general the altitude of all fragments during this pass was between 200 and 300 km, i.e. near perigee.)

The fragment with the second highest ejection velocity (satellite 90100 in Appendix A1) also experienced one of the largest inclination changes of the 23° debris cloud. This suggests that the object might have been less massive than the majority of the debris cloud. Unfortunately, no subsequent data collected by Eglin or the SSN in general could be correlated with this particular object. Thus, no estimate of its ballistic coefficient or mass was possible.

A summary of the initial distribution of the 23° debris cloud by inclination and period is provided in Figure 5. Overall, the dispersion is moderately symmetric with the exception of the lower period pieces which had already fallen out of the environment and the trend noted earlier in which the low period, higher inclination fragments are more widely separated. An examination of eccentricity versus period for each fragment (Figure 6) reinforces the classic satellite breakup pattern seen in Figure 4.

Finally, the early Eglin data on the 23° debris cloud was analyzed to determine the relationship between inclination and right ascension. If the collision had taken place at a node (i.e. equator crossing), any cross-track (perpendicular to the orbit plane) velocity component would have been converted directly into a change of inclination and no alteration of the right ascension would have occurred. However, the collision actually took place at about 10° N latitude, resulting in a conversion of a portion of the cross-track velocity component into a torquing of the orbit plane. This relationship is well illustrated in Figure 7 and conforms to the expected trend. Moreover, this relationship was vital to differentiating debris associated with the event from other debris in these inclinations which are often used for missions originating from Cape Canaveral.
4.2 39° Debris Cloud

The Eglin observations of the 39° debris cloud collected on 5 September produced only marginal data. Shortly after the event the debris cloud penetrated Eglin's coverage volume, passing from north to south and hampering the acquisition of high quality track data. In fact only 21 identifiable fragments associated with this cloud were tracked and all these possessed orbital periods very close to that found for the parent, satellite 16937. Orbital element sets for these objects are provided in Appendix A2, but they are not referenced further in this report.

Like the 23° debris cloud, the 39° debris cloud experienced a very favorable pass through Eglin's coverage only 16 hours after the event (Figure 8). Somewhat remarkably, the total number of objects identified with the 39° debris cloud was 191, virtually the same as seen in the 23° debris cloud at the same time. Orbital element sets created by TBE from the Eglin observations for this period can be found in Appendix A3.

Several factors should have combined to make this "coincidence" highly unlikely. First and foremost, the mass of satellite 16937 (the 39° parent) is estimated to have been as much as 2.5 to 3 times that of satellite 16938 (the 23° parent). Presently unknown is the mass of the instrument packages added to the Delta second stage, which conceivably could have increased its mass to be comparable to that of satellite 16937. Therefore, a larger number of debris might be expected in the 39° debris orbital regime. Furthermore, the closer approach of the 39° debris cloud to Eglin (i.e. higher elevation angle) should have resulted in a greater probability of detection for the smaller fragments when compared to the 23° debris cloud.

On the other hand, the density of the 39° debris cloud was greater at the beginning of the observation period (Figure 2), possibly suggesting that the leading edge of the cloud was somehow missed. However, the 90-minute interval selected from the Eglin tapes was specifically tailored to prevent this potential problem. An examination of the element sets in Appendix A3 will reveal that the lower period pieces, the leading edge of the cloud, were in fact detected in the first 15 minute interval. Thus, the likelihood of Eglin "missing" a significant number of detectable fragments during the observation period is assessed to be quite low. At no time during the 90 minute interval did the combined densities of the both clouds reach a level which might have exceeded the hardware/software limitations of Eglin resulting in the loss of observations.
Other factors which might have influenced the number of detectable fragments created by the respective spacecraft are the relative densities of the vehicles and the location of the impact on the vehicles. The Delta second stage may have been not only less massive but also less dense than satellite 16937. Despite these unknowns, it is interesting to note that the total number of objects observed - 381 - is very close to that estimated in Section 2.

The spread of orbital inclinations for the 39° debris cloud was approximately twice that of the 23° debris cloud, i.e. 34.7° to 41.4°. Perhaps more importantly, a noticeably greater deviation is found at the lower inclinations of the 39° debris cloud (Figure 9). This appears to correspond to the trend toward greater inclinations in the 23° debris cloud. If the two colliding objects were of roughly the same mass and the collision were largely inelastic, the debris might be expected in inclinations centered around 31°. In reality, the collision apparently possessed features of both elastic and inelastic collisions, the latter being in part reflected in the debris migrating from both clouds towards a median inclination.

The Gabbard diagram of Figure 10 for the 39° debris cloud is virtually identical to that for the 23° debris cloud (Figure 4). One small difference is the larger number of fragments ejected into high orbits. In addition, a slightly smaller percentage, 15%, of the debris appear to be on reentry trajectories. As indicated in Figure 10, two fragments fell outside the confines of the graph: one with an orbital period of 242.5 minutes and the other with an extraordinary orbital period of more than 518 minutes. The latter object, satellite 94768, was subjected to a velocity increase in excess of 2.2 km/s or approximately three-fourths of the collision velocity. As with most of the Eglin observations reduced by TBE, no RCS data for this object was available.

Although the magnitudes are not comparable, it is curious that two objects in the 23° Debris cloud and two objects in the 39° debris cloud are clearly separated from the remainder of the clouds. A similar (and possibly related?) characteristic was noted in the only other known hyper-velocity collision in space (Reference 10).

The distribution of the 39° debris cloud in inclination and period is markedly different from that observed with the 23° debris cloud (Figure 11). The majority of pieces are in inclinations below that ascribed to the parent and exhibit a tendency of higher period/lower inclination pieces.
An examination of the relationship between eccentricity and orbital period (Figure 12) reveals a trend identical to that for the 23° debris cloud and in keeping with the Gabbard diagram of Figure 10.

An apparent structure did arise during the analysis of the inclination versus right ascension of the 39° debris cloud. Three distinct striations are apparent in Figure 13. No such pattern was visible in a similar plot for the 23° debris cloud (Figure 7). Since a time variation of up to 90 minutes exists in Figure 13, the values of right ascension appearing in Appendix A3 were propagated to a common epoch of 86249.48, just after the 90-minute observation interval. The resultant inclination versus right ascension data are presented in Figure 14. The striations have largely disappeared. The significance of the phantom structure which must be related to the time of detection and hence the orbital period has not yet been examined in depth. Also note that the scale factors for Figures 7 and 14 are the same, indicating that for an equal change in inclination the debris in the 39° debris cloud underwent a smaller change in right ascension as expected for a higher initial inclination parent.
5. Evolution of the Debris Clouds

At irregular intervals during the two months following the collision of satellites 16937 and 16938, TBE obtained orbital data on the two debris clouds from two primary sources. Magnetic tapes of Eglin observations were acquired for passes on 12 October, some 37 days after the event. On five occasions TBE received summaries of debris being tracked by the SSN as a whole either as a cataloged satellite or as a provisional 8X,XXX satellite. These summaries were compiled by the Naval Space Surveillance System (NAVSPASUR) in its role as the alternate SSC. NAVSPASUR personnel were instrumental throughout the period in converting observations on unknown objects from a variety of sensors into orbital elements which were then fed to the SSN via the SSC for tracking. The job was made more difficult by the small size of some of the debris and by solar activity during the period which temporarily degraded SSN capabilities.

5.1 23° Debris Cloud

5.1.1 Eglin data

Figure 15 is a Gabbard diagram of the fragments of satellite 16938 tracked during a 100-minute interval on 12 October 1986. In all, 132 objects were unambiguously associated with the 23° debris cloud. On this occasion the site was in its normal surveillance mode (SLBM fence erected). The quality of the element sets appears high with only three objects possessing questionable values of eccentricity. The diagram appears very similar to Figure 4 (note scale differences), particularly regarding the two high period fragments. Unfortunately, with Eglin data from only 6 September and 12 October, it was not possible to unequivocably correlate the two high period pieces in each figure.

5.1.2 SSN data

Table 1 and Figures 16-20 illustrate that portion of the 23° debris cloud being tracked by the SSN between 30 September and 2 November. The number of fragments varied considerably between 48 and 82, all substantially below the assessment of Eglin on 12 October. This discrepancy is the result of the exceptional ability of Eglin to detect objects on a single pass which are not large enough to be routinely tracked by either Eglin or the SSN as a whole. Of particular note is the high period fragment which appears for the first time in Figure 19. This may be one of the two high period pieces detected by Eglin alone two weeks earlier.
For the five-week period analyzed, 20 objects were selected for special study to ascertain their decay characteristics. The fact that all debris have virtually the same perigee heights should permit this technique to make assumptions regarding the relative nature of the respective ballistic coefficients. All fragments must be followed to their decays before any such assessments can be formulated. The preliminary results of this analysis are provided in Figure 21 where the decay rates of all debris in like orbits are clearly not uniform.

5.2 39° Debris Cloud

5.2.1 Eglin data

An attempt to define the status of the 39° debris cloud on 12 October using the Eglin radar met with mixed results. Only 69 fragments were detected during the same 100-minute interval examined for the 23° debris cloud (Section 5.1.1). Although some debris from the 39° debris cloud did pass through Eglin prior to this observation period, this does not fully explain the low piece count. The data obtained (Figure 22) is similar to the SSN database of 9 October but of slightly poorer quality.

5.2.2 SSN data

The apparent evolution of the 39° debris cloud based on SSN data is depicted in Figures 23-27. The total number of known fragments (Table 1) in orbit actually increased from mid-October to early November. The characterization of the 39° debris cloud was made easier by the contribution of the higher latitude sensors, particularly NAVSPASUR. Thus, almost two full months after the event approximately half of the 39° debris detected by Eglin during the first 24 hours was still in orbit. Like the experience with the 23° debris cloud, the SSN was better able to define fragments in high altitude orbits after several weeks had passed (see Figures 24 and 25).

An investigation into the decay characteristics of 20 selected objects from the 39° debris cloud was also undertaken. As noted with the 23° debris cloud (Figure 21) differences in decay rates at like altitudes are more prominent as the higher altitude pieces enter lower period orbits. In general this supports the theory that the "lighter" pieces are initially thrown into higher orbits. Once they reach lower altitudes they tend to decay faster than those fragments which began at that altitude. Again, further monitoring of the fragments is required before a more quantitative evaluation is possible.
REFERENCES


23° DEBRIS CLOUD

Figure 4

B-20
23° DEBRIS CLOUD

Figure 5

B-21
23° DEBRIS CLOUD

Figure 6

B-22
39° DEBRIS CLOUD
(2 pieces with periods greater than 160 min)

Figure 10
B-26
39° DEBRIS CLOUD

Figure 11

B-27
39° DEBRIS CLOUD

Figure 12

B-28
39° DEBRIS CLOUD

Figure 13

B-29
39° DEBRIS CLOUD
(common epoch)

Figure 14

B-30
$23^\circ$ DEBRIS CLOUD: EVENT + 25 DAYS

Figure 16

B-32
23° DEBRIS CLOUD: EVENT + 34 DAYS

Figure 17

B-33
23° DEBRIS CLOUD: EVENT + 44 DAYS

Figure 18

B-34
23° DEBRIS CLOUD: EVENT + 51 DAYS

Figure 19

B-35
23° DEBRIS CLOUD: EVENT + 58 DAYS

Figure 20
39° DEBRIS CLOUD: EVENT + 37 DAYS

Figure 22

B-38
Figure 23

B-39
39° DEBRIS CLOUD: EVENT + 34 DAYS

Figure 24

B-40
39° DEBRIS CLOUD: EVENT + 44 DAYS

Figure 25

B-41
39° DEBRIS CLOUD: EVENT + 58 DAYS

Figure 27
B-43
39° DEBRIS CLOUD: SELECTED FRAGMENTS

Figure 28
APPENDIX A1

EGLIN 23° DEBRIS CLOUD, 6 SEPTEMBER
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APPENDIX A2

EGLIN 39° DEBRIS CLOUD, 5 SEPTEMBER
APPENDIX A3

EGLIN 39° DEBRIS CLOUD, 6 SEPTEMBER
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2 94845 48.2854 36.6981 8247618 359.7525 34.5304 15.69739329000000 1446
1 94845 48.2955 36.7129 8287073 358.3135 37.7804 15.62677499000000 1445
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Appendix C

the SRS Report

Appendix C contains the text, with figures and tables, of the Systems Planning Corp./Remote Sensing report on their observations of the reentering debris following the breakup of satellites 16937 and 16938. Included as SPC/RS appendices are field notes taken during the observations, and a theoretical study of the velocity of the reentering debris.
VHF RADAR BACKSCATTER OBSERVATIONS DURING DELTA 180

Prepared For

LOCKHEED ENGINEERING AND MANagements SERVICE COMPANY, INC.

And

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
LYNDON B. JOHNSON SPACE CENTER
HOUSTON, TEXAS

Under Contract NAS9-15800

February 1987
VHF RADAR BACKSCATTER OBSERVATIONS DURING DELTA 180

TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. OVERVIEW</td>
<td>1</td>
</tr>
<tr>
<td>2. EXPERIMENTAL SETUP AND ACTIVITY</td>
<td>3</td>
</tr>
<tr>
<td>2.1 Radar Configuration</td>
<td>3</td>
</tr>
<tr>
<td>2.2 Summary of Field Activity</td>
<td>9</td>
</tr>
<tr>
<td>3. OBSERVATIONAL RESULTS AND DISCUSSION</td>
<td>13</td>
</tr>
<tr>
<td>3.1 Range-Time-Intensity of Debris Events</td>
<td>13</td>
</tr>
<tr>
<td>3.2 Debris Particle Velocity (Indirect Measurement)</td>
<td>53</td>
</tr>
<tr>
<td>3.3 Debris Particle Velocity (Direct Measurement)</td>
<td>56</td>
</tr>
<tr>
<td>3.4 Entry Mass</td>
<td>61</td>
</tr>
<tr>
<td>3.5 Mass Calculation Sensitivity</td>
<td>70</td>
</tr>
<tr>
<td>4. SUMMARY AND RECOMMENDATIONS</td>
<td>74</td>
</tr>
<tr>
<td>4.1 Summary</td>
<td>74</td>
</tr>
<tr>
<td>4.2 Recommendations</td>
<td>74</td>
</tr>
<tr>
<td>APPENDIX A</td>
<td>76</td>
</tr>
<tr>
<td>APPENDIX B</td>
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1. OVERVIEW

Limited statistical evidence, from recent VHF radar studies of meteor fluxes, indicate that orbital debris decay processes can lead to the production of meteor-like ionization trails in the upper atmosphere. Unpublished works by Jost and Potter (NASA/JSC, 1983-1986) show, in several cases (e.g., Shuttle, ASAT, and other orbiting vehicles), that an increase in the observed radar meteor flux occurs at times when the vehicle orbital plane intersects the radar radiation patterns.

With this basis, SPC Remote Sensing Corporation (SRS) installed and operated a complex VHF, backscatter radar system to measure ionization trails produced by entering debris from an SDI DELTA 180 (D-180) experiment. A dual-frequency radar "farm" was located at a remote site in Kauai, Hawaii to optimize the backscatter geometry for detecting entering debris ionization trails in the upper atmosphere. The system was activated several days prior to the space-based experiment to establish the background meteor flux. Data were collected throughout a period extending from 24 hours pre-mission to four days post-mission.

Operation during a critical phase of the mission indicated an order of magnitude increase in meteor-like echoes over the background flux for a 2 minute period. This flux increase, com-
bined with its corresponding, measured particle velocities in the range of 6.5 to 7.5 km/s, provides unequivocal evidence for the detection of entering orbital debris. The mass range for the debris particles was determined to range from a few grams to nearly a kilogram with a strongly decreasing number distribution for increasing mass.
2. EXPERIMENTAL SETUP AND ACTIVITY

2.1 Radar Configuration

The VHF backscatter system was deployed on the northern shore of the island of Kauai just east of Hanalei in the Princeville Development Community. This region is delineated in Figure 1 with the radar icon. An expanded view of the specific remote site is shown in Figure 2; Block 25 is the field site where the entering debris radars were located.

Two long-wavelength radars were deployed with slightly different operational objectives. Standard meteor-radar frequencies of 27.66 MHz and 49.92 MHz were selected to enable wavelength dependent studies of the return echo signatures. Also, the frequency span provided a high probability for ionization detection as well as providing system redundancy. The 27.66 MHz radar was operated as a fixed fan-beam, monostatic system. An interferometric detection concept was incorporated into the 49.92 MHz radar configuration to allow vector measurements of velocity and location of the entering debris particles.

The radar interferometer antenna layout consisted of two orthogonal sets of linear dipole arrays. A total of five fan-beam sub-arrays were arranged, as shown in Figure 3, to provide three azimuthal baselines and three elevation baselines for the vector measurements. The elevation (vertical) plane was covered by antennas 1, 2, and 3, while the azimuthal (horizontal) plane consisted of antennas 3, 4, and 5. Antenna 3 served as the pri-
mary transmit (and receive) antenna with the other four sub-arrays operating as passive receive-only antennas. All sub-arrays were constructed from 24 half-wave dipole sections. As a result, the 49.92 MHz antenna arrays were each 47.4 meters in length. The monostatic 27.66 MHz antenna was designed to view the same volume of space as the interferometer, and therefore, also consisted of 24 half-wave dipoles with a total length of 85.5 meters.

The radiation patterns were controlled by the array orientation (i.e., horizontal azimuth) and height above the ground. All antennas were placed 1/2 wavelength above the ground plane and aligned on an east-west baseline. This provided twin, mirror-image fan beams (opposed at the zenith) directed along a true north-south plane with an elevation angle of 30° for the beam centers. The half-power beam widths were approximately 40°. Figure 4 shows the radiation pattern geometry in the elevation and azimuth planes relative to the D-180 ground tracks for both the immediate post-event phase groundtrack and the ground track for one orbit later.

The radar systems were operated in a standard single pulse mode with a pulse width of 10 μs and an interpulse period of approximately 2 ms. A system synchronizer controlled both radars so that their transmitted pulses occurred simultaneously. The peak-pulse (radiated) power of the 50 MHz system was about 10 kW; 6 kW of radiated power was produced by the 28 MHz radar.
Figure 2. VHF radar field site near Princeville Development Community (Block 25).
Figure 3. Physical layout of antenna arrays for the 50 MHz interferometer and 28 MHz monostatic radars.
Figure 4. General geometry for ground track intercepts and areas of sensitivity for radars.
2.2 Summary of Field Activity

The field-site design calculations, radar testing, equipment inventory, and the acquisition of materials were carried out during a period of several weeks prior to field-team arrival at Kauai. With the exception of the site selection, these activities were conducted at SRS facilities and at NASA/JCS.

The site selected on the north coast of Kauai was located at geographic coordinates 22.2° N and 159.5° W. This region was given first priority for radar location based on geometrical requirements for observing the entering debris ionization trails. Radar echoes are highly aspect sensitive to the long meteor-like ionization tails, which required in this case, that the radiation patterns be directed as near perpendicular to the groundtracks as possible (i.e., a north-south azimuth).

Astronomical observations were made on the night of August 30, 1986. Antenna deployment began on the following day. The azimuthal orientation for both radars was determined independently by these observations and by compass readings. Azimuth and elevation angles of 0 and 30 degrees, respectively, were selected to provide optimum coverage and to maximize the line-of-sight doppler anticipated from the relatively low altitude events.

A 12-passenger van (without rear seats) was used to house the radar hardware and data recording system. Power was derived from a portable generator. A 14-track Honeywell Model 101 tape recorder was used to record the radar signals, time code, and
synch pulses. General site photographs are shown in Figure 5. The radar operations log is provided in Appendix A -- Hawaii Meteor Campaign Field Notes.

Standard radar calibration procedures were implemented. These included feedline/receiver phase angle and transmitter power measurements. The power at the antenna feed point was 6.0 kW for the 27.66 MHz system and 10.2 kW for the 49.92 MHz radar. Power measured at the respective transmitters was approximately 3 dB greater than the power measured at the end of the feedline (3 dB feedline loss).

Forty-two tapes of data were collected which comprise over 35 hours of total radar observations. Background ionospheric and meteoric measurements were made for periods both before and after the mission. Observations of subsequent orbital crossings were made for four days following the prime D-180 event.

All equipment was secured and readied for shipment on September 9-10, 1986 and shipped back to JSC on September 10. The shipment was available for pickup at JSC on September 19 at which time items relevant to the data reduction process were re-routed to Cornell University, Ithaca, New York.

Data processing had been pre-arranged to be conducted at Cornell University and began on September 22, 1986. The requirements established for the Hawaii data processing greatly exceeded those normally conducted with the Cornell data reduction system.
Consequently, a number of software changes were necessary which introduced delays in processing these data.

Analysis was focused on the period immediately surrounding the initial influx of debris particles that occurred approximately eight minutes after the event at closest approach. This effort has been directed toward determining the range-time-intensity (RTI), line-of-sight doppler spectra, cross-spectra between interferometer baselines, free-space velocities, entry-process velocities, and preliminary mass estimates of the debris particles. Prior to initiating the bulk processing, several areas of system software upgrades were identified and implemented (improvements are still being implemented). Staff members at Cornell (SRS consultants) are currently involved in these targeted upgrades.
Figure 5a. Radar van at the Kauai field site; 28 MHz antenna in background.

Figure 5b. VHF radar electronic equipment in van.
3. OBSERVATIONAL RESULTS AND DISCUSSION

3.1 Range-Time-Intensity of Debris Events

RTI displays are shown, for the time period surrounding the initial debris observations, in Figure 6 (49.92 MHz) and Figure 7 (27.66 MHz). As illustrated, both radars observed a large increase in echo activity at approximately 18:01 UT (on day 248). This increased activity is attributed to debris entering the upper atmosphere following the event at closest approach for the D-180 payload. For future reference, the debris events have been cataloged according to the numeric designators shown in Figures 8 and 9 for the two sets of data.

The extent in slant range of detectable debris varied from 70 to 250 km. To first order, this corresponds to an altitude extent of 35 to 125 km based on the limits of the radiation patterns. Natural meteors seldom penetrate to altitudes below about 100 km due to the velocity dependent energy loss mechanisms involved in meteoric evaporation. The altitude of maximum ionization generally scales with velocity. Extraterrestrial meteor velocities are higher than orbital escape velocity and range from about 20 km/s to greater than 80 km/s. Entering debris particles should not exceed 10 km/s and as a result should "burn up" at comparatively lower altitudes (≤ 70 km).

Although most of the debris echoes last no more than a fraction of a second in duration, a few echoes persisted for
longer than a second. The duration of the debris echo is theo-
retically proportional to the square of the wavelength, and the
power returned is proportional to the wavelength cubed.

At VHF, however, the cosmic noise level increases as wave-
length to the 2.4 power. Consequently, with the relatively lower
transmitter power at 27.66 MHz and the increase in background
noise, a S/N > 1 is more difficult to achieve at 27.66 MHz than
at 49.92 MHz. For this reason, relatively fewer echoes were
observed at 27.66 MHz and the echoes were, in general, shorter
lived than those at 49.92 MHz. RTI displays for "Rev 2" (i.e.,
an hour time period centered on the time 92 minutes past initial
debris contact) are shown in Figures 10-38).

Two display formats are provided to give insight into
the debris identification process. Figure 39 shows the range of
each event during the one-hour period of time studied and Figure 40
depicts the instantaneous frequency of particle detection for the same
period. These displays provide a powerful method for obtaining a
first-order determination of debris related activity.

In general, debris particles with their inherently lower
velocities decay at altitudes significantly lower than meteor
particles. Furthermore, an increase in the frequency of detection
should occur as the time of orbital crossing is approached. As is
apparent from Figures 39-40, these signatures are not readily
evident and therefore indicate that no sizeable collection of debris
particles were detected during Rev 2. There is, however, the
possibility that up to 4 of the events shown in Figure 39 are D-180 debris. These events contain signatures (range, time, intensity) which are consistent with those expected for entering debris.
Figure 6a. RTI for 50 MHz radar; 2 minute period preceding primary activity.
Figure 6b. RTI for 50 MHz radar; 2 minute period of primary activity.
Figure 7a. RTI for 28 MHz radar; 2 minute period preceding primary activity.

C-18
Figure 8. Labeled debris events for 50 MHz radar.
Figure 9. Labeled debris events for the 28 MHz radar.
Figure 13.  Rev 2 RTI.
Figure 16. Rev 2 RTI.
Figure 17. Rev 2 RTI.
Figure 18. Rev.2 RTI.

C-30
Figure 19. Rev 2 RTI.
Figure 20. Rev 2 RTI.
Figure 24. Rev 2 RTI.
Figure 25. Rev 2 RTI.
Figure 26. Rev 2 RTI.
Figure 32. Rev 2 RTI.

C-44
Figure 34. Rev 2 RTI.
Figure 38. Rev 2 RTI.
C-50
Figure 39. Slant range for each Rev 2 event. Debris candidates are labelled numerically.
Figure 40. Instantaneous detection frequency for Rev 2 events.
3.2 Debris Particle Velocity (Indirect Measurement)

Since the location and time of payload destruction are known, it is possible to determine the transit velocity from the point of closest approach to the radar detection volume for the events depicted in Figure 8. The total minimum path length between these points can be calculated simply using spherical geometry. It is assumed that a ballistic expansion of the debris cloud along with a spread in velocity accounts for the spread in the arrival times of the detected events and that no "lob" trajectories or other unusual flight paths were associated with the prime data set. Combining the total (minimum) path length for the particles with the time of arrival and location in the radiation pattern gives the minimum exit velocity of the individual debris pieces from the source region. For a given slant range from the radar and time from payload destruction, Appendix B gives the velocity of the debris particles (as well as the software routine used to calculate the time-of-flight velocities).

Velocity contours against the RTI data are shown in Figure 41. All events presented in the figure have an associated velocity in the range of 6.5 - 7.5 km/s, which is less than the initial circular orbital velocity (approximately 7.8 km/s). These data, along with the order-of-magnitude increase in meteor flux, provides irrefutable evidence that the events during this period are associated with the D-180 experiment.
Perhaps the most important information contained in the time-of-flight measurements is that they represent the velocities (at least in part) of the debris particles immediately after the interaction. Direct velocity measurements at a point in the decay-entry process yields information on the particle mass and direction and on the decay process itself, but do not determine the free-space expansion rates from the source event itself.
Figure 41. Overlay of time-of-flight velocities on RTI plots for primary 50 MHz events.

C-55
3.3 Debris Particle Velocity (Direct Measurement)

There are generally two types of echoes which may be identified with radar techniques -- head echoes and tail echoes. The head echo is attributed to reflections from a cloud of plasma enveloping the entering particle during the formation of the ionized trail. The head echo, therefore, moves with the velocity of the particle (i.e., several km/s). In this case, direct velocity measurements of the particle may be determined through line-of-sight doppler or as a change in range with time.

The tail echo is produced by radar energy reflected from the persistent ionized trail left behind the parent body. Since this trail is relatively stationary, the doppler frequency associated with the echo is small when compared to that from a head echo. Atmospheric winds are the primary contributors to particle trail motions; meteor tail echoes have been used by many researchers as tracers for measuring the neutral wind speeds which are typically less than 100 m/s at 50-100 km. As an example, the doppler velocity obtained for Event 1 is shown in Figure 42. Here the line-of-sight velocity is about 40 m/s (the total velocity is not determined with a single look direction) and has been determined from the fully developed echo. Since this measured line-of-sight velocity is similar to those expected for neutral winds, it is presumed that this particular event is a tail echo. All other events examined to date support the general belief that most (if not all) observed echoes from the debris particles are tail
echoes. Head echo returns, however, would be expected from larger pieces (10's of kilograms) and further processing of all 30+ debris events detected with the 50 MHz system is required to determine the frequency of debris head echoes.

Significantly, the doppler measurements were made on the fully developed echoes and it is reasonable to expect standard, meteor-like tail behavior (e.g. neutral wind line-of-sight doppler velocity). However, a more detailed investigation of the initial "attack" phase of the developing echo indicates that a signature of particle velocity is present in the data.

Direct velocity measurements of Event 1 are indicated in the data presented in Figure 43. In contrast to the 40 m/s doppler measurements of this event, discussed above, these data indicate an average velocity of about 2.3 km/s. This large difference is attributed to the measurement technique and the point in time during the development of the echo that the measurement was made. Both measurements are valid and accurately describe a particular phenomenological observation.

The 2.3 km/s measurement represents the azimuthal (east-west) component of the total particle velocity at the time of detection. This value was determined by the transit-time delays associated with the ionization trail developing across the longest bistatic baseline of the azimuthal interferometer. It should be noted that along with this relatively low apparent
velocity (vs. meteors) the direction of motion is clearly from west to east. Combining the elevation (north-south) and radial velocity components would provide the total velocity vector at the time of detection. For the debris events, the motion of the particles are assumed to be predominately west-to-east with only small velocity components in the other vector directions. With this, 2.3 km/s may be interpreted as the total average velocity of Event 1 through the interferometer radiation pattern.

By comparing the differential time lags between the various baselines there is an apparent slowing of the velocity from an initial 3.3 km/s to 1.3 km/s. Again, only one velocity component of this event has been studied. Also, with these very slow velocities, questions on the ionization mechanism must be raised.

The following section presents a technique for determining the mass of an entering particle. This technique is extremely sensitive to velocity and shows that particle mass cannot be accurately estimated without reliable velocity information.
Figure 42. Doppler spectra for Event 1. Line-of-sight velocity equals approximately 40 m/s and is comparable to neutral wind speed.
Figure 43. Time shifts in bistatic echoes during development of the echo power profile provide direct velocity measurement.
3.4 Entry Mass

A relationship between the mass of the entering particle, the maximum radar echo strength from its ionization trail, and the measured velocity may be derived. Assume that the rate of loss of mass of the entering object is proportional to the kinetic energy

\[
\frac{dm}{dt} = -\frac{\Lambda A}{2\zeta} \left( \frac{m}{\rho_m} \right)^{2/3} \rho_a V^3
\]

(1)

where:

\[\zeta\] = Heat of ablation  \\
\[\Lambda\] = Heat transfer coefficient  \\
\[A\] = Shape factor  \\
\[\rho_m\] = Effective object density  \\
\[m\] = Object mass  \\
\[\rho_a\] = Air density at entry altitude  \\
\[V\] = Velocity of object

Now, the power going into the production of ionization is assumed to be proportional to the kinetic "power" loss of the ablated atoms from the surface of the object. If \[q\] is the number of electrons produced per unit length and \[\eta\] is the mean ionization potential per atom involved, the energy associated with the ionization process per unit time is

\[
qV\eta = -\frac{1}{2} \tau_q \frac{dm}{dt} V^2
\]

(2)

where \[\tau_q\] is the (dimensionless) ionization-efficiency factor.

Substituting the differential mass equation (1) into (2) gives an ionization equation relating mass and velocity to the
resulting line density

\[ q = \tau_q \frac{\Lambda A}{4\zeta n} \left( \frac{m}{\rho_m} \right)^{2/3} \rho_a V^2 \]

(3)

The power returned from an ionization trail in a radar echo can be expressed as a function of the radar wavelength and the trail electron line density. Assuming that the echo returns are from aspect sensitive tail structure (as the doppler data indicate) which fills several Fresnel zones, the return power can be expressed as

\[ P_R = \frac{P_T G^2 \lambda^3 e}{128\pi^3} \frac{C + S}{2 R_0^3} q^2 \]

(4)

Condensing the known constants and isolating \( q \) gives

\[ q = \frac{6(10^{15})}{G} \left( \frac{R_0}{\lambda} \right)^{3/2} \frac{P_R^{1/2}}{P_T^{1/2}} \]

(5)
Cosmic background establishes the noise limit of the receiver system for both radars. Generalizing equation (5) to express the return power in terms of signal-to-noise ratio (S/N) can be done by following Hogg and Mumford (1960) where

\[ P_R = (S/N) 100 \lambda^{2.4} \]  

Combining equations (3), (5), and (6) produces an expression of mass as function of slant range, signal-to-noise ratio, particle entry velocity, transmitted power, and radar wavelength. The parametric mass relationship is given as

\[ m = C_T \left[ \frac{R_0^{3/4}}{V^2 P_T^{1/4} \lambda^{3/20}} \right]^{3} \]  

\( C_T \) represents a combination of all the constants contained in the previous derivation expressions. The value of this constant has been carefully estimated to enable a first-order measurement of the masses of the detected entering debris particles. For reference, the values used for this determination are presented in Table 1.

TABLE 1.

ENTRY MASS CONSTANTS

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>VALUE (cgs units)</th>
<th>RANGE/COMMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ionization efficiency</td>
<td>$\tau_q = 10^{-2}$</td>
<td>$10^{-1} - 10^{-4}$</td>
</tr>
<tr>
<td>Shape factor</td>
<td>$A = 1.0$</td>
<td>$0.6 - 1.7$</td>
</tr>
<tr>
<td>Heat of ablation</td>
<td>$\zeta = 10^9$</td>
<td>$10^9 - 10^{10}$</td>
</tr>
<tr>
<td>Heat transfer coef.</td>
<td>$\Lambda = 0.15$</td>
<td>$0.1 - 0.6$</td>
</tr>
<tr>
<td>Ionization potential</td>
<td>$n = 1.6 (10^{-11})$</td>
<td>$O_2 = 10 \text{ eV}$</td>
</tr>
<tr>
<td>Atmospheric density</td>
<td>$\rho_a = 10^{-8}$</td>
<td>$O_2 \text{ at 50-100 km}$</td>
</tr>
<tr>
<td>Particle density</td>
<td>$\rho_m = 2.7$</td>
<td>Aluminum</td>
</tr>
</tbody>
</table>

Using these parameter values in equation (7) gives the masses of the individual entering particles as a function of radar wavelength, slant range, echo signal strength, transmitted power, and entry velocity. The resulting values for Rev 1 are presented in tabular form in Table 2 and in a mass distribution plot shown in Figure 44. The values for the four debris candidate events from Rev 2 (see Figure 39) are: 1) 2g; (2) 97g; (3) 28g; and (4), 98g.
### Table 2.

**Debris Particle Mass Estimates**

<table>
<thead>
<tr>
<th>EVENT</th>
<th>50 MHz Radar Mass (grams)</th>
<th>28 MHz Radar Mass (grams)</th>
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<tr>
<td>1</td>
<td>72</td>
<td>63</td>
</tr>
<tr>
<td>2</td>
<td>122</td>
<td>24</td>
</tr>
<tr>
<td>3a</td>
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<td>24</td>
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<tr>
<td>3b</td>
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<td>168</td>
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</table>

*Revised November, 1986*
These data must be considered preliminary because of the number of assumptions that were associated with deriving the mass equation. It is assumed that the energy loss mechanisms for the relatively slow orbital particles are equivalent (or at least similar) to those for meteors. Also, inspection of the mass equation shows that the strongest controlling variable is the velocity at the time of the measurement. The mass estimates presented were based on the free-space velocities determined from time of arrival in the radar beams. As suggested by the preliminary direct measurement data, at the time an echo is detected, the particle velocity may be considerably slower than its initial entry velocity.

Derivation of the mass equation also neglected the effects of spatial diffusion of the ionized trail. There is a strong wavelength dependence on the signal strength of the return echo for finite width ionization columns. As the width of the tail expands to a scale size approaching a wavelength, destructive interference of reflections from opposite sides of the ionization column quickly quenches the received signal. For the derivation presented, the line density, \( q \), was assumed to be an infinitely thin trail which contains no wavelength dependence.

Generally, the mass data presents an expected functional form in that the low-mass debris strongly dominates the high-mass debris in number density. Refined velocity data will likely cause the mass estimates to increase since mass is inversely dependent
on velocity and it is expected that the velocities will be slower than presently determined. Mass increases are also expected by incorporating the finite tail-width geometry.

Considering the mass-range plot in Figure 45 indicates an altitude dependence on the detected mass. Increasing slant range may be interpreted as increasing altitude to first order. There are a number of possible explanations (and combinations of explanations) that would account for this effect -- (1) range sensitivity of radar system; (2) body kinetic energy dependence on the ionization process; (3) a mass-area (density) dependence; or (4) other unknown processes. Regardless, further investigation is warranted.
Figure 44. Observed mass distribution for D-180 debris entering over Kauai. (Revised November 1986)
Figure 45. Mass vs. slant range for the 50 MHz debris events. Reference curve suggest an altitude dependence on the maximum ionization vs. mass.
(Revised November 1986)
3.5 Mass Calculation Sensitivity

The problem of evaluating zeroth-order mass estimates is straightforward. However, it is important to understand the variables which comprise equation 7 so that its limitations are known. A large collection of radar meteor literature is available which has been referenced to provide estimates for the parameters used in the debris mass calculation. Thus, meteor related results have been tailored or extended to the debris problem to provide the zeroth-order mass estimate.

Below is a synopsis of each of the parameters listed in Table 1 followed by a description of how the mass equation is affected by the value selected.

Three of the parameters listed in Table 1 have values associated with them which can be relatively easy to determine. These are the particle density, \( \rho_m \), atmospheric density, \( \rho_a \), and the ionization potential, \( \eta \). In the altitude interval (50-100 km) where debris particles burn up the atmosphere is composed primarily of \( O_2 \). The ionization potential of molecular oxygen is \( 1.6 \cdot 10^{-11} \) ergs and the peak density encountered by the entering particle is \( 10^{-8} \) g/cm\(^3\). To first order the ionization potential won't vary significantly from this value. However, particles that burn up higher in the atmosphere will do so at a lower density than those that burn up lower. In general, debris particles, with their inherently lower velocities, burn up at lower altitudes where the densities are greater. In the
mass equation, higher atmospheric densities result in lower mass estimate.

The debris particle is assumed to be composed of aluminium with a density of $2.7 \text{ g/cm}^3$. Higher particle densities result in larger mass estimates.

The shape factor, $A$, is a dimensionless quantity which represents the geometry of the decaying particle. For a sphere, $A = 1.2$, and for a cube $A = 1.0 - 1.7$ depending on its orientation relative to the flight path. Values of $A < 1$ are found for long narrow bodies in the streamline aspect and $A > 1$ for the broadside-on aspect. Owing to rotation though, irregularly shaped objects generally have a value close to that of a sphere. For this study the value $A = 1$ is used. Smaller (larger) masses will result for larger (smaller) values of $A$.

Various processes exist for the ablation of atoms from the entering particle with the mass loss dependence being inversely proportionate to the heat of a ablation, $\xi$, and directly proportionate to the heat transfer coefficient, $A$. The heat of ablation is usually taken to lie in the range $10^9 - 10^{10}$ ergs/g for meteor particles consisting chiefly of iron. Aluminum, with its lower melting point requires less energy to ablate than iron. Consequently, the value selected for use in the mass equation should lie at the lower end of the range given above. In the mass equation, a larger mass will result for larger $\xi$.

The heat transfer coefficient is a measure of the efficiency of the collision process in converting kinetic energy to heat. From meteor studies, this parameter has values which range from 0.1 - 0.6.
Speculation maintains that the energy transfer efficiencies of debris particles are less than those for the faster moving meteors. Consequently, a value near the lower limit of this range is used in the mass calculation. A larger value of $M$ would produce a smaller mass according to the mass equation.

The power going into the production of ionization is assumed to be proportional to the kinetic power loss of the ablated atoms. The dimensionless ionization efficiency factor, $\tau_q$, is not easily evaluated for meteor particles and is similarly difficult to evaluate for debris. Past studies suggest that $\tau_q$ is slightly to moderately dependent on velocity, e.g., $v^n$ where $n=0-2$, and ranges from $10^{-1} - 10^{-4}$ for meteor particles. A similar range should be expected for debris particles. Smaller $\tau_q$ results in larger mass estimations.

The debris particle mass estimates given in Table 2 are based on the values listed in Table 1. As has just been shown, some of the parameters which make up the mass equation have values which are only known approximately. By varying these values a change will be introduced into the mass estimate. The degree of the change is largest when each value is set to its limit in such a way as to either maximize or minimize the mass estimation. Such an exercise, however, certainly would not represent a realistic portrayal of the problem at hand. The values given in Table 1 and used in deriving masses are based on our current understanding of the physics involved.

C-72
By taking into account a reasonable range of acceptable values for debris particles for each of the parameters listed in Table 1, the uncertainty in the mass estimate is placed at approximately ± an order of magnitude. Thus, a 100 g mass could be as large as 1 kg or as small as 10 g.
4. SUMMARY AND RECOMMENDATIONS

4.1 Summary

Several significant results were obtained from the VHF, backscatter radar measurements and resulting analysis for the D-180 debris entry studies:

1) Unequivocal detection of ionization trails produced by orbital debris particles entering the upper atmosphere

2) Measurement of the free-expansion velocity distribution at immediate post-encounter

3) Preliminary demonstration of a direct measurement technique for the velocity for small debris particles during entry

4) Preliminary data on rapid deceleration of debris particles during the entry process

5) Demonstrated technique for estimating the mass of an entering particle producing detectable ionization

6) Evidence for mass-area or kinetic energy effects of the decay process

Some of these results are preliminary estimations while others are complete in themselves. The radar observations clearly provided an invaluable complement of data to aid in the interpretation of the D-180 close encounter.

4.2 Recommendations

The debris radar results, along with providing new information on debris expansion and decay-entry processes, suggest several new areas of research. With these positive results on detection of orbital debris entry, a better understanding of the entry process is required to advance the interpretation of the
data. Proper interpretation and analysis will contribute to the understanding and development of debris math models in general. Demonstration of the measurement technique for the location and velocity of the entering objects could lead to the development of a continuous-operation, automatic system to monitor the general influx of decaying orbital debris. Further work needs to be conducted in the following areas:

1) Demonstration of the interferometer technique to determine the vector location of the echo events

2) Development of the bistatic determination of vector velocity through the interferometer interference patterns

3) Development of the physical model of the ablation and ionization processes associated with the entry of "slow", low-mass debris particles

4) Refinement of the mass measurement model and multiple wavelength approach

5) Specifically for D-180, extended data reduction for determination of the debris influx on subsequent orbit plane intersection with the Kauai-based radar beams

Continued study of the entry processes should be initiated well ahead of anticipated opportunities to conduct controlled experiments. Improved understanding of the measurement technique and the physics of small body entry will constructively guide field measurements.

C-75
APPENDIX A

HAWAII METEOR CAMPAIGN FIELD NOTES
HAWAII METEOR CAMPAIGN

8-28-86 → 9-3-86

* John & Keala met with Richard Tan at Territorial Savings & Loan in Honolulu to make final request for usage of property at Primeville. The request was denied—no strong rationale was given. They were apparently concerned about liability and interference with the selling of their property. To date (9-4-86) there has been no activity whatsoever on that land.

* Nobile, Standberg, & DeMoura assembled antennas and checked out matching networks with the network analyzer.

* The 25 MHz TX was powered-up & tuned at Sand's; Tuning procedure resulted in burning out some components of the T/R switch.
* Since the prime site was not available, the 1st backup site was selected as the field for the antenna farm. Jost & Noble shot the North Star on 8-20-86 on 8-31-86 the field was surveyed and the antenna array was laid out.

* The antennas for the 50 MHz interferometer were raised on 9-1 & 9-2. Some problems with dipole joint failures were experienced. A field test technique was devised to find failed joints & a repair procedure implemented. All antennas were operational (including the 25 MHz) by 9-3-86.
50 MHz TX was powered up & tuned. A solid-state "booster" stage was added between the exciter & 1st stage to increase the drive level. Output power was kept at about 15 kW for testing purposes.

After TX tuning and about 30 minutes of operation the matching network for the TX antenna failed. Repairs were completed with stronger components & no further problems encountered.

28 MHz TX was powered up & tuned into antenna w/ repaired T/R switch. An operational level of about 12 kW was achieved.
Early operational tests showed:

- Strong echo returns from (presumably) the isopshere for the 28 MHz radar - possible sea-state returns in early range gates as well.
- Good meter echoes were obtained over ranges of 0.75 - 2.5 mg,
  w/ the 28 MHz system.
- Ionospheric echo disappeared at sundown.
- 58 MHz echoes are apparent in all five receiver channels.
- Echo strength seems a little weak; will use higher TX power for experiment.
- Channel 3 (antenna 4) contains strong intermittent interference.
  It is believed the interference is coming from a local wireless telephone.
**Honeywell 101 tape recorder.**

15 channels - all direct.

**Channel assignment:**

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<th>Input</th>
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<tr>
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<td>SYNC</td>
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<td>15</td>
<td>1R1K-Q-B</td>
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</table>
9-4-86 Hawaii

* Test tape was started about 1300 LT to set levels, etc.

* Tape 2 started ~ 1350 LT w/ all channels of 50 MHz

* 28 MHz being tested - evidence that high voltage corona or breakdown is getting into RX. TX power solid ~ 12 kW

* 28 MHz \( V_f / V_r \approx 8 \)

* Visual inspection shows no obvious corona

* Tape 2 started ~ 1550 LT / 248/0150 UT

* From here on, all times will be reported in UT

* Further work on 28 found that RF choke was corona discharging to ground (probably) near its base
- 9.4.87 HAWAII

- 248/03:46  Corne started real bad again

* Strong E-region (?) returns observed in 28 RX again. Range ~ 2.5 mgs (center) & extent ~ 1 mgs

* Meteors have been observed on both the 28 & 50 simultaneously for several hours

* Subjectively, the meteor flux seems relatively low

- 248/04:00 → 05:00  50 MHz RX & tape recorder were re-configured slightly to improve RX dynamic range & to improve signal quality

* 05:15 : 28 MHz activated at ~ 6 kV (minimum corona) -- meteor was immediately detected in both systems

* Strospheric returns have stopped at sundown

* To 28 MHz HV → 8 kV - corona noise increases
Pulse configuration:

\[ P_d = 20 \, \mu s \]

\[ T_{PP} = 2 \, ms \]

\(+50 \, MHz\) Directional coupler = 25.5 kW

\[ VSWR = \frac{V_F}{V_R} = 7.0/0.9 = 7.8 \ (50 \, MHz) \]

\(+28 \, MHz\) (4.5 dB coupler) = 8.8 kW

\[ \text{returning} = 10.8 \, kW \]

\[ * \ VSWR = \frac{6.2}{0.6} = 10.3 \ (28 \, MHz) \]

2/8:06:20:20 Tape speed increased

7.5 ips → 15 ips

06:25 Intermittent inoplane returns

At 0.8 ms (2.0 + 0.8 ms) range valued

Very very weak ~ 2:1 SN, slow Doppler
9.4.87 HAWAII

248:06:37 Discovered tape rewinding
- Don't know when finished
- This tape will not be rewound
- Anticipate slow changeover

248:06:53 Start TAPE 5

07:00 Continued checking of RX channels indicate that all receivers are working well; no man-made interference; and simultaneous meteor echoes appear in all channels most of the time (depending on amplitude)

07:21 - 07:21.15 sec pulse off to check trigger level

07:24 Discovered that Recorder was in reverse again! Don't know what's going on.
248:07:28 Tape position that reversal occurred was located & tape restored (in record) from that point (~5 min delay?) It was noticed that the tape counter was at ~2000 when the recorder went into auto-rewind. Recorder was difficult to get past the 2000 mark - tape didn't seem stuck - maybe an auto feature that can be reset.

248:07:34 Meteors still appearing in 50 & 26 simultaneously
+ Echo strength about the same in most cases (S/N)
+ Echo persistence about the same in most cases
+ Most echoes appear in all interferometer channels
+ Event flux ~ 1 per minute
END TAPE 5 - START TAPE 6

08:15 Strong interference in 50 MHz System

08:39 Testing Bandwidth select.

08:41 BW set at 20 µs
Outside interference still very bad w/ 50 MHz

09:05 END TAPE 6
09:09 START TAPE 7

09:12 Interference finally is disappearing

09:25 Pulse width reduced from 20 µs to 10 µs; BW = 10 µs (from 20 µs)

09:28:55 Very strong meteor in both systems at 10 µs

10:11: End Tape 7

10:16+: Start Tape 8; Counter: 100' (15 ips)
9-5-86 Hawaii

24/10/21 bug fried in 50 MHz Tx
10:24 all channels checked and ok.

11:16: end Tape 8

11:20: Start Tape 9

11:22: all channels checked and ok.
   50 MHz: 3.4 kV / 10 mA
   28 MHz: 8 kV / 17 mA

11:54: 2500' good event - simultaneous deflection; 19.4 m/s

12:04:50: 3330' good event - s.d.

12:09:40: 3690' 28 MHz echo

12:11:30: 3820' simultaneous deflection

12:22: End Tape 9

12:26: Start Tape 10

12:28: all channels checked and ok
   - both Tx's ok.

12:30:00: 320' a event
9-5-86 Hawaii

248/12:37:30 875' summit unit

12:46:30 1550' ground unit

12:52:15 1990' quick sim. det. unit

12:58:02 2470' Ign. unit - in close arched

Heavy rainfall for ~15 min @ ~2:45 am

248:13:28 END TAPE 10

248:13:33 START TAPE 11 30 IPS

All channels check OK

PS Readings:

28 Tinal: 8KV/17ma

50 Driver: 3.4KV/10 ma

Tinal: 6.35KV/53 ma

PW = 10 μs

BW = 10 μs

Tape Speed: 30 IPS

1PP = 2 ms

248:14:05 END TAPE 11

14:07 START TAPE 12 30 IPS
9.6.82 HAWAII

248:14:38 End TAPE 12
14:41 Start TAPE 13  30 ips

+ System stable - no changes
+ Frequent, good meteor events, all channels

15:45 TAPE 14 end

15:48 TAPE 15 start  30 ips

16:03:30  30 ips → 60 ips

* Anticipate crossing 2006:20 LT (according to John Stanley)

16:10 TAPE 15 end

248/16:13 TAPE 16 start  60 ips
General comments during observation period: 0615 - 0630 (1415 - 1430 UT)

* Very strong persistent echo in both radars at ≈ 0618
* Strong multiple strike at ≈ 0623
* Very strong single event at ≈ 0627
* General background level increased
* 28 MHz more active than 50 MHz
* Interferometer channels all operational
* No outside interference
* Weather excellent

248:16:45 End TAPE 16
248:16:47 Start TAPE 17  30 ips

17:30  30 ips → 60 ips
17:33  50 MHz interference returns (weakly)

248:17:37:45 Excellent persistent return for calibration v 0.3 m

248:17:40 End TAPE 17
17:41  Start TAPE 18  30 ips
248:17:46:50 (approx.) good bistatic echo
47:30 strong interference
49:10 interference gone
50:00 strong meteor 1.8 ms
248:17:53.6 Nominal impact time

248:18:35 30 → 60 ips
18:11 End TAPE 18
16:14 Start TAPE 19 STOP TAPE 19 @ 16:40

Review of TAPE 18 near event time

18:0 4:55
06:15 6 div quick bath
30 8.5 long med bath
7 7.6
07
00
8:09 8.5
16 9.5
13 8
9:00 no echo
9:42 6.8
50 7.2
10:11 3 multiple range
9:58 Hawaii

- 248:18:58 Start TAPE 20 15 ips

248:20 Troubleshooting an RX problem in 50 MHz channel 0 (Q)

20:06 Back online - all channels

Total data gap ~ 15 min

21:42 30 ips -> 60 ips

21:52 Tape 20 end

21:54 Tape 21 Start

22:36 Discovered a of channel 0 nonoperotive

22:37:00 Pulses off

38:00 Pulses on

X 50 MHz output = 25.5 kW

Web w/ RX-0 (Q)

* 248:22:42:00 Power down for today
9.5.86 HAWAII

End of data on TAPE 21 at ~ 8200 on tape counter

Data review indicates that the channel "0" receiver was good until about 248:21:30, then went into periodic intermittent operation until EOT.

Discussions w/ Don Keeler
- Delta launch time 248:15:09:00
- Interaction 9874.9 sec. later
- Time of interaction 248:17:53.4 UT
- Location of interaction from Preliminary groundtracks showed latitude at 166°
- Kauai located at ~ 157°W

⇒ ~35° of orbital rotation; assume ~90 mins/w
⇒ 8.75 min after interaction it should be detected at Kauai

Time of crossing 248:17:53.4
8.75

248:18:02
9.5.86 HAWAII

249/05:23 Start TAPE #22

05:54  End TAPE 22  

249:05:57 Start TAPE 23  

06:05  E-region echo growing strong in 28 & 50 MHz systems; all channels

06:08 Range check on E-region echo

2ms → 3ms for ~ 15 sec

06:28  End TAPE 23

End of observations 9.5.86

9.6.86 HAWAII

* Gene Staudberg provided orbital plane information:
  - Ascending pass of high inclination "end" cross Kauai 15:45 → 16:00
  - Peak of low inclination orbit crosses Kauai once a day for extended period
  ~ 17:00 → 19:45
9/8/81 Hawaii

1249:17:00 Start TAPE 24
   * Channel 2 on 50Rx acting up; tape recorder filtering and a high frequency oscillation, however. Data recorded looks fine.

1249:18:00 Stop TAPE 24
   18:05 Start TAPE 25

19:05 Stop TAPE 25  20 ips
19:07 Start TAPE 26 (10", 30 ips)
19:40 Stop TAPE 26
19:42 Start TAPE 27 (10", 30 ips)

249:20:00 Excellent airplane calibration in all interferometer channels and 26 MHz RX
**Tape review for impact pass:** (Start 17:53)

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Calibration:

Feedline loss: Power measured at antenna and of feedline. Directional coupler & dummy load placed (connected) to feedline; transmitter operated, and forward power measured.

28 MHz

\[
\text{Forward power} = 4.6 \times 2 \text{ volts pp}
\]

Directional coupler \(\Rightarrow 64.5 \text{dB} \text{ atten.}

\[
\therefore \text{Transmitted power} = 5.96 \text{ kW}
\]

50 MHz

\[
\text{Forward power} = 3 \times 0.5 \text{ Vpp}
\]

Directional coupler \(\Rightarrow 62.6 \text{dB} \text{ atten.}

\[
\therefore \text{Transmitted power} = 10.2 \text{ kW}
\]
Phase Calibration

* All receiver channels driven simultaneously through full length antenna feed lines

* 249:22:02 Start time
* Input signal = $9.92 \pm 7.15 \text{dB}$ (approx)

* 249:22:06 Start test (about 700 ft)
  06-08 channel 9 was oscillating
  249:22:10 Restart test (about 1300 ft)
  Clipping discovered in channel 5 & 6
  249:22:12 Restart test (about 1650 ft)

22:16:15 Stop recorder
Add ¼ λ to input of power divider
~ 22:16:50 Start recorder

22:20:30 Stop

22:42 Start reduced feed line length
Cal. 1/40 μs PW 900 μs 1PP

44:45 - 45:00 go to 500 μs 1PP
07 Sept 86

250/15:17 UT check up / recording tape

\[ f_{10M} = 10,000 \text{ Hz} \]

50 MHz TX: \(~3.5 \text{ KV} / 10 \text{ mA} \) \(~6.5 / 50 \)

28 MHz TX: \(~8 \text{ KV} / 17 \text{ mA} \)

All channels checked and ok.

PW = 10 \mu s

1PP = 250 \mu s

Tape speed: 30 ips

Meteor confirmed both radars.

15:30 - 15:48 All channels show meteor activity.

15:53 28 MHz dir. cup. checked 8-10:1

50 MHz checked earlier; ok.

15:58:30 Good event - both radars, 19 ampl.

16:19 Tape 28 end

16:21 Tape 29 start

All channels checked and ok.

17:23 Tape 29 end

17:25 Tape 30 start

All channels checked and ok.

Tx's are also ok.

18:18 - 18:21 Good meteor echoes
07 Sept 86

250/18:27 Tape 30 end

18:29 Tape 31 start

all channels checked and ok
Tx's pulling current as usual

19:23 Tape airplane event both channels

19:27:15 Tape motion event both channels

19:31 Tape 31 end

19:33 Tape 32 start

250/20:04 End Tape 32 Ran over
08 Sept '86

11/16:29 UT 25 MHz up

11/16:40 pulses off
11/16:42 pulses on 50 & 25 MHz systems up
50 MHz drain = 16 V in 5V/div
rf = 1 V in 1V/div

Antennas were checked @ 16:00 only. 50 MHz tuned as found to not provide proper freq. response. Further testing indicated that water had entered band connection at a tower and shorted the line. Barrel was replaced on 50 MHz was brought up @ 16:44. The worst weather of the campaign occurred throughout yesterday and last night. Thunderstorms, high winds, and frequent rain storms occurred.

\[ \text{EFM} = 10 \text{sec} \]
\[ \text{Type speed} = 20 \text{ cps} \]
50 MHz: 3.4 kV / 110 mA; 0.8 kV / 30 mA
25 MHz: ~5 kV / 20 mA

25 MHz RX signal is not as strong as before, all other channels are ok.

11/16:59 Tape 33 end

11/17:01 Tape 34 start
25/17:06    echoes confirmed at 50 MHz / 28 MHz shift in question

17:10    airplane echo at 50 - not observed on 28 MHz
(very lg echo at 50 MHz)

17:15    50 MHz feed line connector & antenna is mainly warm

17:32    Tape 34 end

17:33    Tape 35 start

18:04    Tape 35 end

18:06    Tape 36 start

18:34    airplane echo shows in all channels except 28 MHz

18:37    Tape 36 end

18:39    Tape 37 start

Heavy rains have returned

19:53    airplane in all channels X 28 MHz
weak in channels 7-18

25/19:10    Tape 37 end    Takeoff
252/16:20  50 MHz up
28 MHz down for run
m 1 V/div scale
52 MHz direct 38 div.
ref 1.4 div.

PS: 3.4 kV/10 mA; 6.6 kV/45 mA
Waterschoor confirms radar operation.

Panel connector @ antenna was cleaned prior to turn on.
After 10 min operation this methane is cold.
Film < 1000.

252/16:30  Tape recorder - record on 3 clips
/ Tape 38 START
Tape 38 end
/ Tape 39 START
Tape 39 end
/ Tape 40 START
All channels checked and ok.

/ 16:54  Connector still cold
/ 17:00  Tape 38 end
/ 17:02  Tape 39 end
/ 17:24  Mekas dekled
/ 17:33  Tape 39 end
/ 17:35  Tape 40 start
All channels o.k.
C-104
09 Sept 86

252/18:06 Tape 40 end

18:07 Tape 41 Start

18:38 Tape 41 end

18:40 Tape 42 start

19:08+ Meteor echo

19:09 All channels lost, good

19:11 Tape 42 end

end report
APPENDIX B

TIME-OF-FLIGHT VELOCITY CALCULATIONS
DERIVATION OF TIME-OF-FLIGHT- VELOCITY RELATIONSHIP

Position and time of "event":

\[
\begin{array}{l}
14.915 \text{ N Lat} \\
165.828 \text{ E Long} \\
248:17:52:35.5 \\
Alt = 117.42 \text{ NM} \\
= 217.46 \text{ km}
\end{array}
\]

(1 NM = 6076.12 feet = 1852 meters)

Observer coordinates:

\[
\begin{array}{l}
159^\circ 27' \text{ W Long} = 159.45^\circ \text{ W} \\
22^\circ 11' \text{ N Lat} = 22.18^\circ \text{ N}
\end{array}
\]

Longitudinal and Latitudinal traversal:

\[
\Delta \text{Long} = 180 - 165.828 + 180 - 159.45
\]

\[
\Delta \text{Long} = 34.72^\circ
\]

\[
\Delta \text{Lat}_0 = 22.18 - 14.915 = 7.27^\circ
\]

\[
\Delta \text{Lat} = 7.27^\circ
\]

Great-Circle Path Length

Law of sines: \[
\frac{\sin a}{\sin A} = \frac{\sin b}{\sin B} = \frac{\sin c}{\sin C}
\]

Law of cosines: \[
\cos a = \cos b \cos c + \sin b \sin c \cos A
\]

C-107
\[ b = 34.72^\circ \]
\[ c = 7.27^\circ \]
\[ A = 90^\circ \]

\[
\cos a = \cos(34.72) \cos(7.27) + 0
\]

\[
a = 35.37^\circ \quad \text{(Orbital angular displacement for zenith of observer)}
\]

Total angular displacement,

\[
\cos a = \cos(34.72 - \Omega_t) \cos(7.27)
\]

\[ a(t) = \cos^{-1}\left[\cos(34.72 - \Omega_t) \cos(7.27)\right] \]

Considering latitudinal displacement

\[ a(\Delta l, t) = \cos^{-1}\left[\cos(34.72 - \Omega_t \cos(7.27 + \Delta l))\right] \]

again,

\[ a(\Delta l, t) = \cos^{-1}\left[\cos(34.72 - \Omega_t \cos(7.27 + \Delta l))\right] \]

\[ \Delta l = \cos^{-1}\left[\frac{a^2 + b^2 - c^2}{2ab}\right] \]

\[ b = a + 60 \]

\[ \Delta l = \cos^{-1}\left[\frac{a^2 + (a + 60)^2 - c^2}{2a(a + 60)}\right] \]

C-108
\[ c = \text{slant range} \]

let \( c = R_s \)

\[
a(R_s, t) = \cos^{-1}\left[\cos(34.72 - \Omega t)\cos(7.27 \pm \cos^{-1}\left[\frac{a^2 + (a + 60)^2 - R_s^2}{2a(a + 60)}\right])\right]
\] (1)

\[
v_a = \frac{a(R_s, t)}{t}
\]

(2)

\[
v_h = \frac{217-60}{t} \approx 160/t \text{ (km/s)} = 1.6(10^5)/t
\]

(3)

\[
v_t = (v_a^2 + v_h^2)^{1/2}
\]

(4)

Equations (1), (2), (3), and (4) were evaluated numerically with the following BASIC program. The results provided a velocity dependence on the time-of-arrival (detection) and range of meteor-like echoes.
TIME-OF-ARRIVAL VELOCITY CALCULATIONS

RE = EARTH RADIUS
OMEGA = EARTH ANGULAR VELOCITY
ALT = ALTITUDE OF CLOSEST APPROACH
HT = HEIGHT OF ENTRY
RS = SLANT RANGE FROM RADAR

FOR IR=1 TO 6
RS=IR*50000!

CALCULATE DIFFERENCE IN LATITUDE WITH SLANT RANGE
CAR=(RE^2+(RE+HT)^2-RS^2)/(2*RE*(RE+HT))
IF CAR>1 THEN CAR=1!
CR=ATN((1-CAR^2)^.5/CAR)
FOR I=0 TO 260 STEP 1
T=465+I

CALCULATE FLIGHT PATH LENGTH
AA=COS(PI*34.72/180-OMEGA*T)*COS(PI*7.27/180+CR)
A=ATN((1-AA^2)^.5/AA)

CALCULATE VELOCITIES
VA=A*(RE+ALT)/T: VH=(ALT-HT)/T
VT=(VA^2+VH^2)^.5/1000
PRINT RS,T,VT
NEXT I
NEXT IR
### Time-of-Flight Velocities

**(Northern Beam)**

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