IN-SITU DETECTIONS OF A SATELLITE BREAKUP BY THE SPADUS INSTRUMENT

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ABSTRACT

For the first time, a particle detector in Earth orbit has provided evidence to directly link sub-millimeter orbital debris to a specific satellite breakup. The University of Chicago's Space Dust Instrument (SPADUS), on the U.S. Air Force's *Advanced Research and Global Observation Satellite*, has been operating in a nearly polar orbit, at an altitude of about 830 km, since soon after its launch on 23 February 1999. The experiment was designed primarily to detect small natural and man-made particles less than 100 μm in diameter. Using a dual-plane Polyvinylidene Fluoride (PVDF)-based detection system, SPADUS can measure dust particle flux, mass distribution, velocity, and trajectory.

From *ARGOS* launch through 2000, SPADUS recorded 327 impacts, about one impact every two days. In late March 2000, the instrument detection rate increased by approximately an order of magnitude, suggesting a potential encounter with a cloud or stream of debris. A review of the impact times and *ARGOS* orbital characteristics indicated that most of the detections occurred at multiples of half-revolution intervals over high northern and southern Earth latitudes, with a clear majority of impacts found over the southern hemisphere. Orbital analyses linked these impact events to the orbital plane intersections of *ARGOS* and the debris cloud of a Chinese orbital stage (International Designator 1999-057C, U.S. Satellite Number 25942), which had undergone a severe fragmentation on 11 March 2000 at an altitude 100 km below that of *ARGOS*. Approximately 45 of the SPADUS detections during the period 25 March - 23 April were associated with the postulated Chinese debris cloud. Other periods of high impact flux on SPADUS may be related to debris clouds from other sources.

1. INTRODUCTION

The Space Dust (SPADUS) instrument is currently being carried aboard the *Advanced Research and Global Observation Satellite*. *ARGOS* was launched into a altitude on February 23, 1999 on the Air Force *ARGOS* P91-1 Mission. The instrument provides time-resolved measurements of dust particle flux, mass distribution, and trajectories, as well as high time resolution measurements of energetic charged particles from the SPADUS ANCILLARY DIAGNOSTIC SENSOR (ADS) subsystem, during the nominal three-year *ARGOS* mission.

SPADUS uses Polyvinylidene Fluoride (PVDF) dust sensors developed at the University of Chicago [1]. PVDF sensors have been used earlier on the *Vega-1* and *Vega-2* missions to Halley's Comet, and are currently being carried on experiments aboard the Cassini spacecraft to Saturn, as well as the *Stardust* spacecraft to Comet WILD-2. The SPADUS PVDF sensors have a total area of 576 cm^2, and the SPADUS velocity/trajectory system permits distinction between orbital debris and cosmic (natural) dust, as well as a determination of the orbital elements for some of the impacting particles. The SPADUS instrument measures particle mass over the mass range $\sim 5 \times 10^{-11}$ g (3.3 μm diameter) to $\sim 1 \times 10^{-5}$ g (200 μm diameter), and also measures integral flux for particles of mass > $\sim 1 \times 10^{-5}$ g.

In earlier reports, we presented brief descriptions of the SPADUS instrument and its measurement objectives [2]-[5], and of the *ARGOS* mission [6]. In the first of two recent reports, we provide an exhaustive description of the SPADUS instrument [4], and in the second recent report [5], the experimental results obtained by SPADUS during the first sixteen months of flight are presented.

In this paper, we first outline a brief list of the characteristics of the SPADUS instrument. Although SPADUS instrument descriptions are presented elsewhere, the brief overview given here will provide a background for the modeling and analysis results provided afterward, when we discuss experimental data relating to the detection by SPADUS of orbital debris streams. Finally, the analysis carried out by the Johnson

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The stream detections were first reported in [5]. However, the source of these detections was unknown during the drafting period of the paper. Preliminary analysis by the UC group of the particle impact times on SPADUS of the most prominent stream (designated stream #3) indicated that the detections occurred at multiples of *ARGOS* half-revolution intervals. Further, all of the stream #3 impacts occurred at two loci on the *ARGOS* orbit, located at opposite ends of a line passing through the center of the Earth.

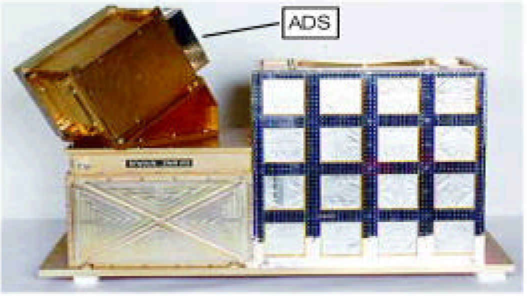
Although possible sources of the debris stream had been suggested, including satellite disintegrations, solid rocket motor firings, rocket body explosions, etc., the origins of the stream particles could not be determined. One of the UC investigators (A.J.T.) contacted Nicholas Johnson, Chief Scientist for orbital debris studies at NASA Johnson Space Center (JSC), informing him of the SPADUS detections. Johnson immediately suspected that *ARGOS* had intercepted the debris cloud generated by the March 11, 2000 explosion of a Chinese *Long March 4* third stage. At this point, the UC group requested that Johnson assist in identifying the source of the stream #3 particles and carry out more detailed analysis and modeling. The results of the JSC analysis are reported below.

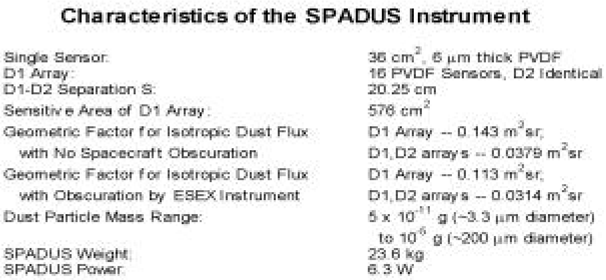
2. ARGOS MISSION AND SPADUS INSTRUMENT

The objective of the *ARGOS* mission, which includes 9 experiments, is to demonstrate advanced attitude and position determination, electric propulsion, and conduct upper atmosphere imaging and environment studies. For the latter, SPADUS provides measurements of the particulate environment. Fig. 1 shows a photograph of the SPADUS instrument and lists the basic characteristics of SPADUS.

The *ARGOS* P91-1 mission is supported by the U.S. Air Force Space Test Program. As previously noted, the spacecraft was launched February 23, 1999 into a circular near-polar (98.7° inclination) ~830 km altitude sun-synchronous orbit for a nominal mission duration of 3 years.

As discussed in [6], *ARGOS* is a three-axis stabilized spacecraft providing attitude control to 0.3°, and attitude knowledge to 0.05°. Spacecraft position knowledge is to within 15 meters and velocity knowledge to within 0.08 m s^{-1}. Throughout the mission, the spacecraft attitude is such that the body-fixed axes x_B, y_B, z_B, are continuously maintained with the $+x_B$ axis along the direction of the spacecraft velocity vector, the $+z_B$ axis pointing toward the center of the Earth, and the y_B axis forming a right-handed system.





Characteristics of the SPADUS Instrument

Single Sensor:	36 cm^2, 6 µm thick PVDF
D1 Array:	16 PVDF Sensors, D2 Identical
D1-D2 Separation S:	20.25 cm
Sensitive Area of D1 Array:	576 cm^2
Geometric Factor for Isotropic Dust Flux with No Spacecraft Obscuration	D1 Array -- 0.143 m^2sr; D1,D2 arrays -- 0.0379 m^2sr
Geometric Factor for Isotropic Dust Flux with Obscuration by ESEX Instrument	D1 Array -- 0.113 m^2sr; D1,D2 arrays -- 0.0314 m^2sr
Dust Particle Mass Range:	5×10^{-11} g (~3.3 µm diameter) to 10^{-5} g (~200 µm diameter)
SPADUS Weight:	23.6 kg
SPADUS Power:	6.3 W

Fig. 1. Photograph of the SPADUS instrument and instrument characteristics.

2.1 SPADUS Instrument

The primary scientific objectives for the SPADUS instrument are:

- To characterize the flux, size spectrum, velocities and trajectories of small ~3.3 - 200 µm diameter, $\sim 5 \times 10^{-11}$ g to $\sim 1 \times 10^{-5}$ g dust particles in Low Earth orbit.
- To determine, by measurement of the orbits of dust particles, the 3-dimensional distribution of dust particles intercepting the orbit of *ARGOS*, and to separate particles of natural origin from man-made debris.
- To search for transient variations of the dust flux from man-made and natural sources (e.g., debris streams from satellite erosion or fragmentation, collisions, interplanetary meteor streams, launches, etc.).
- To compare the SPADUS data obtained for debris particles with the predictions of current debris models.

A secondary sensor subsystem, the Ancillary Diagnostic Sensor (ADS), was added to SPADUS to provide measurements of the ambient intensity of electron and nucleon radiation at energies above ~25 keV. During the mission, possible anomalies in payload instrument performance, which might be related to transient backgrounds of intense charged-particle fluxes, could be investigated using the ADS data as a monitor. Flight data from ADS is presented in [5].

2.2 Overall Instrument

SPADUS is shown schematically in Fig. 2. The main components are:

- A dust trajectory system consisting of two identical planar arrays (D1 and D2) of polyvinylidene fluoride (PVDF) dust sensors, providing particle mass measurement, velocity (by time-of-flight) and trajectory measurement. Also shown is the assignment of the 16 D1 sensors and 16 D2 sensors to corresponding electronic channels (analog and digital) located in the analog and digital electronics boxes.
- A digital electronics box, also containing an Ancillary Diagnostic Sensor (ADS) system for measurement of the fluxes, energy spectra, and arrival directions of energetic nucleons.
- An analog electronics box.

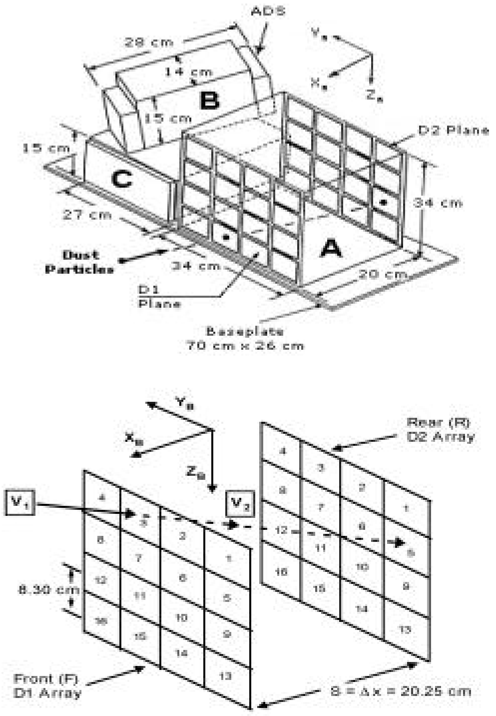


Fig. 2. Schematic of the SPADUS instrument showing the dust trajectory system (A), the digital electronics box containing the ADS energetic particle telescope (B), and the linear electronics box (C). The numbering scheme and location of each of the 16 D1 sensors and 16 D2 sensors is shown. A sensor referred to as F1 corresponds to sensor #1 on the Front D1 plane, and similarly R refers to sensors on the Rear D2 plane.

3. DUST TRAJECTORY SYSTEM

Each of the two sensor arrays (D1 and D2) contain sixteen 36 cm^2 6 µm thick polyvinylidene fluoride (PVDF) sensors (Fig. 2). Although the sensor thicknesses are referred to as ``6 µm", their actual thicknesses are in the range 6 µm to 9 µm, with most of them being closer to 9 µm thick. Our dust calibrations have shown that, within experimental error, the output signal from a 6 µm thick PVDF sensor is identical to that from a 9 µm thick PVDF sensor.

The theory, fabrication and details of PVDF dust sensor operation have been described in earlier reports. In brief, a PVDF sensor consists of a thin film of permanently polarized material whose polarization vector is normal to the film surface. A hypervelocity dust particle with velocity v_1 impacting the sensor produces rapid local destruction of dipoles (crater or penetration hole) which results in a large and fast (ns range) current pulse at the input to the electronics. The output pulse from the linear electronics is sharp in time, with a maximum amplitude depending on impacting particle mass and velocity.

Particles which fire only a D1 sensor are termed D1 events, and particle which impact and fire a D1 sensor, and then exit D1 and impact and activate a D2 sensor, are termed D1-D2 events.

4. STREAM PARTICLE RESULTS

In Fig. 3, the number of impacts in consecutive four-day time intervals (bins) is plotted vs. bin number. The arrows labeled 1-3 indicate time periods when short-term enhancements in particle flux occur. The first bin corresponds to the first four days of the *ARGOS* mission, Days 54 through 57 of 1999. Clearly, periods of enhanced particle fluxes are evident, with a particularly obvious spike beginning on Day 85 (March 25) of 2000 and continuing until Day 92 (April 1).

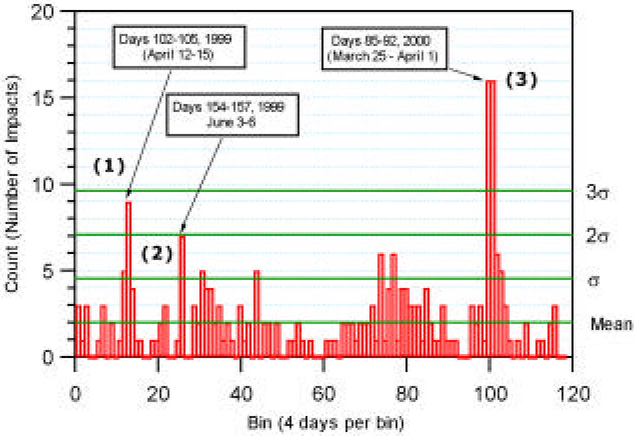


Fig. 3. Number of impacts per four day interval (bin) from *ARGOS* launch up to Day 159 (June 8), 2000. The numbered event spikes correspond to the numbers in panel (a). The time periods 1-3 indicate periods when orbital debris clouds (streams or swarms) were encountered by the *ARGOS* spacecraft.

Table 1 shows the particle impact times for the forty-five stream #3 impacts, as well as the time intervals between successive impacts. It is clear that the time intervals ΔT_2 are integer multiples of half of the *ARGOS* orbital period. T, in seconds, is the time from the first stream particle impact; ΔT_1, in seconds, is the time between a stream particle impact and the preceding impact; and ΔT_2 is ΔT_1 expressed in units of 1/2 of the *ARGOS* orbital period, α 0.5 × 101.33 min = 3040 seconds.

Table 1. Particle Impact Times for Dust Stream #3

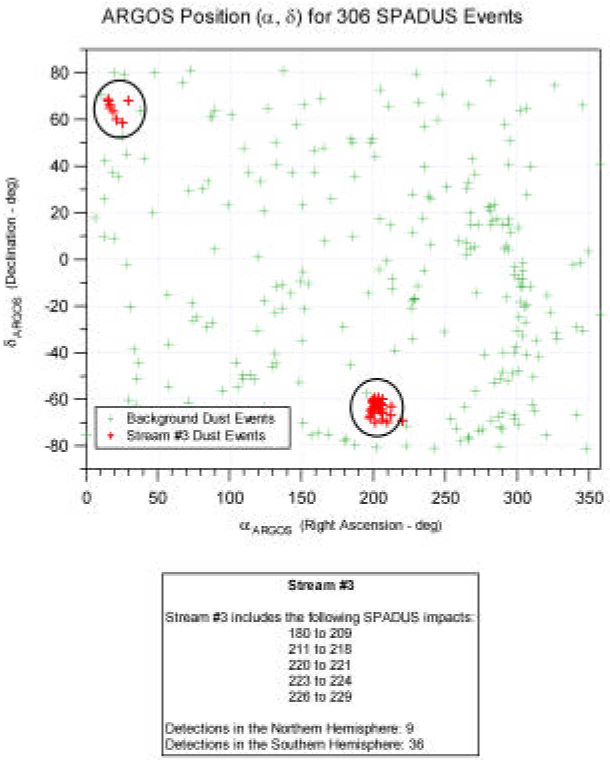
Stream Particle	SPADUS Impact	Day	Time (UT)	T (sec)	ΔT_1 (sec)	ΔT_2
1	180	86	4:41:32	0	0	0
2	181	86	4:41:32	669 µs	669 µs	2.2×10^{-7}
3	182	86	6:23:26	6114	6114	2.01
4	183	86	14:51:42	36610	30496	10.03
5	184	86	20:48:32	58020	21410	7.04
6	185	86	21:37:36	60964	2944	0.96
7	186	86	23:19:25	67073	6109	2.01
8	187	87	2:42:41	79269	12196	4.01
9	188	87	15:24:48	124996	45727	15.04
10	189	87	16:15:56	128064	3068	1.01
11	190	87	20:31:30	143398	15334	5.04
12	191	87	22:12:14	149442	6044	1.99
13	192	88	2:26:38	164706	15264	5.02
14	193	88	4:08:00	170788	6082	2.00
15	194	88	21:56:16	234884	64096	21.08
16	195	88	22:45:20	237828	2944	0.97
17	196	89	5:32:14	262242	24414	8.03
18	197	89	6:24:32	265380	3138	1.03
19	198	89	10:35:42	280450	15070	4.96
20	199	89	12:18:41	286629	6179	2.03
21	200	89	19:06:07	311075	24446	8.04
22	201	90	10:20:17	365925	54850	18.04
23	202	90	12:01:38	372006	6081	2.00
24	203	90	13:42:28	378056	6050	1.99
25	204	90	13:42:55	378083	27	0.01
26	205	90	22:12:16	408644	30561	10.03
27	206	90	23:00:19	411527	2883	0.95
28	207	91	1:33:54	420742	9215	3.03
29	208	91	15:06:42	469510	48768	16.04
30	209	92	6:21:24	524392	54882	18.05
31	211	92	11:25:24	542632	2016	0.66
32	212	92	11:25:57	542665	33	0.01
33	213	92	23:17:23	585351	42686	14.04
34	215	93	21:18:27	664615	79264	26.07
35	216	94	2:24:04	682952	18337	6.03
36	217	94	12:33:41	713415	30463	10.02
37	218	96	0:07:33	810951	97536	32.08
38	220	97	1:33:29	881097	70146	23.07
39	221	97	18:28:23	939047	57950	19.06
40	223	100	2:22:34	1134189	195142	64.19
41	224	100	22:40:12	1195051	60862	20.02
42	226	102	22:57:48	1323180	128129	42.15
43	227	104	9:40:31	1445075	121895	40.10
44	228	105	9:23:57	1515147	70072	23.05
45	229	114	23:43:20	2338266	823119	270.76

T : Time from first stream particle, in seconds.

ΔT_1: Time between a stream particle impact and the preceding impact, in seconds.

ΔT_2: Defined as ΔT_1/3040 sec, where 3040 sec is half of the *ARGOS* orbital period of 101.33 minutes.

Fig. 4 depicts a plot of the *ARGOS* position in right ascension-declination coordinates at each point where a SPADUS detection occurred. The circled points contain all of the stream impact positions and correspond to the two endpoints of a line passing through the center of the Earth with a length equal to the diameter of *ARGOS*. Fig. 5 shows the stream #3 particle size distribution.



Stream #3

Stream #3 includes the following SPADUS impacts:
180 to 209
211 to 218
220 to 221
223 to 224
226 to 229

Detections in the Northern Hemisphere: 9
Detections in the Southern Hemisphere: 36

Fig. 4. Plot of *ARGOS* position in (α, δ) coordinates at the time of each confirmed D1 event (launch through Nov. 11, 2000).

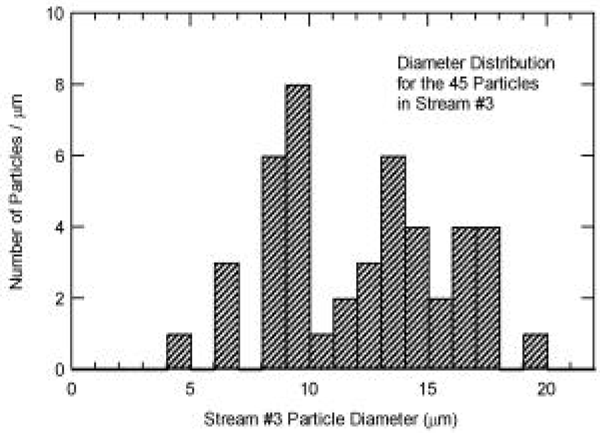


Fig. 5. Stream #3 particle size distribution.

As indicated above, a preliminary study of the results shown in Figs. 4 and 5 and Table 1 carried out by the UC group led to the conclusion that the stream #3 impacts resulted from the repeated passage of *ARGOS* through a transient particle cloud. However, the group was unable to determine the source of the cloud and initiated a collaboration with the JSC group, whereby JSC would proceed with the ultimate source identification, analysis, and modeling effort.

5. POTENTIAL ORIGINS OF STREAM PARTICLES

The population of man-made debris circling the Earth has grown drastically since a Soviet rocket body entered Earth orbit along with Sputnik 1 in October 1957. By the beginning of the year 2001, more than 9,000 debris objects greater than 10 cm in diameter were being tracked by ground-based sensors around the world. More importantly, the population of debris greater than 1 cm is known to exceed 100,000 objects, while the number of debris greater than 1 mm is estimated to be on the order of 10^9 [7].

The source of much of these debris, as well as smaller particles, has been the fragmentations, both accidental and intentional, of spacecraft and launch vehicle upper stages. More than 165 satellite breakups are known to have occurred since 1961, representing a rate of approximately four per year. Perhaps the single greatest contributor of hazardous debris to the space environment has been the unexpected explosions of upper stages, normally after completing successful spacecraft delivery missions [8]. A single such breakup can generate more than 500 debris greater than 10 cm in diameter and orders of magnitude more, smaller debris.

Fortunately, most upper stage breakups can now be prevented by depleting residual propellants and pressurants from the vehicles after mission completion. These passivation measures have proven highly effective for a diverse selection of American, European, Russian, and Ukrainian launch vehicles. China's first major upper stage explosion occurred in October 1990 after the second flight of the Long March 4 launch vehicle, and an extensive investigation of that event led to the implementation of new passivation procedures when flights resumed in 1999 [9]. Therefore, the major fragmentation of a Long March 4 third stage (International Designator 1999-057C) on 11 March 2000 came as a surprise.

Part of the Long March 4 launch vehicle which carried the China-Brazil Earth Resources Satellite (CBERS 1) into a sun-synchronous orbit on 14 October 1999, the third stage had been in an orbit about 735 km altitude for five months, four months longer than the ill-fated third stage of 1990 (International Designator 1990-081D). While the cause of the fragmentation is still being investigated, the event's effect on the near-Earth environment has become apparent.

More than 300 associated fragments were detected and tracked by the U.S. Space Surveillance Network, and by January 2001 a total of 267 debris had been officially cataloged (of which 34 had already decayed from orbit). The majority of the debris were scattered into a wide range of elliptical orbits with altitude excursions up to 500 km from the original orbit (Fig. 6). Using a technique of backward propagation, specialists at the U.S. Naval Space Command in Dahlgren, Virginia, were able to calculate the probable time of the breakup as 1304 UTC, when the Chinese third stage was deep in the Southern Hemisphere at 51.2^o S, 48.5^o W [10]. A similar analysis by Russian space surveillance experts relying on independent Russian data yielded a breakup time of 1301 UTC [11].

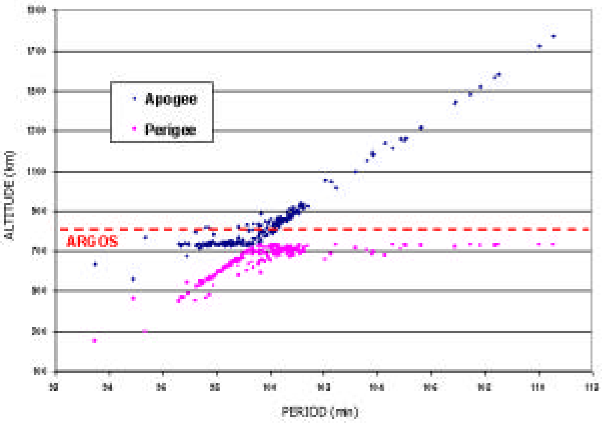


Fig. 6. Altitude distribution (Gabbard diagram) of tracked debris from the CBERS 1 orbital stage on 23 March 2000 with indication of *ARGOS* spacecraft altitude.

The Long March 4 third stage has a dry mass estimated to be about 1000 kg with a length and diameter of approximately 8 m and 3 m, respectively. The stage carries an initial hypergolic propellant load of up to 14,000 kg with an unknown amount of residual propellants at the conclusion of orbit insertion. The number of large debris (> 10 cm in diameter) linked with the March 2000 explosion was nearly four times greater than that of the October 1990, suggesting that the more recent breakup may have involved more energy, since the debris altitude excursions were similar in both cases.

The amount of debris produced with sizes smaller than 10 cm is difficult to estimate. Using the most recent NASA breakup model [12], the number of 1 cm or larger debris was possibly on the order of 10^4. For 1 mm and larger debris, the number generated may well have been on the order of 4×10^5. Estimates for the number of debris of 10 µm and 100 µm cannot yet be made with confidence using current explosion models. However, due to the greater range of ejection velocities the variety of orbits for these small debris will be greater in initial orbital period, eccentricity, argument of perigee and right ascension. Hence, the orbits of the tracked satellite population are a reflection of only a portion of the very small debris.

6. LINKING THE SPADUS DETECTIONS TO A PARTICLE STREAM

When the NASA Orbital Debris Program Office was first contacted by the SPADUS team at the University of Chicago about potential sources for the elevated detection rates which had begun on 26 March, the Long March 4 third stage debris cloud was quickly identified as a possible source candidate. An initial examination of preliminary SPADUS impact detection times for the period 26 March through 5 April found that 36 of 38 detections occurred at multiples of one-half revolution of the *ARGOS* spacecraft about the Earth. This implied that ARGOS was encountering a specific debris cloud which intersected the orbit of ARGOS near 60^o S and 60^o N. In fact, 78% of the detections occurred in the Southern Hemisphere.

The next step was to examine the orbital planes of *ARGOS* and of the debris from the Long March 4 third stage which had fragmented two weeks earlier. Orbital data for *ARGOS* and for the Long March 4 debris, which had been archived from U.S. Space Surveillance Network sources, were compared. Indeed, the planar intersections occurred in the extreme northern and southern regions at locations very similar to the detection events. Fig. 7 illustrates the relative geometry and positions of the *ARGOS* spacecraft and 262 Long March 4 debris on 26 March. At the time of the first detection on 26 March, the respective right ascensions of *ARGOS* and the Long March 4 third stage remnant were 35.63^o and 162.65^o. However, due to their approximately 100 km difference in mean altitude, the planes were separating at a rate of about 0.02^o per day.

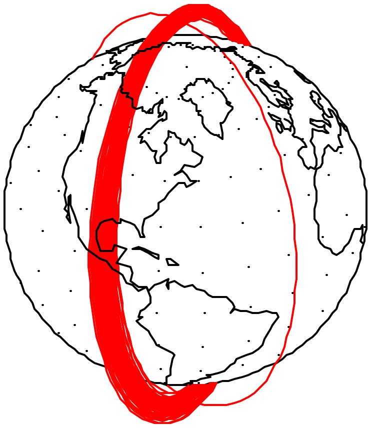


Fig. 7. Orbital planes of CBERS 1 orbital stage debris and the *ARGOS* spacecraft on 26 March 2000.

When the Long March 4 third stage fragmented while flying over the South Atlantic near the Falkland Islands, heading south, the *ARGOS* spacecraft was over Africa heading north. However, due to the approximately two-minute difference in their orbital periods, their relative positions were rapidly changing. By 26 March, the geometry for potential collisions between *ARGOS* and the Chinese debris cloud were favorable, especially in the Southern Hemisphere.

A necessary condition for the Chinese debris to impact the SPADUS instrument on ARGOS is that the debris apogees must be equal to the *ARGOS* altitude or higher. In reality, the situation is much more complex, and conjunctions are influenced by the debris orbital period, argument of perigee, rate of precession of the argument of perigee, rate of precession of the orbital plane, and orbital decay rate (ballistic coefficient and atmospheric density). These factors are, of course, dependent upon the nature and the ejection velocity of the debris.

Consider a piece of debris with a perigee of 735 km (near the original Long March 4 third stage altitude) and an apogee of 835 km (near the *ARGOS* altitude). With an eccentricity of 0.007, such an orbit would exhibit a rate of precession of the argument of perigee of nearly -3^{o} per day. Hence, from the time of the breakup until 26 March, the argument of perigee in such an orbit would have shifted more than 40^{o}. More eccentric, higher altitude orbits, e.g., 735 km by 1100 km, would have shifted less but not significantly. Unless the argument of perigee is precisely positioned with respective to the *ARGOS* spacecraft, a collision is not possible.

The next step was to confirm that detections of the Chinese debris were possible in both hemispheres two weeks after the breakup. The orbits of two tracked Long March 4 debris illustrate how this can happen. Satellite 80253 with only a slightly eccentric orbit of 715 km by 880 km and an argument of perigee of 225° crossed the ARGOS altitude near 65° N, whereas satellite 80040 with a more eccentric orbit of 725 km by 1445 km and an argument of perigee of 210° crossed the ARGOS altitude near 70° S.

From a complete orbital mechanical analysis, one can see that a SPADUS impactor from the Chinese debris cloud would likely have an apogee greater than that of the *ARGOS* altitude, perhaps many hundreds of kilometers higher. The maximum ejection velocity of very small debris (10-100 microns) is much higher than that of the trackable debris; thus, a higher proportion (as well as actual numbers) of the smaller debris would be expected to penetrate the *ARGOS* altitude. Unfortunately, the SPADUS data did not permit a reconstruction of the impactor's orbit.

Finally, debris of the size detected by SPADUS are subject to orbital perturbations from solar radiation pressure and other factors which normally have only minor influences on larger debris. In fact, solar radiation pressure can exert drastic effects on orbital lifetime for 10 μm-sized particles, like those detected by SPADUS. Such particles in circular orbits near the breakup altitude can decay within a matter of days. Particles of this size ejected with high posigrade velocities can remain in orbit for considerably longer. However, after a few weeks both the number and spatial density of the particles would have decreased significantly and orbital geometries would have changed, leading to fewer SPADUS detections.

7. EXAMINATION OF AN ALTERNATIVE DEBRIS SOURCE

Another potential source of 10 μm-sized particles was the firing of a STAR-37FM solid-rocket motor (SRM) on 25 March 2000 during the launch and orbital insertion of the NASA IMAGE (Imager for Magnetopause-to-Aurora Global Exploration) spacecraft. SRMs are known to emit large amounts of 10 μm-sized particles, though normally at very high velocities. In the case of the IMAGE STAR-37FM, the firing occurred near 1000 km and was used to propel the spacecraft into a highly elliptical orbit with a posigrade burn. Consequently, the effluents would be ejected in a retrograde direction for reentry into the atmosphere in less than one hour. However, if some particles were ejected with very low velocities (not included in current SRM effluent models) or if some higher velocity particles were ejected with sufficient radial and cross-track components, the particles would be longer lived.

The orbital plane intersections of *ARGOS* and the assumed STAR-37FM SRM effluents coincidentally bear a strong resemblance to those of *ARGOS* and the Long March 4 debris cloud. However, the altitudes of those intersections are quite different and not conducive to the ARGOS detections. Northern Hemisphere detections would have been especially difficult, if not impossible. Although such detections cannot be ruled out, they appear to be a much less likely source than the Long March 4 debris.

8. CONCLUSION

The significant increase in the detection rate of the SPADUS instrument beginning 26 March 2000 was likely the result of the impacts of very small debris from the breakup of the CBERS 1 orbital stage two weeks earlier. Other periods of high impact flux on SPADUS might be related to debris clouds from other sources and may be the subject of future work.

9. ACKNOWLEDGEMENT

The assistance of Dr. Phillip D. Anz-Meador of Viking Science and Technology, Inc., Houston, Texas, for calculating the effects of solar radiation pressure on 10 μm particles and for suggesting an examination of the potential influence of the IMAGE solid rocket motor burn is greatly appreciated.

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