An 82º Inclination Debris Cloud Revealed by Radar

D. Gates[(1)] and P. Anz-Meador[(1)]

[(1)] Jacobs, NASA Johnson Space Center, Mail Code XI5-9E, 2101 NASA Parkway, Houston, TX 77058, USA, drake.j.gates@nasa.gov

ABSTRACT

The statistical debris measurement campaigns conducted by the Haystack Ultrawideband Satellite Imaging Radar on behalf of the NASA Orbital Debris Program Office are used to characterize the long-term behavior of the small, low Earth orbit (LEO) orbital debris environment. Recent analyses have revealed the presence of a persistent LEO small debris cloud, which has no accompanying large component, cataloged by the U.S. Space Surveillance Network. This cloud, at an inclination of approximately 82° and below 1200 km in altitude does, however, correspond to the heavily trafficked region of space that has suffered several known, accidental collisions, *e.g.*, Cosmos 1934 and Cosmos 2251. In this paper, we describe the observed cloud and model it using the NASA Standard Satellite Breakup Model. Key features of the cloud model, including source attribution and debris mass constraints, are presented to enable further observations and characterization.

1 INTRODUCTION AND STUDY MOTIVATION

Objects in low Earth orbit (LEO) ranging from approximately 5 mm to 10 cm are modeled using observational data from ground-based radar, namely the Haystack Ultrawideband Satellite Imaging Radar (HUSIR – formerly known as Haystack). HUSIR is a 37-meter; X-band radar operated by the Massachusetts Institute of Technology Lincoln Laboratory and provides data for LEO debris larger than approximately 5.5 mm. The sensor is located at a latitude of 42.6° N and operates in a staring mode for debris observations. Hence, the radar, with its 0.058° 3-dB two-sided beamwidth at 10 GHz, is pointed at a fixed point in space with respect to the local topocentric coordinate system, and objects pass through the radar beam [1]. The data in this paper is a composite set of observations collected during calendar years (CY) 2013–2015 observation campaigns with staring directions of 75° elevation, or 15° from zenith, due East.

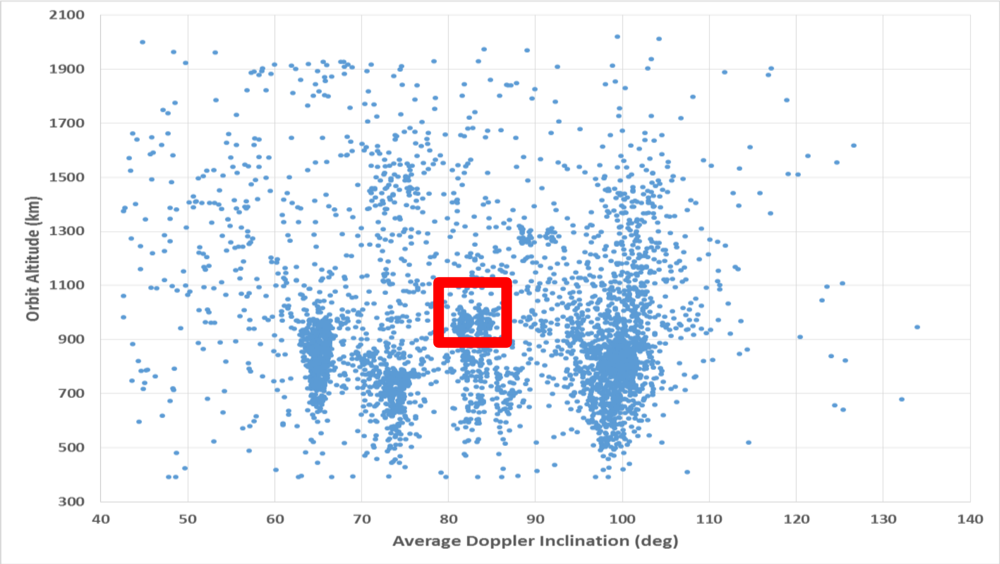

Fig 1. The CY2013–2015 composite HUSIR data. Of interest is the debris cloud at 900 km to 1100 km and 82° inclination with no known energetic breakup event.

In Fig. 1, a debris cloud can be seen in the 82° inclination band. A review of radar data back to the 1990s indicated that the cloud first appears in the U.S. Government Fiscal Year (FY) 1998. The persistence of the debris cloud(s) is curious, as no known fragmentation events, either breakups or anomalous events, are associated with this cloud. Therefore, we hypothesize that it is the result of a non-energetic event, possibly associated with satellite degradation.

2 HISTORICAL ANTECEDENTS

A satellite breakup is the usually destructive disassociation of an orbital payload, rocket body, or structure, often with a wide range of ejecta velocities. A satellite breakup may be accidental or the result of intentional actions. An anomalous event is the unplanned separation, usually at low velocity, of one or more detectable objects from a satellite, which remains essentially intact. Anomalous events can be caused by material deterioration of items such as thermal blankets, protective shields, or solar panels, or by the impact of small particles. Generally, a satellite breakup will produce considerably more debris, both trackable and non-trackable, than an anomalous event. From one perspective, satellite breakups may be viewed as a measure of the effects of man's activity on the environment, while anomalous events may be a measure of the effects of the environment on man-made objects.

Source attribution began with an examination [2] of fragmentation candidates at or near this inclination. Fourteen breakup event candidates were identified by inclination, and these are presented in Table 1. Shaded cells indicate that the event is discarded from consideration based on altitude, event date, or other factors, and the "on-orbit" reference date is 4 July 2018.

Table 1. Source Candidates, Breakup Events

common name	international designator	public catalog number	launch date	breakup date	cataloged debris	on-orbit debris	apogee alt. [km]	perigee alt. [km]	inclination [deg]	assessed cause
COSMOS 1045 R/B	1978-100D	11087	26-Oct-78	9-May-88	42	32	1705	1685	82.6	PROPULSION
CASSIOPE R/B	2013-055B	39266	29-Sep-13	29-Sep-13	16	1	1490	320	81.0	PROPULSION
COSMOS 2157-62 R/B	1991-068G	21734	28-Sep-91	9-Oct-99	40	40	1485	1410	82.6	PROPULSION
COSMOS 1691 (1695)	1985-094B	16139	9-Oct-85	22-Nov-85	21	18	1415	1410	82.6	BATTERY
COSMOS 1275	1981-053A	12504	4-Jun-81	24-Jul-81	479	421	1015	960	83.0	BATTERY
COSMOS 1934	1988-023A	18985	22-Mar-88	23-Dec-91	3	3	1010	950	83.0	COLLISION, ACCIDENTAL
METEOR 2-16 R/B	1987-068B	18313	18-Aug-87	15-Feb-98	108	42	960	940	82.6	PROPULSION
METEOR 2-8	1982-025A	13113	25-Mar-82	29-May-99	53	53	960	935	82.5	UNKNOWN
METEOR 2-17	1988-005A	18820	30-Jan-88	21-Jun-05	45	45	960	930	82.5	UNKNOWN
METEOR 1-1 R/B	1969-029B	3836	26-Mar-69	28-Mar-69	37	0	850	460	81.2	UNKNOWN
STEP II R/B	1994-029B	23106	19-May-94	3-Jun-96	754	82	820	585	82.0	PROPULSION
COSMOS 1703 R/B	1985-108B	16263	22-Nov-85	4-May-06	50	2	640	610	82.5	PROPULSION
COSMOS 1869	1987-062A	18214	16-Jul-87	27-Nov-97	2	1	635	605	83.0	UNKNOWN
COSMOS 1906	1987-108A	18713	26-Dec-87	31-Jan-88	37	0	265	245	82.6	DELIBERATE

Table 2. Source Candidates, Anomalous Events

common name	international designator	public catalog number	launch date	breakup date	cataloged debris	on-orbit debris	apogee alt. [km]	perigee alt. [km]	inclination [deg]
COSMOS 206 R/B	1968-019B	3151	14-Mar-68	Nov-90	0	0	515	450	81.2
METEOR 1-7 R/B	1971-003B	4850	20-Jan-71	Jun-87	1	0	665	535	81.2
METEOR 1-12 R/B	1972-049B	6080	30-Jun-72	Sep-89	1	1	935	860	81.2
COSMOS 1043	1978-094A	11055	10-Oct-78	Feb-93	1	0	435	435	81.2
METEOR 2-5	1979-095A	11605	31-Oct-79	before 1-Jan-05	83	60	881	862	81.2
METEOR 2-7	1981-043A	12456	14-May-81	Mar-04	20	15	895	825	81.3
METEOR 2-7 R/B	1981-043B	12457	14-May-81	Oct-96	1	1	920	825	81.3
METEOR 2-17	1988-005A	18820	30-Jan-88	2000-2001	0	0	960	936	82.5
OKEAN 3	1991-039A	21397	4-Jun-91	12-Oct-98	1	0	655	620	82.5
BRIZ-KM R/B	2015-020E	40556	31-Mar-15	29-Apr-15	6	6	1342	1339	82.5
COSMOS 1417 R/B	1982-102B	13618	19-Oct-82	Early-09	1	1	1000	955	83.0
NADEZHDA 2 R/B	1990-017B	20509	27-Feb-90	22-Jun-05	1	1	1015	950	83.0

An additional 12 anomalous events at or near this altitude were observed, and these are presented in Table 2; again, shaded cells are disqualified from further consideration due to the same constraints as Table 1 events. At the current time, the two remaining anomalous events do not provide a compelling source to the observed, persistent cloud.

Of the four candidate breakup events, Cosmos 1275 (hereinafter C1275) and Cosmos 1934 (C1934) were, respectively, a battery-induced fragmentation and an accidental collision. Both utilized the Information Satellite Systems-Reshetnev (formerly the Scientific and Production Association of Applied Mechanics, NPO PM), KAUR-1 standard bus (Kosmicheskiy Apparat Unversalnogo Ryada-1, [Космический Аппарат Универсального Ряда]), which can be translated as Spacecraft Bus from the Standardized Line (Group)-1, and belonged to known satellite functional classes and regularly replenished constellations. The Meteor 2-8 meteorological spacecraft experienced a relatively minor breakup due to unknown cause. The Meteor 2-16 rocket body (R/B) was an SL-14 *Tsyklon* third stage, which has fragmented five times between 1988 and 2006; this event produced the most cataloged debris objects of the five. While the Meteor-related events appear to have occurred at or near the correct time in both orbit and the initial time of observation (FY1998), there is at present no logical framework that would account for the persistence of the cloud.

An examination of space traffic to the 81–83° inclination band, from 1960–2018 inclusive, indicates that the primary utilization of this band was between 1972 and 1998. A total of 465 resident space objects (RSOs) were launched by the USSR and the Commonwealth of Independent States, 23 by the U.S., and 14 by other agencies. The 502 RSOs can be further categorized by type or identity, as in Fig. 2.

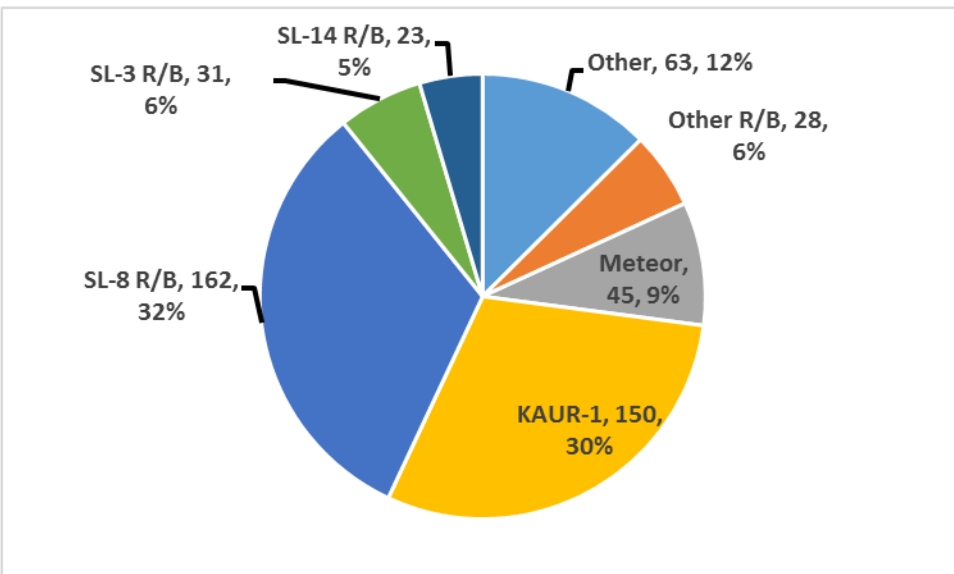

Fig 2. RSOs identified by bus (KAUR-1, Meteor), rocket body type, or as other. Numbers indicate absolute number and overall percentage of the space traffic ensemble.

Based on this distribution, KAUR-1 bus-type spacecraft and SL-8 rocket bodies, often lofting the KAUR-1 bus spacecraft, account for the majority of RSOs in this inclination band. The SL-8 rocket body (also designated the C-1 in the U.S. Library of Congress system and as the *Kosmos-3M*) has historically broken up twice on or near the launch date; as such, both events were likely propulsion-related. However, this stage is well known for unplanned, or inadvertent, maneuvers [3], likely due to outgassing, up to 22 years after launch. Because this mechanism is not fully understood, or the production of small debris is not positively correlated with such events, we discount the SL-8 from further consideration in this study. We, however, reserve the right to further assess likely breakup progenitors pending further measurements and analysis.

The next most numerous category is those spacecraft using the KAUR-1 bus. The majority served as navigation and store-dump communications spacecraft supporting all, or in part, the launches of the *Zaliv*, *Parus*, and *Tsikada* programs and, with the addition of search and rescue transponders, the *Nadezhda* program. In addition, they also facilitated the *Sfera* geodysy and Informator prototype communications programs in this inclination band. KAUR-1 bus spacecraft typically have a mass of approximately 900 kg, and the body consists of a 2 m-diameter cylinder with lengths of 2 m to 3 m. Attitude control is maintained via an extended gravity gradient boom. On-board stored energy sources are known to include the battery subsystem and a pressurized main instrument compartment. The instrument compartment is surrounded by a cylindrical solar array. A typical spacecraft is depicted, in partial cross-section, in Fig. 3.

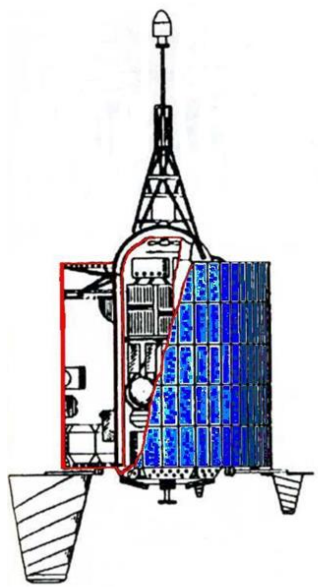

Fig 3. A typical KAUR-1 bus spacecraft, cross-sectioned to display the inner, pressurized instrumentation compartment. The cross-sectioning planes are indicated by a red line. The gravity gradient boom is shown in a launch/stowed position, adapted from [4].

Given the number of KAUR-1 bus spacecraft in this inclination bin and at the correct altitude, and a demonstrated history of both explosive and collisional breakup events, the authors chose to model the 82° cloud using this spacecraft as a possible progenitor.

3 MODELING

Without a specific source, modeling the event requires that a model object is generated with orbital elements that guarantee the debris produced is in the correct location. In this paper, we consider such an object in a circular orbit at an altitude of 1010.28 km, an inclination of 82.955°, and a mass of 810 kg. This orbit is similar to C1934's but we are not presuming or positively identifying C1934 as the source of this cloud.

To produce a debris model from a low-velocity event requires modifications to the NASA Standard Satellite Breakup Model (SSBM) [5]. In general, the SSBM assumes the mass distribution of a given breakup event is a double-Gaussian distribution that was fit to ground-based test data and two line element set-derived area-to-mass ratio data, and the velocity of each fragment is drawn from a log-normal distribution [5]. In addition, the breakup model assumes two separate velocity distributions, one applicable to explosive events and one applicable to collision events.

$$D_{\Delta v}^{exp}(\chi,\nu) = N(\mu^{exp}(\chi), \sigma^{exp}(\chi), \nu) \quad (1)$$

$$\mu^{exp} = \text{mean} = 0.2\chi + 1.85 \quad (2)$$

$$\sigma^{exp} = \text{standard deviation} = 0.4 \quad (3)$$

$$\nu = \log_{10}(\Delta V) \quad (4)$$

$$\chi = \log_{10}(A/m) \tag{5}$$

where A is the average cross sectional area, m is the mass, and ΔV is the relative velocity.

The velocity distribution in Eq. 1 is a generic fit applicable to energetic explosion events, but the event considered here is explicitly a non-energetic event. Therefore, the maximum allowed value of the relative velocity in the SSBM explosion model, Eq. 4, was lowered to 10 m/s and the subsequent log-normal distribution was adjusted to have a standard deviation, Eq. 3, of 0.04 from 0.4 to ensure that more fragments have velocities closer to the mean. This is consistent with what is expected from a non-energetic event because such an event has no external forces acting upon it, and therefore the vast majority of fragments will have the same velocity as the parent object at the time of release.

In addition to modifying the SSBM velocity distribution for the non-energetic debris events, the production of the debris had to be modeled in a reasonable way. To generate the low-velocity debris it was assumed that some percentage of the mass of the test spacecraft was lost each year, and that the lost mass was assumed to have followed the standard mass distribution of the SSBM with the modified velocity distribution. For each year, from 2004 to 2014, it was assumed that 5% of the remaining mass of the test satellite was shed.

After generating the debris cloud, the modeled event was converted to a detection rate (number of detections per km per hour) that a HUSIR-like radar system would see for a meaningful comparison to be made to the radar data. The results for two size thresholds (≥5.6 mm and ≥1.0 cm) are shown below. Note that the radar data here is broken into a specific inclination band, 80–93°, which allows a more detailed comparison to be made to the modeled event.

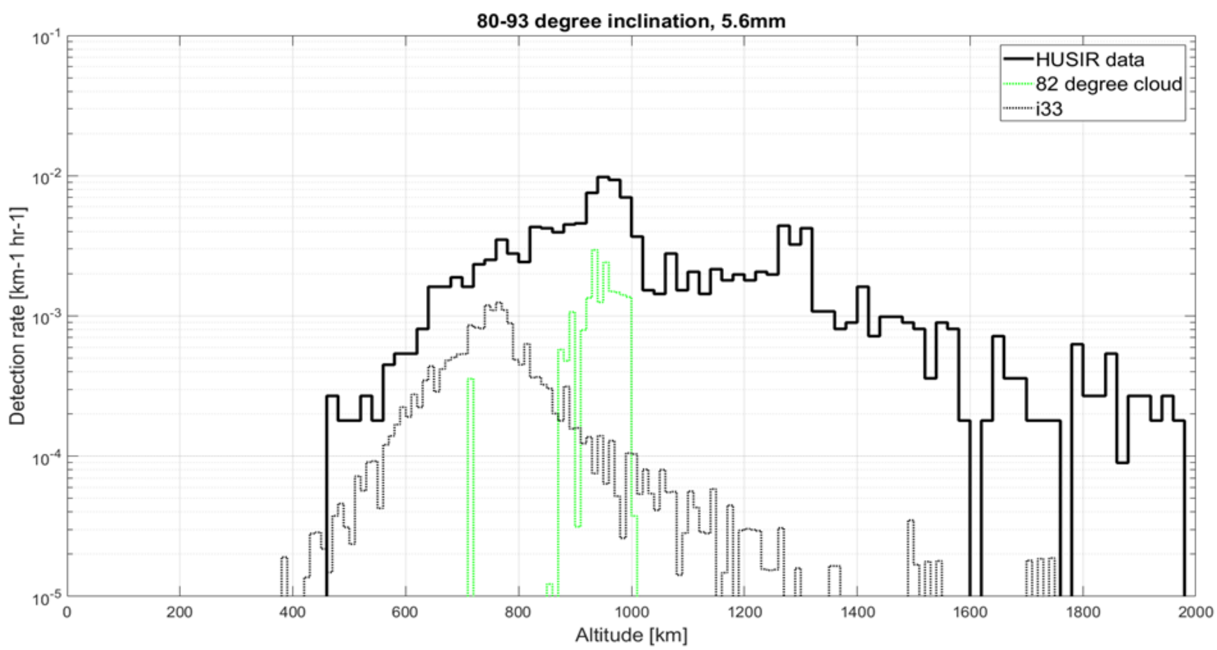

Fig 4. The ≥5.6 mm-composite HUSIR data overlaid with the 82° breakup cloud and the Iridium 33 (I33) breakup cloud data.

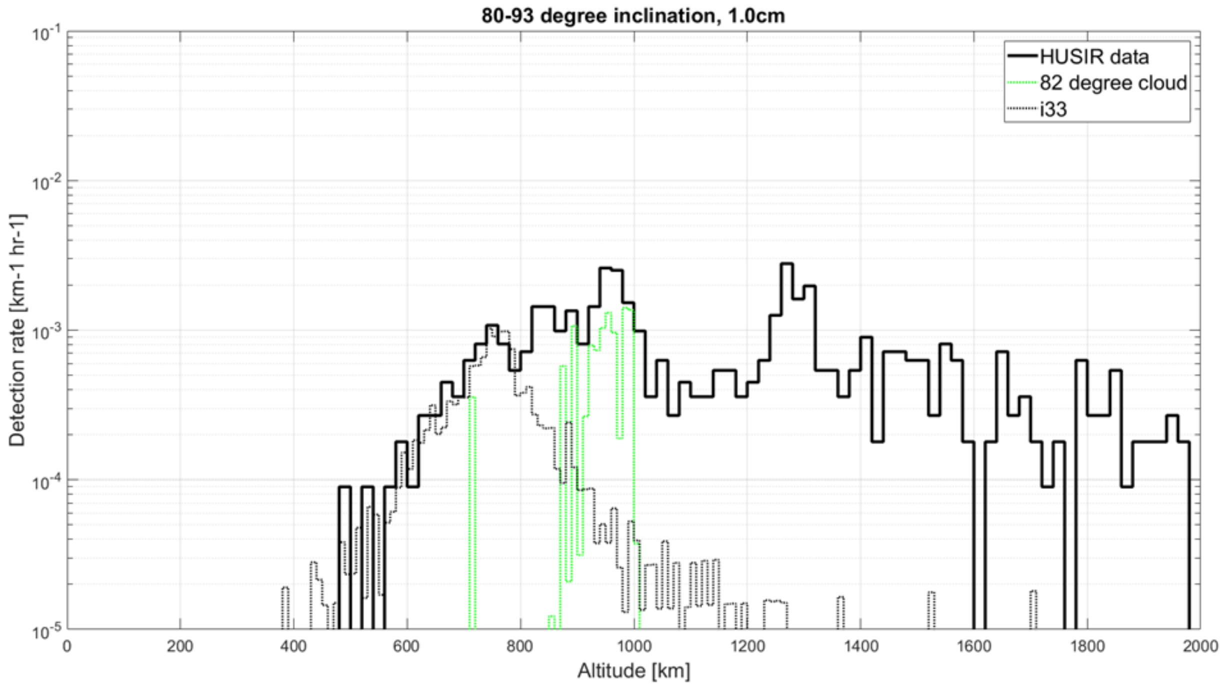

Fig 5. The ≥1.0 cm-composite HUSIR data overlaid with the 82° breakup cloud and the I33 breakup cloud data.

From Figs. 4 and 5, one can see the modeled cloud overlaid with the radar data. In addition, the contribution from the Iridium 33 (I33) cloud is shown to demonstrate that the cloud seen in the HUSIR data is not from that event and to show how the modified, low-energy 82° debris cloud compares to a highly energetic breakup cloud. As expected, more fragments in the 82° cloud are detected closer to the source. From those charts, it can be seen that the modeled cloud produces a result that is in good agreement with the actual data at 1 cm and at 5.6 mm.

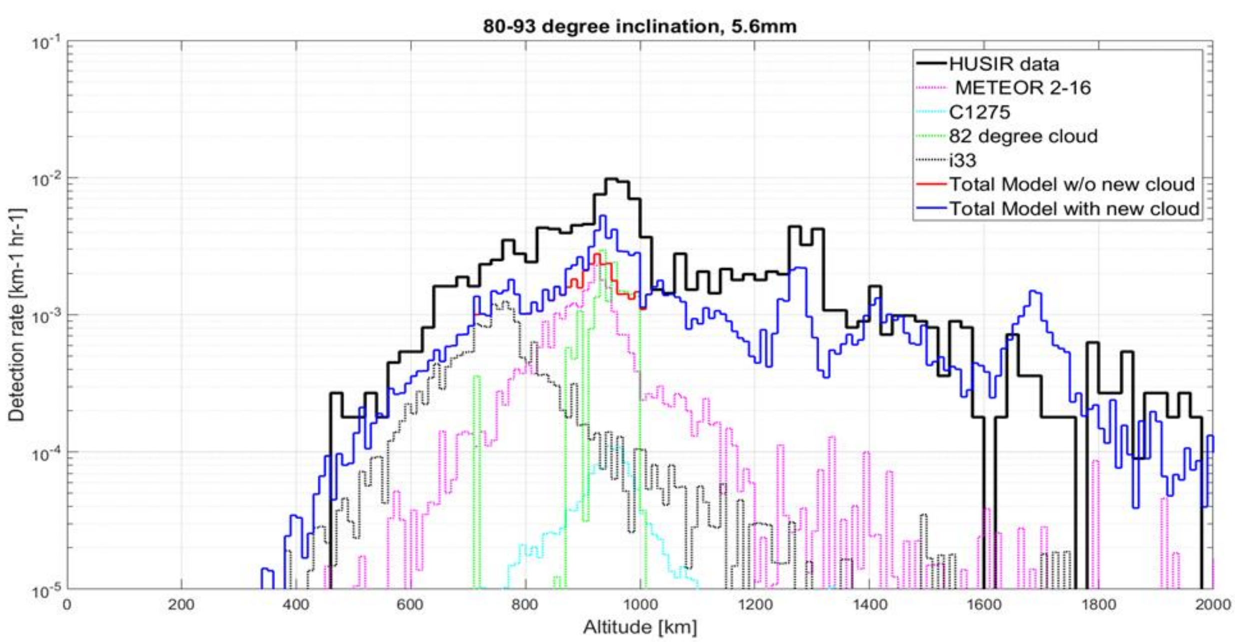

Fig 6. The ≥5.6 mm-composite HUSIR data overlaid with the 82° breakup cloud, the I33 breakup cloud, the C1275 breakup, and the Meteor 2-16 breakup data, including the total contribution of the new cloud to the model.

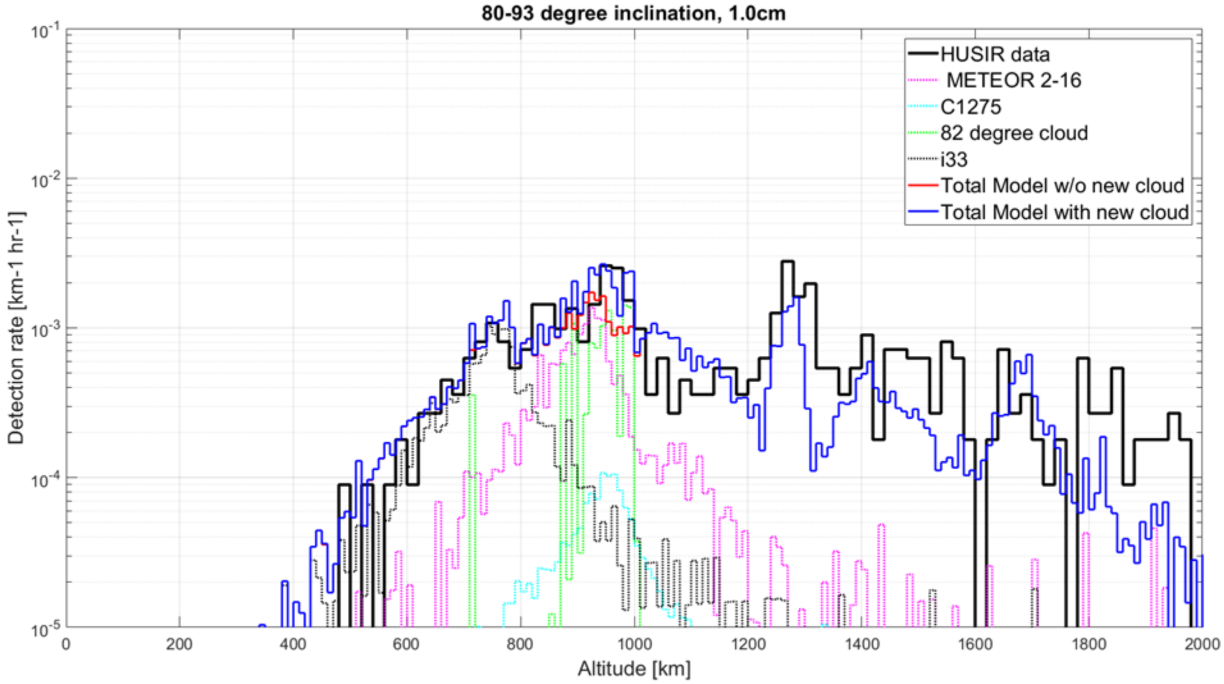

Fig 7. The ≥1.0 cm-composite HUSIR data overlaid with the 82° breakup cloud, the I33-breakup cloud, the C1275 breakup, and the Meteor 2-16 breakup data, including the total contribution of the new cloud to the model.

Note, that while the ≥5.6 mm-size cloud looks low, this is consistent with the I33 cloud. In actuality the debris at 5.6 mm (and smaller) has significant contributions from other sources, *i.e.*, too good of a "fit" to the radar data at 5.6 mm actually would produce too much debris. From Figs. 6 and 7 we can see the effect the new breakup cloud has on the total modeled cloud in the 80–93° inclination band. At 5.6 mm and larger, the model is a better fit to the data after inclusion of the new cloud.

4 DISCUSSION & CONCLUSIONS

In Figs. 4–7, one can see the modeled cloud overlaid with the radar data. In addition, the contribution from the I33 cloud is shown to demonstrate that the cloud seen in the HUSIR data is not from that event and to show how the modified, low-energy 82° debris cloud compares to a highly energetic breakup cloud. From those charts, it can be seen that the modeled cloud produces a result that is in good agreement with the actual data at 1.0 cm and at 5.6 mm. Note, that while the ≥5.6 mm-size cloud looks low, this is consistent with the I33 cloud. In actuality the debris at 5.6 mm (and smaller) has significant contributions from other sources, i.*e.*, too good of a "fit" to the radar data at 5.6 mm would actually produce too much debris. Therefore, we conclude it is likely that the 82° debris cloud is a low velocity, non-energetic event because the model of such an event produced a very good match to available data. Future radar observations will provide additional evidence for this hypothesis and help the NASA Orbital Debris Program Office determine if this cloud needs to be included as a separate event in future debris models.

5 REFERENCES

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