Open Source Analysis of Iridium Failures and the Implications for Big LEO Constellations

Spacecraft Anomalies and Failures (SCAF) 2017 Workshop

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Overview

• Iridium Constellation and Spacecraft Background
• Analysis Methodology and Terminology
• Analysis Results and Discussion
• Implications for Big LEO Constellations
• Post Mission Disposal Plan “B” Importance, Options, and Suggestions
• Reference Sources/Notes
Iridium Background

- Satellite telephony network of 66 satellites (95 launched)
- Launched to orbit in the late 1990s
- Orbit: 485 mi (781 km) and inclination of 86.4°
- 6 orbital planes, spaced 30 degrees apart, with 11 satellites in each plane (not counting spares)
- 95 satellites launched in total (including spares)
Iridium LM-700A Bus

- 3-axis stabilized
- Hydrazine propulsion system
- Power was supplied by two solar panels with 1-axis articulation
- L-Band using FDMA/ TDMA to provide voice at 4.8 kbps and data at 2400 bps with 16 dB margin
- 48 spot beams for Earth coverage
- Ka-Band for crosslinks and ground commanding
- 4 inter-satellite links: 1 each to neighbors fore and aft in the same orbital plane, and 1 each to satellites in neighboring planes to either side
- Orbit from pole to same pole with an orbital period of roughly 100 minutes
- 7 Motorola/Freescale PowerPC 603E processors running at roughly 200 MHz
- 1 processor is dedicated to each cross-link antenna ("HVARC"), and 2 processors ("SVARC"s) are dedicated to satellite control, 1 being a spare. Late in the project an extra processor ("SAC") was added to perform resource management and phone call processing.
- Design Life: 8 years
- Length: 4.00 m (13.10 ft)
- Diameter: 1.30 m (4.20 ft)
- Mass: 689 kg (1,518 lb)

Credit - Lockheed-Martin.
Class: Communications.
Manufacturer: Motorola, Lockheed.
Analysis Methodology

Underlying Question: “If Iridium issues occurred to satellites at Big LEO altitudes (i.e. 1000km), could the satellite still comply with the 25-year post-mission disposal guidelines?”

1. Use Open Source Data
2. Validate results with SME’s
3. Look at data through the first launch of Iridium Next (i.e. evaluate Iridium’s first constellation only)
4. When in doubt – assume compliance
5. Do not negatively consider collisions with other satellites
6. Expect the results of this methodology to lead to optimistic failure data – it is human nature to under-report failures
Terminology

1. Failed Satellite = A satellite unable to deorbit itself within 25 years of end of life (if it were at Big LEO altitudes)
2. P = Partially Active (could have issues with its primary payload, however no reports of propulsion/control issues – it can maintain orbit and point)
3. D = Failed and Decayed
4. T = Tumbling (uncontrollable, unable to deorbit)
Operational Satellites

<table>
<thead>
<tr>
<th>Planes</th>
<th>Orbital Slots within a Plane</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plane 1</td>
<td>21 72 75 70 62 14 64 65 66 67 68 74p</td>
</tr>
<tr>
<td>Plane 2</td>
<td>22 94 76 25 23p 46 47 20 49 11 3</td>
</tr>
<tr>
<td>Plane 3</td>
<td>55 95 45 31 30 32 91 58 59 60</td>
</tr>
<tr>
<td>Plane 4</td>
<td>19 34 35 97 5 6p 7p/51p 8 96 37 61</td>
</tr>
<tr>
<td>Plane 5</td>
<td>50 56 52 53 84 10 54 12 13 83 86 90</td>
</tr>
<tr>
<td>Plane 6</td>
<td>18 98 40 15 80 77 81 82 41 43</td>
</tr>
</tbody>
</table>

Legend:
- **Green:** Active Satellites
- **Yellow:** Partially Active Satellites

67 Active or Partially Active Iridium Satellites through 1H17
Non-Operational Satellites

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<tr>
<td>Plane 1</td>
<td>73t 63</td>
</tr>
<tr>
<td>Plane 2</td>
<td>69t 24t 71t 26 48d</td>
</tr>
<tr>
<td>Plane 3</td>
<td>28 29 33t 57 27d</td>
</tr>
<tr>
<td>Plane 4</td>
<td>4 36t</td>
</tr>
<tr>
<td>Plane 5</td>
<td>2t 914t 911t 16t 85d 9d</td>
</tr>
<tr>
<td>Plane 6</td>
<td>920t 921t 44t 38t 17t 42t 39 79d</td>
</tr>
</tbody>
</table>

Legend:
- **Red**: Tumbling (t) or Failed and Decayed (d) Satellites (counted as failed)
- **Orange**: Satellite Destroyed by Collision (not counted as failed)

20 Failed Iridium Satellites through 1H17
Analysis Summary (as of 1H17)

1. **95** Satellites launched
2. **67** Satellites Operational (or Partially Operational)
3. **1** Collision
4. **7** Satellites at end of life and still capable of end of life deorbit maneuvers
5. **20** Failed Satellites

21% of Iridium Satellites would have been stranded at Big LEO altitudes
Iridium Failure Rate Thoughts

• Failure rate likely driven by dramatically exceeding design lifetime
  • 19 years into an 8 year mission...

• Some reasons why Iridium kept its first constellation running for so long include:
  • Slower than planned market uptake
  • Financial difficulties/delays (including bankruptcy)
  • Delays in 2nd generation satellite design and production
  • Launch provider delays

Many of these challenges have been historically common with new satellite services
Big LEO Constellation Implications

• Over 8000 new satellites announced to be launched over next decade

• Performing important missions – valuable to the US economy and national security, and humanity as a whole

• All Constellations are targeting high reliability, but...

• If their failure rate was similar to Iridium:
  • 21% of 8000 would imply up to 1,680 additional Failed Satellites
  • This would approximately double the number of large debris objects (>100kg) in LEO

To remain long-term viable Big LEO Constellations need to be much more reliable at Post Mission Disposal than Iridium’s first constellation
The Need for a Plan “B”

• Big LEO’s Plan “A” = High propulsion system reliability with propellant reserves for end of life disposal

• This is a Good Plan “A”, but what when Plan “A” does not work?
  • At 1000-1400km altitudes, failed satellites would remain for centuries
  • Most of that time would be spent drifting through their constellation’s operational orbits and that of neighboring Big LEO constellations

• There are potential backup methods for deorbit if Plan “A” fails:
  • On-board backup end of life propulsion systems
  • Deorbit tug services

Responsible Big LEO Constellations Should Have a Plan “B”
Characteristics of Plan “B” Options

1. On-board Backup End of Life Propulsion Solutions
   - (+) No Rendezvous/Proximity Operations (RPO) required
   - (-) Most passive solutions (drag sails, balloons, etc.) don’t work well at 1000+km
   - (-) Applies solution to full Constellation, even though only failed satellites need this
   - (-) Front loaded costs (Pre-Revenue)

2. Deorbit Tug solutions
   - (+) Back loaded cost
   - (+) Can enable other satellite servicing (life extension, upgrades, etc.)
   - (-) RPO is still considered a high-risk operation
   - (-) Sophisticated robotics have historically driven cost per deorbit above what constellation operators might want to pay
BullDog Satellite Servicing
Design for Cooperative Servicing/Deorbit Aids

- **Optical Fiducials**
  - Passive systems that simplify RPO, providing easier machine vision targets
  - GSFC fiducial decals, Altius DogTags™

- **Grappling Fixtures**
  - Make it easier to grapple a failed spacecraft than relying on existing s/c features
  - MDA Grappling Fixtures
  - Altius DogTags™
    - <250g, $1000 installed cost
    - Grappleable with a wide range of technologies (magnets, mechanical, electroadhesion, gecko adhesion, harpoons, etc.)

- **GSFC Cooperative Servicing Valves**
  - Satellite fill/drain valves designed for easy robotic interfacing
  - Same size, weight, cost, sealing redundancy, and interfaces as traditional fill/drain valves
  - Designs in testing at GSFC for Xenon, Hydrazine, and most other standard satellite propellants
What’s your Plan B?

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Sources

2. www.ucsus.org/nuclear_weapons_and_global_security/space_weapons/technical_issues/ucs-satellite-database.html
3. www.satobs.org
5. http://www.n2yo.com/satellites/?c=15
10. www.spaceflightnow.com/delta/d290/status.html

Note – due to the focus of our research (open source research into Iridium failures), Altius is unclear if all of the notes that follow (slides 18-24) are 100% generated by Altius Space Machines. It is possible some of the notes section was copied from these sources above. Altius is interested in the results of the analysis and by no means attempting to claim the work of others as its own. Our sincerest apologies if any of these notes are plagiarized in any way.

Regardless, Altius owes a debt to these sources above, without which, Altius could not have performed the analysis contained in this deck.
Notes (1)

1. In their quarterly report dated 30 June, 2016, Iridium Satellite LLC acknowledged the failure of two satellites in the preceding quarter year.

2. In June 2016, Iridium 15 (24869, 1997-034A) was moved from Plane 6, Slot 7 to Plane 6, Slot 4, replacing Iridium 39 (25042, 1997-069D). The intention may have been to swap over the two satellites but, in any case problems were experienced with Iridium 39, which was then removed from the operational constellation, leaving a gap at Plane 6, Slot 7. No spare was available to replace it.

3. In May 2016, Iridium 57 (25273, 1998-019B) began to drift away slowly from its nominal position (Plane 3, Slot 8) and has presumably failed. See Iridium 57 looks to have a bad attitude.

4. In the middle of 2015, Iridium 45 (25104, 1997-082A) which had been migrating from orbital plane 2 towards orbital plane 3 for about 14 months, arrived in orbital plane 3. It appears to have already been in operational use as part of orbital plane 3 for some months previously, even though it was not in its final orbital location (Plane 3, Slot 3).

5. In early December 2014, Space-Track catalogued four items of debris (40324-40327, 2002-05G to 2002-05K) associated with the 2002-05 launch. These are labelled by Space-Track as "IRIDIUM 91 DEB", and seem to be associated with Iridium 91 (27372, 2002-005A) which appears, however, to remain fully operational.

6. In early October 2014, Iridium 51 (25262, 1998-018A), which had been paired with Iridium 7 (24793, 1997-020B) was moved within orbital plane 4 to be paired with Iridium 6 (24794. 1997-020C).

7. At the end of August 2014, Iridium 14 (25777, 1999-032A), which had been spare in orbital plane 1 since launch, was raised to operational altitude to replace Iridium 63 (25286. 1998-021B), which had presumably failed.
8. At the end of August 2014, Iridium 98 (27451, 2002-301B), which had been spare in orbital plane 6 since migrating from plane 4, was raised to operational altitude a few seconds behind Iridium 42 (25077, 1977-077) which had presumably failed. Iridium 42 has since been reported to be flashing.

9. By early 2014, Iridium 45 (25104, 1997-082A) was no longer maintaining its place in orbital plane 2, and was evidently migrating towards orbital plane 3. Its place in orbital plane 2, slot 5 was taken by Iridium 23 (24906, 1997-043D).

10. By early 2014, Iridium 29 (24944, 1997-051A) had ceased to maintain its position in the constellation, and had presumably failed. At that time, there was no spare available in plane 3 to replace it.

11. On 20 November, 2012, Iridium 96 (27376, 2002-005E), previously spare in orbital place 3, began migrating towards orbital plane 4, which had no on-orbit spare. This left orbital place 3 without a spare. The migration took around twelve months. Iridium 96 took over from failed Iridium 4 (24796, 1997-020E). Iridium 96 was raised to operational altitude several months before its arrival in plane 4 and appears to have been brought into use at that time.

12. On 13 November, 2012, Iridium 94 (27374, 2002-005C), which had been migrating over the past year from orbital place 3, arrived at orbital plane 2, and was immediately raised to operational altitude to replace Iridium 23 (24906, 1997-043D) which had evidently failed, though retaining at least some functionality. Iridium 23 initially remained at operational altitude a few seconds behind Iridium 94, but was later used to replace Iridium 45 (25104, 1997-02A).

13. In mid 2012, Iridium 4 (24796, 1997-020E) ceased to maintain its position in the constellation. At that time, Plane 4 had no on-orbit spare.

14. In late July 2012, Iridium 51 (25262, 1998-018A), which had been out of the operational constellation for many years, was moved in the position previously occupied by Iridium 7 (24793, 1997-020B), while Iridium 7 was moved to follow slightly behind it. The two satellites were each providing some of the functionality for the given slot. Orbital Plane 4 has no other spare satellite.
Notes (3)

15. In early August 2011, Iridium 11 (originally 25577, 1998-074A, but currently labelled by Space-Track as 25578, 1998-074B), which had apparently taken over from Iridium 23 (24906, 1997-043D) in November 2010, was moved around the plane, evidently to take over from Iridium 26 (24903, 1997-043A).

16. This suggests that Iridium 26 must have failed on station, and also that Iridium 23 retained some functionality.

17. Orbital Plane 2 had no other spare satellite, but Iridium 94 (27374, 2002-005C) was in process of migrating from Orbital Place 3.

18. In early November 2010, Iridium 11 (originally 25577, 1998-074A, but currently labelled by Space-Track as 25578, 1998-074B), previously spare, was raised to the operational orbit, just a few seconds behind Iridium 23 (24906, 1997-043D). This suggests that Iridium 23 must have failed on station, but possibly only partially.

19. In early March 2009, Iridium 91 (27372, 2002-005A) [note that some sources still label this satellite as Iridium 90] was raised to the operational orbit to fill the gap left by the loss of Iridium 33.


21. In late July 2008, Iridium 95 (27375, 2002-005D), up till then a spare satellite in orbital plane 3, entered the operational constellation, evidently to replace Iridium 28 (24948, 1997-051E). Initially, Iridium 28 remained close to its nominal position in the constellation, so had presumably failed on station.
22. (January 2008) Iridium 90 [previously labelled as Iridium 91] which had been maneuvering since mid October 2005, has arrived in orbital plane 5

23. (May 2007) Iridium 98, which had been maneuvering since late June 2005, has arrived in orbital plane 6

24. In early January 2007, Iridium 97 (27450, 2002-031A), a spare satellite in orbital plane 4, entered the operational constellation, evidently to replace Iridium 36 (24967, 1997-056C). Iridium 36 initially remained close to its nominal position in the constellation - it had evidently failed on station.

25. On or about January 10, 2006, Iridium 21 (25778, 199-032B), one of two spare satellites in orbital plane 1, was raised to operational altitude, presumably to replace Iridium 74 (25345, 1998-032B), which was lowered to the engineering orbit. It is unclear whether Iridium 74 has failed completely.

26. On January 1, 2006, the Spacecom labelling of Iridium 90 and Iridium 91 was interchanged. There was no change to the operational constellation.

27. In August 2005, Iridium 17 evidently failed, and Iridium 77 took its place in the operational constellation. This left orbital plane 6 without a spare satellite.

28. In April 2005, Iridium 16 was removed from the operational constellation, and subsequently Iridium 86 took its place in the operational constellation. This left orbital plane 5 without a spare satellite.
Notes (5)

29. On January 29, 2004, the OIG/Spacecom labelling of Iridium 11 and Iridium 20 was interchanged.

30. There was no change to the operational constellation.

31. Iridium 82 replaced Iridium 38 in orbital plane 6 on or about September 17, 2003.

32. Iridium 30 and 31 exchanged places in the constellation on September 19-22, 2002.

33. 2 further spares (Iridium 97 and 98) were launched at 0933 UT on 20 June 2002 from Plesetsk Cosmodrome by Eurockot. This launch was directed at orbital plane 4. Iridium 98 was subsequently moved to orbital plane 6.

34. 5 additional spare Iridium satellites (Iridium 90, 91, 94, 95 and 96) were launched from Vandenberg AFB aboard a Delta II rocket on 11 February 2002 at 17:43:44 UT. The originally intended launch on 8 February 2002 at 18:00:30 UT was scrubbed at the last moment, while the launch opportunities on 9 February 2002 at 17:54:55 UT and 10 February 2002 at 17:49:19 UT also had to be scrubbed. See http://www.boeing.com/news/releases/2002/q1/nr_020211s.html and http://spaceflightnow.com/delta/d290/status.html for more details on the launch. This launch was directed at orbital plane 3, which previously had no spares. Perhaps surprisingly, there was initially no indication that it was intended to drift some of the spares to other orbital planes. However, Iridium 90 (initially labelled as Iridium 91) was subsequently moved to orbital plane 5, and Iridium 94 was later moved to orbital plane 2. Iridium 96 is now being moved towards plane 4.

35. Iridium 5 and Iridium 51 were confused during August 2001.
The previous change to the operational constellation was the replacement of Iridium 9 by Iridium 84.

Iridium 2 has drifted far from its original orbital plane (as have several of the tumbling satellites). At one time, it was deliberately allowed to drift to become the spare in another plane (plane 4?), but it evidently failed on arrival in the new plane, and continues to drift out of control.

At the Iridium Satellite LLC press conference call on 12 December 2000

(see http://www.ee.surrey.ac.uk/Personal/L.Wood/constellations/iridium/conference-call-Dec-2000.html), a figure of 8 operational spares was quoted. This would include Iridium 82, 84 and 86 which have since become operational.

Also at the Iridium Satellite LLC press conference call on 12 December 2000

(see http://www.ee.surrey.ac.uk/Personal/L.Wood/constellations/iridium/conference-call-Dec-2000.html), plans were announced to launch further spare satellites for the constellation:

"We'll be launching seven more in the next year or so. We have the first launch scheduled for next June, June of 2001. That will be a Delta 2 launch; we'll be putting five spare satellites into orbit. The following spring, roughly March of 2002, we'll be launching two more and in that case we'll be using the Russian rocket. So we will inject seven more spares into the system, so we'll have more than two spares in each orbit, and that will give us the life that we believe is there"
Notes (7)

43. These launches were in fact delayed until 2002.
44. Iridium 79 (25470, 1998-051D) decayed on 29 November 2000
45. (see http://www.satobs.org/seesat/Nov-2000/0256.html),
46. Iridium 85 (25529, 1998-066C) decayed on 30 December 2000
47. (see http://www.satobs.org/seesat/Dec-2000/0409.html),
48. Iridium 48 (25107, 1997-082D) decayed on 5 May 2001
49. (see http://www.satobs.org/seesat/May-2001/0028.html), and
50. Iridium 27 (24947, 1997-051D) decayed on 1 February 2002
51. (see http://www.satobs.org/seesat/Feb-2002/0002.html)
52. Iridium 9 (24838, 1997-030C) decayed on 11 March 2003
53. (see http://www.satobs.org/seesat/Mar-2003/0116.html)
54. Iridium 11 (until recently referred to by OIG as Iridium 20), Iridium 14, Iridium 20 (until recently referred to by OIG as Iridium 11) and Iridium 21 are the second (i.e. replacement) satellites known by those names. They were previously known as Iridium 20a, Iridium 14a, Iridium 11a and Iridium 21a respectively.
55. Iridium 911, Iridium 914, Iridium 920, Iridium 921 are the (failed) satellites originally known as Iridium 11, Iridium 14, Iridium 20 and Iridium 21 respectively.
56. Iridium 21, 27, 20, 11, 24, 71, 44, 14, 79, 69 and 85 all suffered from issues before entering operational service soon after their launch in 1997.