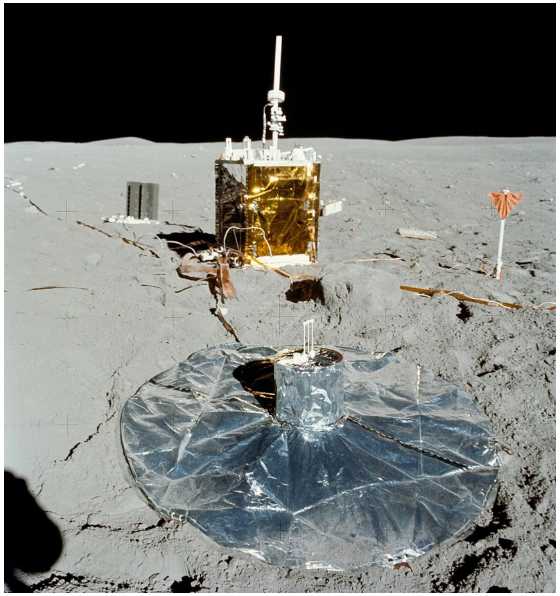
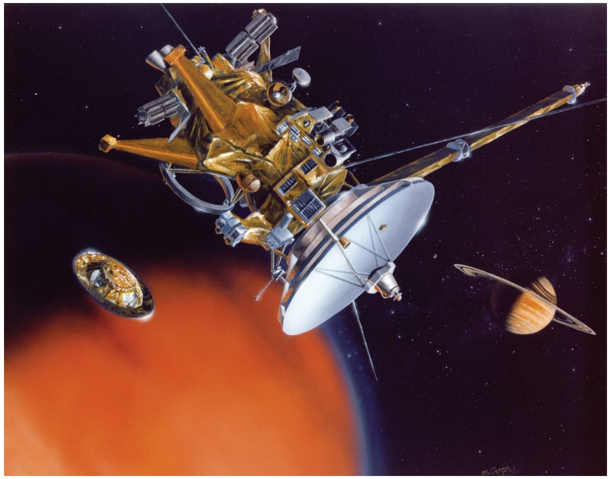
FURTHER OUT:
KEEPING TRACK OF DEEP SPACE OBJECTS

Jonathan McDowell





CENTER FOR ASTROPHYSICS
HARVARD & SMITHSONIAN

https://planet4589.org/space/deepcat/index.html

I will use the term **Deep Space** to mean:

- Earth orbit beyond 150,000 km or so (DEO, Deep Earth Orbit)
- Everything beyond - Moon, Lagrange points, solar orbit, other worlds

(c) Paramount

Keeping track:

The short answer – we can’t.
BUT we can know what we sent out there and which way it was heading when last seen
AND that can be helpful.
I’ve made a list!

In Near Space (in Earth orbit below about 50,000-150,000 km altitude) things are relatively OK

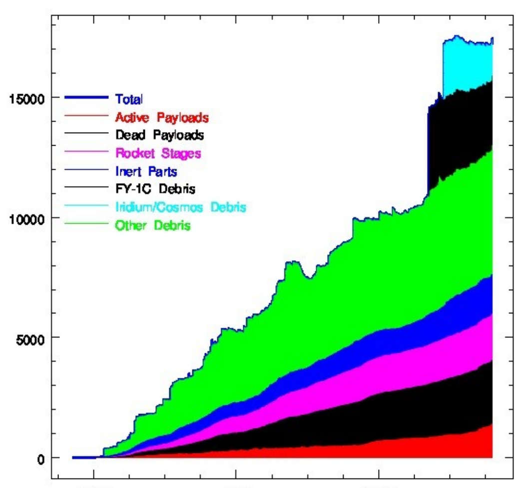
The US DoD (specifically, USAF 18 SPCS) attempts to catalog orbiting objects
- In LEO, attempt to be complete to about 10 cm size
- Less complete at high altitudes

Active tracking of passive debris objects
- Ground based radar for LEO objects (but F ~ 1/r **4)
- Ground based optical telescopes for GEO objects
- Space based optical telescopes coming on line to supplement these

Russian network also operational but thought to be not as capable for small debris
Russian-led ISON network **more** complete for GEO objects?
European SSA still at experimental stage
Independent hobbyists provide orbit data for US secret objects

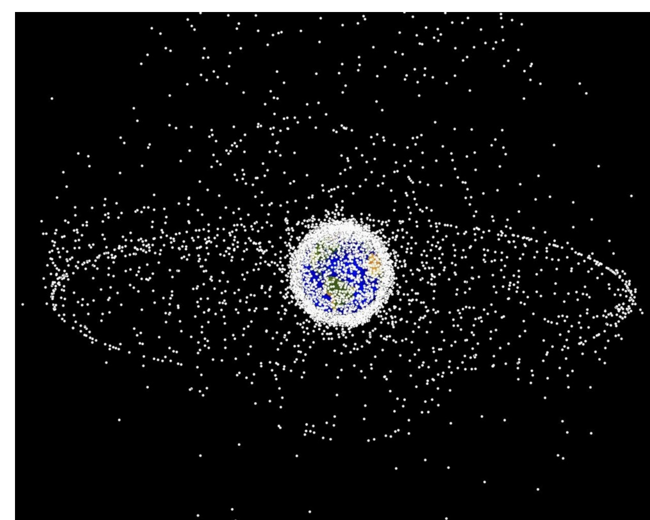
Summary: There are problems, but overall

our knowledge of artificial objects below 50000 km is in pretty good shape
Above 150,000 km it is very poor



McDowell 2018

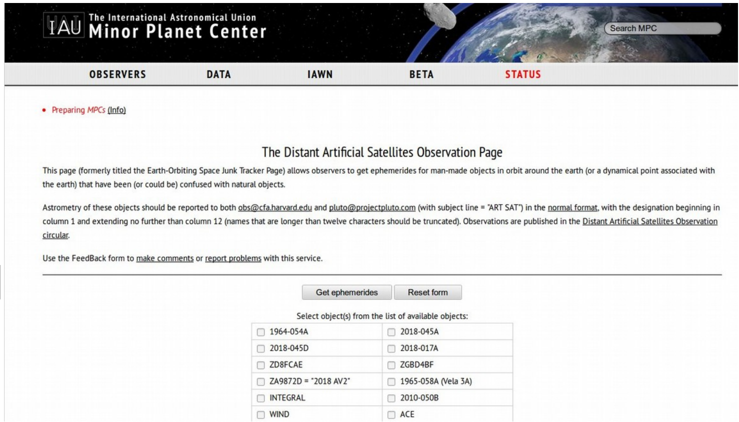
NASA
ODPO



In contrast, **beyond 150,000 km**:

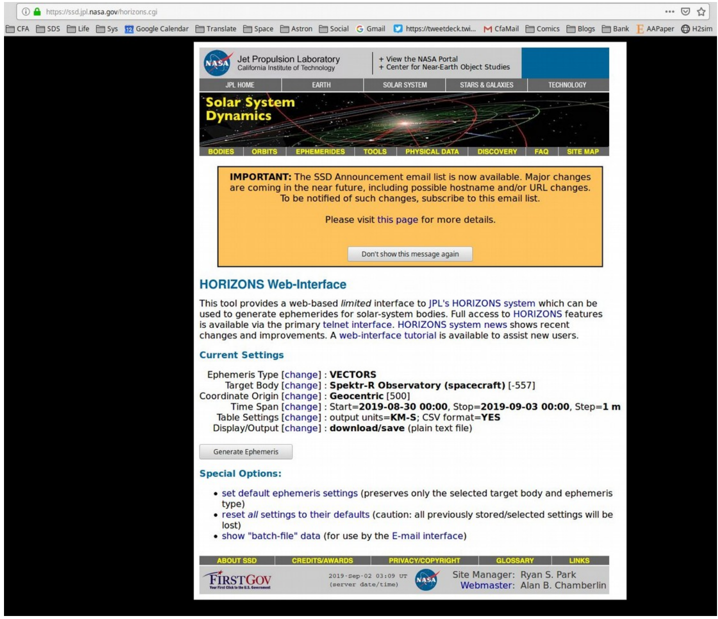
No-one is responsible for keeping track

The **US does a half-hearted job** on deep Earth orbit (DEO) objects
Enters some but not all known Earth escape objects in the satellite catalog with no orbital data.



Near-Earth Asteroid **astronomers accidentally find** DEO and some Earth escape objects. Small **unfunded** group keeping track of a subset to avoid confusion with real asteroids. (Gareth Williams, IAU MPC; Bill Gray, Project Pluto)

Active deep-space probes tracked by their operators. But **no systematic archive for this data once they are dead**.



JPL HORIZONS (Jon Giorgini) provides ephemerides and orbit data for a subset of active and dead probes: basically the ones JPL tracks or tracked (and didn't throw away the data). An immensely valuable contribution but **incomplete**.

It's all very patchy!

Why do I care?

- Historical interest. We may run into these things again in centuries to come.

- **The inner solar system in 20 years will be like LEO/GEO today** – even if asteroid mining *doesn't* take off. More nations are sending probes to deep space. Commercial missions are already beginning. This will need governance. **Governance needs situational awareness**.

- **Astronomical confusion**. They look like asteroids when they return to Earth's vicinity
    Example: Asteroid J002E3 turned out to be the Apollo 12 SIVB stage.
    Recaptured through SEL1 and spent a year orbiting Earth before departing again

- Earth departure states are often not accurate enough to reliably predict current location of a probe launched years ago. But if it is accidentally rediscovered, having the old orbit is enough to confirm its identity.

- **Planetary protection** concerns

- What about the **Registration Convention**? In practice, states never worried about the deep space stuff. But there is no reason this should be the case: everyone is technically in violation (Art. IV 1(d), "basic orbital parameters" does not specify Earth orbit.) .

Credit: The Expanse

The Deep Space Catalog

I have compiled **a catalog of over 1000 artificial objects in `deep space'** by which I mean:
Anything beyond EL1:4, 152000 km from the center of the Earth.

At this radius a satellite's orbital period is ¼ of the Moon's. That's a nice boundary because it's about where you can no longer pretend for long that you're in a simple Keplerian orbit. But yes, it's pretty arbitrary. The main point is that it's beyond where DoD bothers to track things systematically.

The catalog, available at https://planet4589.org/space/deepcat, includes:
- Object ID and launch information
- Each Hill sphere transition date for the object (Earth to Sun, Sun to Mars etc)
- Approximate orbital data for each such phase (**peri, apo, inc**)

The intent is that this first version of the catalog will be succeeded by a **future release** in which **full orbital elements** or state vectors will be provided where possible.

D00998	S43458	2018-042B	2018 May 5	MarCO-A	Mars Cube One	NASA/JPL	US	13.500	13.500	0.200	0.800	0.300
D00999	S43459	2018-042C	2018 May 5	MarCO-B	Mars Cube One	NASA/JPL	US	13.500	13.500	0.200	0.800	0.300
D01000	A09124	2018-042A	2018 May 5	Mars InSight Cruise Stage	Mars InSight Cruise Stage	NASA/JPL	US	79.000?	79.000	0.950	3.400	0.300?
D01001	A09125	2018-042	2018 May 5	Mars InSight Back Shell	InSight Aeroshell	NASA/JPL	US	63.000?	63.000?	2.640	2.600	0.500
D01002	A09126	2018-042	2018 May 5	Mars InSight Heat Shield	InSight Aeroshell	NASA/JPL	US	189.000	126.000?	2.640	2.600	1.100
D01003	A09127	2018-042	2018 May 5	Mars InSight Parachute	InSight Parachute	NASA/JPL	US	0.000	0.000?	11.800	26.000	1.100
D01004	S43473	2018-045D	2018 May 20	CZ-4C Y27 Stage 3	CZ-4C Stage 3	CNSA	CN	1000.000?	1000.000?	2.900	7.500	7.500
D01005	S43470	2018-045A	2018 May 20	Queqiao	Chang'e-4 Relay	CASC	CN	425.000	325.000	1.500?	4.200?	2.000?
D01006	S43471	2018-045B	2018 May 20	Longjiang 1	DSLWP-A	CASC/HARB	CN	45.000	45.000	0.400	0.500	0.500
D01007	S43472	2018-045C	2018 May 20	Longjiang 2	DSLWP-B	CASC/HARB	CN	45.000	45.000	0.400	0.500	0.500
D01008	S43592	2018-065A	2018 Aug 12	Parker Solar Probe	Parker Solar Probe	GSFC	US	685.000	605.000	2.300	3.000	3.000
D01009	S43594	2018-065C	2018 Aug 12	Delta 380 Third Stage	Star 48BV	GSFC	US	140.000?	140.000?	1.400	2.100	2.100
D01010	S43593	2018-065B	2018 Aug 12	Delta 380	DCSS-5 F20	ULAB	US	3450.000	3450.000	5.000	12.000	12.000
D01011	A09203	2016-055	2016 Sep 8	TAGSAM cover	TAGSAM cover	GSFC	US	1.200	1.200	0.300?	0.300?	0.010?
D01012	S43654	2018-080B	2018 Oct 20	ESC-A L5105	Ariane 5 ESC-A	AE	F	5000.000?	5000.000?	5.500	7.000	7.000
D01013	A09205	2018-080D	2018 Oct 20	BepiColombo MTM	Mercury Transfer Module	ESA	I-ESA	1872.000?	1134.000	3.900?	30.400	1.500?
D01014	S43653	2018-080A	2018 Oct 20	BepiColombo MPO	Mercury Planetary Orbiter	ESA	I-ESA	4121.000	1169.000	3.900	6.000	1.700
D01015	A09206	2018-080E	2018 Oct 20	BepiColombo MOSIF	MMO Sunshade and Interface	ESA	I-ESA	127.000?	127.000	2.200?	2.200?	1.900?
D01016	A09204	2018-080C	2018 Oct 20	Mio	Mercury Magnetospheric Orb.	JAXA	J	285.000?	285.000	1.800	30.000	0.900
D01017	S43845	2018-103A	2018 Dec 7	Chang'e-4	Chang'e-4	CASC	CN	3780.000	1200.000	1.700	10.000?	2.200
D01018	S43846	2018-103B	2018 Dec 7	CZ-3B Y30 Stage 3	CZ-3B Stage 3	CASC	CN	2800.000?	2800.000?	3.000	12.400	12.400
D01019	A09236	2018-103	2018 Dec 7	Yutu-2	Chang'e-4 Rover	CASC	CN	140.000	140.000	1.500?	1.500	1.000?
D01020	S44049	2019-009B	2019 Feb 22	B'reshit	Beresheet	SPAIL	IL	585.000	150.000	2.000	2.300	1.500
D01021	S44432	2019-040A	2019 Jul 13	Spektr-RG	Spectrum X-Gamma	RKA	RU	2712.000	2600.000?	4.000	10.000	6.000
D01022	S44433	2019-040B	2019 Jul 13	Blok DM-03 No. 4L	11S861-03 No. 4L	KVR	RU	2440.000	2440.000	3.700	7.100	7.100
D01023	S44441	2019-042A	2019 Jul 22	Chandrayaan-2	Chandrayaan-2 Orbiter	ISRO	IN	3850.000	682.000	2.100	10.000?	5.800

Key catalog tables:

Table 1: one line per object
- owner, mass, size

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Table 2: For each object, mission phases and approximate orbit for each phase
Central body, start and end time, end status, orbit parameters

D00998								
D00998	MarCO-A	0	Earth	2018 May 5 1105		Launch from VS SLC3E by Atlas V 401		
D00998	MarCO-A	1	Earth	2018 May 5 1105	2018 May 5 1238	Separated from launch vehicle		
D00998	MarCO-A	2	Earth	2018 May 5 1238	2018 May 5 2153	Entered deep space	2018 May 5	115 x -110126 x 63.54
D00998	MarCO-A	3	Earth	2018 May 5 2153	2018 May 10 2355	Entered solar orbit	2018 May 5	115 x -110126 x 63.54
D00998	MarCO-A	4	Sun	2018 May 10 2355	2018 Nov 22 1636	Entered Mars sphere	2018 May 31	1.008 x 1.434 AU x 2.24
D00998	MarCO-A	5	Mars	2018 Nov 22 1636	2018 Nov 26 1945	Flyby Mars	2018 Nov 26 1945	1625 x -18113 x 20.90
D00998	MarCO-A	6	Mars	2018 Nov 26 1945	2018 Nov 30 2251	Entered solar orbit	2018 Nov 26 1945	1625 x -18113 x 20.90
D00998	MarCO-A	7	Sun	2018 Nov 30 2251	-	In solar orbit	2019 Jan 1	1.137 x 1.601 AU x 1.40
D00999								

Table 3: Notes and References

D00045	A00438	JPL (1966); Sjogren et al (1964).
D00046	A00454	Trajectory similar to D00047
D00047	S00785	Clark (1985); Winterbottom and Perry (1992)
D00048	A00455	Remained attached to D00047
D00049	S00843	Wollenhaupt et al (1964), JPL (1964).
D00050	S00842	Wollenhaupt et al (1964), JPL (1964).
D00051	S00879	TLE (2017); initial orbit reconstructed from launch press kit and Emme (1965).
D00052	A00535	Trajectory similar to D00051; no tracking data.
D00053	A00576	Remained attached to D00055
D00054	A00577	Remained attached to D00055
D00055	S00923	Trajectory estimated from data in JPL (1965).
D00056	S00942	Initial trajectory similar to D00057
D00057	S00938	Nutt, Gordon and Tito (1967).
		Note that published flyby areocentric semi-major axis is in error by a factor of 10.
D00058	S00945	Clark (1986); Winterbottom and Perry (1991).
D00059	A00596	Trajectory similar to D00058

Catalog status as of Oct 2019:

1023 total catalog entries:

902 free flying objects
121 entries attached to other objects

Current status:

Deep Earth orbit	46 up	83 down	14 lost	15 attached
Returned from deep space:	9 up	47 down	49 lost	37 attached
At Sun-Earth Lagrange:	5 up			
In solar orbit:	311 up			23 attached
Moon and lunar orbit:	16 up	139 down		30 attached
Mercury and Venus:	7 up	58 down		2 attached
Mars:	20 up	64 down		7 attached
Jupiter and Saturn/Titan:	2 up	13 down		
Asteroids and comets	7 up	12 down		7 attached

Example: Jupiter and Saturn/Titan:
2 up: Juno (at Jupiter), Cassini INMS Instrument Cover (at Saturn)
13 down: Galileo Orbiter, Galileo Probe, 2 Probe debris
Cassini, Huygens, 3 Huygens entry system debris, 4 Huygens instrument covers

Example: Returned from deep space
Up: Asiasat-3, DSLWP-A, etc
Down: Apollo, Zond, Hayabusa-1, etc.
Attached: LuxSpace 4M payload, Apollo LEVA spacesuits

Started collecting orbit data in 1993. About 50% complete so far

Examples of sources used for orbital elements and state vectors:

SPICE kernels from JPL and ESA
JPL Horizons
NSSDC/GSFC
APL mission web sites
Astronomical observations
- e.g. asteroid observers measured orbit of Chinese lunar program final stages

Published Soviet papers (e.g. Kosmicheskiye Issledovanie)
Published JPL documents (e.g. Ranger mission reports)

Personal communications with (a.k.a. harrassment of) mission PIs
- Thanks to F. Bernardini, D. Collins, J. Insprucker, T. Kawamura, D.Lauretta, R. Mitchell, M. Rayman, R. Roads, W. Thompson Thank you thank you thank you!
- Only way to get state vectors for final stages of launch vehicles

Archival research

- Pioneer Venus Orbiter heliocentric transfer trajectory state vector found in pencilled note written on telegram in NASA-Ames history archive!

Takeaway: If you have state vectors or elements for deep space spacecraft (including rocket final stages) that are not in JPL Horizons, please pretty please pass them on to me!

https://planet4589.org/space/deepcat/index.html

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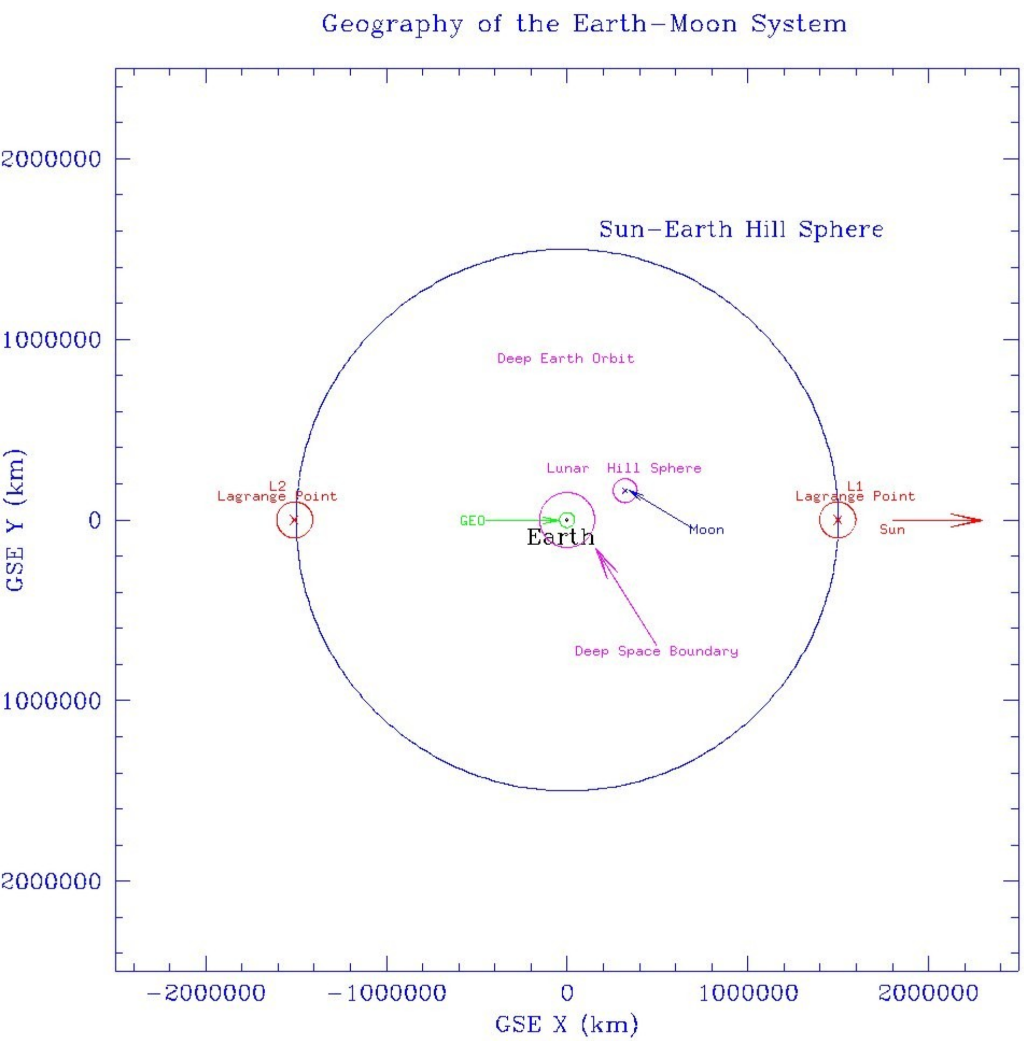
Appendix: local geography (astrography) and the Hill sphere

There are two rival definitions of “gravitational sphere of influence”

- the Laplace sphere   suitable for objects at rest rel to planet
- the Hill sphere   suitable for objects orbiting planet   ←- We’ll use this one!



Consider a small thing orbiting a big thing
Let’s call the small thing “Earth” and the big thing “Sun”
Consider an even smaller thing, called “spacecraft”, moving in their joint gravity – when is it a better approximation to say the spacecraft is orbiting the Earth vs orbiting the Sun?

If you are within E’s Hill Sphere with respect to S
So r < R (m_E /3 m_S)^(1/3)

Then it makes more sense to say you’re in orbit around Earth.

(“orbit” may be elliptical or hyperbolic)