FURTHER OUT: KEEPING TRACK OF DEEP SPACE OBJECTS

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Space situational awareness, for all its challenges, is relatively mature in LEO and GEO. In comparison, the situation beyond GEO is chaotic. No organization is charged with maintaining SSA for deep space objects either in distant Earth orbit or beyond Earth orbit. There is no formal interface between the astronomers who accidentally detect deep space objects while searching for asteroids and the astronautics community. Organizations such as JPL keep track of their own active probes but not of their discarded rocket stages nor the probes of other nations. This situation has been tenable due to the low flight rate of deep space missions to date, but that is changing with the arrival of commercial lunar missions and deep space cubesats, and the increasing number of states carrying out deep space exploration. I present a historical database of about 1000 deep space objects and argue that the time has come to plan for internationally coordinated deep space traffic management.

1. The Current State of Space Situational Awareness (SSA)

1.1 SSA Near The Earth

The Satellite Catalog[1 2] maintained by the US DoD (specifically, USAF 18 SPCS) attempts to catalog (current and historical) Earth orbiting objects. Associated with each catalog entry are Two Line Element Sets (TLEs) giving mean geocentric SGP4 Keplerian elements[3] issued at a cadence of hours to weeks depending on the object.

The catalog is intended to be complete to about 10 cm size for objects in low Earth orbit, but is less complete at high altitudes. Most observations of low orbit objects use ground-based radar. Since radar's sensitivity falls off as the fourth power of distance, it is not useful for high orbit objects for which optical telescopes are used. Space-based optical telescopes are now coming on line to supplement these methods.

In addition to the US catalog, there is a Russian operational catalog; it is not public, but is thought to be not as complete for small debris objects. On the other hand, the Russian-led ISON network appears to be very successful for geosynchronous objects. Additionally, independent hobbyists provide orbit data for US military satellites whose orbit is not made public in the US catalog. European SSA s still at an experimental stage. Although all of these systems have their limitations and problems, in general they provide a rather good knowledge of artificial objects in space within 50,000 km of the Earth.

1 P.A. Jackson, Space Surveillance Satellite Catalog Maintenance, AIAA Paper 1999-1339.

2 P. W. Schumacher, Jr, Prospects for Improving the space catalog, AIAA Paper 1996-4290.

3 F. R. Hoots and R. L. Roehrich, SPACETRACK REPORT No. 3; US Air Force Aerospace Defense Command, Colorado Springs, Colorado., 1980.

1.2 SSA Further Out

In contrast to the comparatively healthy situation in near-Earth space, beyond 50,000 km no-one is responsible for keeping track of space activities. The US system does what can only be characterized as a half-hearted job on objects in deep Earth orbit. See, for example, the incident in which the European Integral satellite changed its orbit substantially, and the US carried on issuing elements based on propagation of the old orbit for many months until the satellite was accidentally found by asteroid observers[4].

No attempt is made to provide orbital data for objects which leave Earth orbit entirely. However, some (fewer than half) of them receive nominal catalog entries. Similarly, owner states do typically notify registrations of their deep space probes to the United Nations in accordance with the Registration Convention [5], but only very rarely do they comply with Art. IV 1(d) which stipulates the provision of `basic orbital parameters' (usually understood to include at least periapsis, apoapsis and inclination). There is no suggestion in the relevant article that it should apply only to Earth orbit.

Near-Earth Asteroid observers often accidentally find objects in deep Earth orbit, on Earth escape trajectories, or objects in solar orbit passing near the Earth. Such objects have apparent celestial motions similar in magnitude to asteroids of interest. There is a small but unfunded effort (notably by Gareth Williams, IAU Minor Planet Center [6], and Bill Gray, Project Pluto [7]) to report these objects.

Active deep space probes are of course tracked by their operators. However, once the probe's mission is over there is no system in place for public archiving of the trajectories. At JPL, the HORIZONS system [8]developed by Jon Giorgini provides ephemerides and orbit data for a subset of active and dead probes. The included missions are largely JPL-managed probes of the 1990s and later, with some missions from other agencies for which JPL has provided support and a

4 McDowell, How IntegralWas Lost, ESA news article, 15 Dec 2015. https://www.cosmos.esa.int/web/integral/how-integral-was-lost

5 United Nations, Convention on Registration of Objects Launched into Outer Space, 6 June 1975, 1023 UNTS 15 (entered into force 15 September 1976).

6 G. Williams, Distant Articial Satellites Observation (DASO) circular. https://minorplanetcenter.net/iau/DASO/DASO.html

7 W. Gray, Project Pluto, https://www.projectpluto.com

8 J. Giorgini, HORIZONS, https://ssd.jpl.nasa.gov/?horizons

handful of other objects added by popular demand. HORIZONS is the single biggest contribution to SSA for deep space but it is far from a complete solution.

2. The need for a deep space catalog

As humanity and its robot avatars spread into the solar system for the first time, ensuring the existence of accurate historical records has its own value. But there are more immediate reasons why the deep space catalog is needed.

Artificial deep space objects are already causing problems for astronomers. As noted above, a subset of them can be mistaken for asteroids - indeed, several were accidentally cataloged as such before the mistake was noticed and the asteroid designation retracted. Asteroid J002E3 was found in an unusual solar orbit in 2002, and was temporarily captured by the Earth-Moon system. Observations [9] suggested that it was actually the upper stage of the Saturn V rocket which launched Apollo 12. Spacecraft in the Sun-Earth L2 region are especially prone to being found like this as they lie near local midnight as seen from Earth; but true solar-orbiting spacecraft passing near the Earth have also been seen. Such objects tend to have relatively low Earth-relative velocities - what a nightmare it would be if one were accidentally selected as the target of an expensive asteroid sample return mission!

Often, the presence of non-gravitational forces such as venting of residual propellant mean that state vectors or orbital elements for artificial objects generated shortly after launch are not adequate to predict the position of the object decades after launch. Nevertheless, they may be sufficient to perform a linkage if the object is serendipitously recovered: the new observations can be propagated backwards and shown to be consistent with the original orbit. Therefore, even approximate trajectory information can be helpful in confirming or ruling out proposed identifications and so space agencies should be encouraged to provide them.

Looking slightly ahead, more and more nations are sending spacecraft beyond Earth orbit, and commercial deep space missions are already beginning. Even if asteroid mining doesn't take off, we may expect that in 20 years time the entire inner solar system will be like Earth orbit today: a busy neighborhood with both scientific and commercial activities and extensive navigation and communications infrastructure. This enviroment will need governance, and governance requires situational awareness.

There is already a limited governance framework in place beyond the Outer Space Treaty. In addition to the Registration Convention already mentioned, planetary protection recommendations [10]are largely honoured by civil

9 K. Jorgensen, A. Rivkin, R. Binzel, R. WHitely, C. Hergenrother, P. Chodas, S. Chesley and F. Vilas, Bull Am.Astron.Soc 35, 981 (2003).

10 COSPAR, The COSPAR Panel on Planetary Protection Role, Structure and Activities, Space Research Today 205, 14. (2019).

government space missions. Commercial missions, in contrast, are raising concern in this respect[11] [12]

An early catalog of deep space objects[13] as created by the UK's Royal Aircraft Establishment (later Defense Research Agency) in 1966 as RAE Technical Report 66103, and updated a number of times[14] [15][16] [17]. Another early effort was a series of tables published by G. Falworth in Spaceflight and JBIS [18] [19] [20] [21] [22] [23]. The present more detailed work is indebted to those earlier studies.

3. The Deep Space Catalog

I have compiled a catalog of over 1000 artificial objects in `deep space'. Version 1.0 of this catalog has been released online at https://planet4589.org/space/deepcat.

By deep space, I mean broadly space beyond the region where the US satellite catalog provides coverage. Note that the term has been used with a variety of definitions. In the context of the SGP4 orbit model [3], `deep space' refers to orbital periods above 225 minutes, corresponding to altitudes of about 5900 km, a region normally thought of as `medium Earth orbit' these days. For our purposes a boundary somewhere beyond 50,000 km seems needed. It also appears desirable to exclude communications satellites on supersynchronous transfer orbits which have apogees typically in the 60,000 to 100,000 km range.

11 H Rein, D. Tamayo, D. Vorkouhlicky, The random walk of cars and their collision probabilities with planets, Arxiv.org paper 1802.04718.

12 L. Grush, Why stowaway creatures on the Moon confound international space law https://www.theverge.com, 16 Aug 2019.

13 H. Hiller, 1966, Table of space vehicles launched in 1958-65, RAE Tech Rept. 66103

14 H. Hiller and J.A. Pilkington, 1973, Table of Space Vehicles Launched During the Years 1958-1972, RAE Tech. Rept. TR 73006 (Royal Aircraft Est., Farnborough).

15 .J.A. Pilkington, 1976, Table of Space Vehicles 1973-1976, RAE Tech Memo Space 242, (Royal Aircraft Est., Farnborough).

16 H. Hiller, A.N. Winterbottom, J.A. Pilkington, and G.E. Perry, 1987, The RAE Table Of Space Vehicles 1958-1986, (Royal Aircraft Est., Farnborough).

17 .A.N. Winterbottom and G.E. Perry, The DRA Table of Space Vehicles 1958-1991, Defense Research Agency, Farnborough, UK, 1993.

18 G. Falworth, 1969, Objects on the Moon - 1, Spaceflight 11, 384.

19 G. Falworth, 1970. Objects in Heliocentric Orbit – 1, Spaceflight 12, 92

20 G. Falworth, 1970. Objects in Selenocentric Orbit -1, Spaceflight 12, 143.

21 G. Falworth, 1971. Objects in Heliocentric Orbit – 2, Spaceflight 13, 298.

22 G. Falworth, 1972, Objects on the Moon - 2, Spaceflight 14, 145.

23 G. Falworth, 1973, Objects in Selenocentric Orbit – 2, JBIS 26, 493.

For definiteness I adopt a boundary I call[24] EL1:4, the Earth-lunar 1 to 4 orbit resonance in which a satellite in a circular orbit will complete four revolutions of the Earth for every one that the Moon does. The choice is motivated by the idea that satellites well within this distance can to first order ignore the Moon and be regarded as being in simple Keplerian orbits on short timescales (clearly, even much closer in at GEO, lunisolar perturbations are important on longer timescales). Satellites at this distance or beyond are more strongly affected by lunar perturbations and should be considered as part of a three-body system. This distinction is obviously not a sharp one and is somewhat arbitrary but it seems as good as any. It also echoes the Sun-Jupiter 1 to 4 resonance which approximately marks the inner edge of the asteroid belt and which serves as a good candidate for a boundary between the inner and outer solar system.

3.1 The Main Catalog Table

The core of the catalog is a table of artificial objects (the `object table') which have at some time been further from the Earth than the EL1:4 distance. For each object, I provide the launch date, one or more names, the international designation of the launch, a deep space catalog ID, and a standard catalog ID.

Table I. Deep Space Catalog, object table columns.

Column Name	Description
DeepID	Sequence, D00001 onwards
StdID	Entry in US catalog or auxiliary catalog
IntDes	COSPAR international designation of launch
LDate	Launch Date (UTC)
Name	Name used by owner agency
AltName	Alternate name for object
Owner	Code for owner organization
State	Code for owner country
Mass	Launch mass of object, kg
DryMass	Dry mass of object, kg

24 J. McDowell, Acta Astronautica 151, 668 (2018).

Column Name	Description
Length	Longest dimension of main body of object, m
Diam	Shortest dimension of main body of object, m
Span	Longest dimension of object including antennas, etc., m

The standard catalog ID requires more explanation. For some objects, a US Satellite Catalog number exists. In this case, the standard catalog ID is that number, prefixed by the letter S. However, a significant number of known artifical space objects, both near-Earth and deep space, don't appear in the US Satellite Catalog. To provide a systematic way of referring to these I have created an `auxiliary catalog' with standard IDs prefixed by the letter A. This auxiliary catalog is also in preparation for publication.

As an example: Deep space catalog entry D00967 is the Lisa Pathfinder spacecraft. Its standard catalog ID is S41043, reflecting its catalog number in the official US catalog. Deep space catalog entry D00968 is the Lisa Pathfinder Propulsion module. Its standard catalog ID is A08465, reflecting its entry in the auxilary catalog since it was never added to the US catalog. Note that the A catalog numbering is entirely separate from the S catalog, so A08465 has no connection to US catalog entry S08465, a debris object from a 1975 Soviet satellite.

The columns in the object table are shown in table I. In the catalog, countries and owner organizations are identified using a standard set of alpanumeric codes whose meaning is given in a separate Organizations table, maintained on the author's website [25].

3.2 The Hill Sphere

The remainder of the catalog treats the time history of each object as a series of mission phases. In this context, a phase is a time interval when either (1) the object may be considered as moving under the gravitational influence of a given astronomical body or (2) the object is on the surface of such a body. Here we introduce the concept of the Hill gravitational sphere of influence [26].

Consider a spacecraft moving in the joint gravitational field of the Earth and the Sun. Close enough to the Earth, we may neglect the Sun's gravity and treat it as being in Earth orbit. Far enough from Earth, and we can ignore our home world and treat the spacecraft as being in solar orbit. The Hill sphere is the boundary at which it becomes better to pick one case over the other. In general for small

25 J. McDowell, https://planet4589.org/space/lvdb/sdb/Orgs; also McDowell, 2020 in preparation.

26 G.W. Hill, Researches in the Lunar Theory, Am. J. Math, 1, 5 (1878).

body B orbiting big body A with an orbital radius R, and a spacecraft feeling the gravity of both of them, it is a better approximation to calculate a B-centered orbit rather than an A-centered orbit if its distance r to B satisfies

$$r < \left(\frac{m_B}{3m_A}\right)^{1/3} R$$

There's another popular definition of the sphere of influence, the Laplace sphere, which is useful when considering points at rest with respect to the body B. The Hill sphere is more appropriate for objects moving in orbit, the case we are considering here. The well-known L1 and L2 Lagrange points lie on the Hill sphere. Note that in this discussion by `orbit' I include unbound (hyperbolic) as well as bound (elliptical) orbits.

3.3 Mission Phase Tables

The mission phase tables contain entries for each contiguous period for which an object is in orbit around a particular body.

The PEnd column is in general the PStart of the next phase, if any. A phase can start by crossing a Hill sphere boundary so that the object is in orbit around a new body, or it can start when the object separates from a parent object to which it was previosly attached (e.g. the separation of a lander from an orbiter). A new phase is also started at periapsis of a hyperbolic encounter (flyby), a planetary orbit insertion or an orbit escape burn.

Table II: Columns for Mission Phase Data

Column name	Description
DeepID	Sequence, D00001 onwards
Name	Name as per Table 1
Phase	Sequential mission phase number for object
Body	Central body
PStart	UTC Start time of phase
PEnd	UTC End time of phase
Dest	Status at end of phase
Epoch	Epoch of orbital data
Orbit	Representative orbital data for phase

As a simple example in table III we consider the Mars Insight spacecraft.
The probe passes the EL1:4 boundary on May 5, leaves the Earth's Hill sphere on May 10, remains in solar orbit until arriving in Mars' Hill sphere on Nov 22, and lands on Mars Nov 26. Each of these phases requires a different form of trajectory data (relative to a different central body, or a surface position).

Table III(a) Mission phases for Mars Insight, columns 1 to 6

DeepID	Name	Phase	Body	Pstart	Pend
D00997	Mars Insight Lander	0	Earth	2018 May 5 1105	
D00997	Mars Insight Lander	1	Earth	2018 May 5 1105	2018 May 5 1238
D00997	Mars Insight Lander	2	Earth	2018 May 5 1238	2018 May 5 2153
D00997	Mars Insight Lander	3	Earth	2018 May 5 2153	2018 May 10 2355
D00997	Mars Insight Lander	4	Sun	2018 May 10 2355	2018 Nov 22 1639
D00997	Mars Insight Lander	5	Mars	2018 Nov 22 1639	2018 Nov 26 1944
D00997	Mars Insight Lander	6	Mars	2018 Nov 26 1944	-

Table III(b) Mission phases for Mars Insight, columns 7 to 9

Dest	Orbit Epoch	Orbit
Launch from VS SLC3E by Atlas V 401		
Separated from launch vehicle		
Entered deep space	2018 May 5	115 x -110126 x 63.54
Entered solar orbit	2018 May 5	111 x -110094 x 63.57
Entered Mars sphere	2018 May 31	1.008 x 1.434 AU x 2.24
Landed on Mars	2018 Nov 26	7 x -16942 x 13.50
Operating on Surface	2018 Nov 26	-

4. Catalog Statistics

The 1023 entries in the initial release of the catalog include 908 free flying objects and 115 attached objects. There are several categories of attached object, which are given catalog entries even though they are not separate spacecraft. These include objects which failed to separate due to mission failure (example: the Apollo 13 lunar module descent stage, which remained attached to the ascent stage at Earth atmosphere entry); objects which I count as separate payloads even though not designed to separate (example: I have separate entries for the Falcon Heavy 001 second stage rocket and the Tesla car permanently affixed to its nose); solid apogee motors attached to spacecraft; and EVA spacesuits, including those that were not actually used on EVA and remained inside the spacecraft.

Of the 902 free objects, only 438 have catalog numbers in the US satellite catalog. The distribution of the current mission phases of these 902 objects is summarized in table IV, separating objects which are still in orbit from those which are now `down'. `Down' here variously means landed, crashed or destroyed in atmospheric entry. I separate objects which have never left the Earth's Hill sphere (`Deep Earth') from those which have returned to it (`Earth Return') after having been in lunar or solar orbit. The latter include lunar mission upper stages which made lunar flybys and then ended up orbiting the Earth at near-lunar distance, often never being tracked post-encounter.

63 deep-space Earth-orbiting objects are noted as `lost'. Objects in deep Earth orbit can be chaotic or nearly so and are susceptible to being perturbed into solar orbit or - even with very high initial perigees - to Earth reentry. Multiple distant lunar flybys are not uncommon and can leave the objects in quite different orbits from their initial ones. For objects last seen decades ago and not recovered with the advent of new, capable survey telescopes there is no way to know what their specific fate was. Objects in other parts of the solar system may also be lost, but at least we usually know whether they are likely still in orbit or not, and around which central body.

Table IV - Distribution of free-flying deep space objects in catalog.

Body	Objects in orbit	Objects down	Lost objects
Deep Earth Orbit	46	83	14
Earth Return	9	47	49
Moon	16	139	0
Sun-Earth L1/L2	5	0	0
Sun	311	0	0
Mercury	0	1	0
Venus	7	57	0
Mars	20	64	0
Jupiter	1	4	0
Saturn	1	1	0
Titan	0	8	0
Asteroids, Comets	7	12	0

For each entry in the mission phase tables, estimates of basic orbital parameters are provided. In the initial release of the catalog, these are periapsis, apoapsis and inclination. For solar orbiting phases, the distances are radii in AU from the Sun's center (note: and not the barycenter) and the inclination is relative to the ecliptic. For other central bodies, distances are heights in km above a sphere corresponding to the body's nominal equatorial radius, and inclination is relative to the body IAU equator of date. The intent is to supplement these orbital parameters with full Keplerian osculating elements at a specific epoch in a subsequent data release.

Table V. Orbital data sources. See online catalog for detailed citations.

Data Sources:
JPL Horizons
SPICE kernel data for JPL and ESA missions from the Planetary Data System and other sources
JPL technical publications (e.g. the Ranger mission reports)
Orbital data published by the Space Physics Data Facility at NASA-GSFC
APL mission web sites (e.g. NEAR)
Astronomical observations (e.g. asteroid observers measured the orbit of Chinese lunar program final stages). Most of these were made available via Project Pluto.
Published Soviet papers, especially in Kosmocheskie Issledovanie
Other published papers
Archival research
Personal communications with mission officials

Unfortunately, the orbital data are approximate in many cases, and sometimes mere guesses. The author began collecting deep space trajectory data in 1993 and the catalog will include a number of previously unpublished orbits. Sources which provided, or which were raided for, data that is being incorporated into the catalog are summarized in Table V.

Archival research can occasion bring useful surprises. The only source I have found for the heliocentric transfer trajectory of the Pioneer Venus Orbiter mission is a state vector scribbled in pencil on a telegram in the history archives at NASA-Ames! I would be remiss if I did not thank the engineers and scientists who kindly have provided trajectory data over the years, including F. Bernardini, D. Collins, J. Insprucker, T. Kawamure, D. Lauretta, R. Mitchell, M. Rayman, R. Roads and W. Thompson. Trajectory information on launch vehicle final stages is impossible to find other than by personal contacts. Detailed citations are provided in the catalog.

5. Conclusion

With the launch of interplanetary cubesats (JPL's MARCO A and B), commercial and non-governmental interplanetary flight (SpaceX's Falcon Heavy test launch and SpaceIL's B'reshit lunar mission) and the advent of garbage disposal in solar orbit (United Launch Alliance's launch of several discarded Centaur stages with extra propellant to escape trajectories after deploying low Earth orbit payloads), humanity's use of deep space is booming despite a situational awareness vacuum. It is time to get serious about public record-keeping for deep space launches.

The initial public release of the Deep Space Catalog was made available in October 2019 at https://planet4589.org/space/deepcat/index.html.

If any reader of this paper has access to deep space trajectory information for objects whose data is not on JPL Horizons or another public site, the author would be very happy to hear from them.