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Technical Note on Simulated Megaconstellation Ephemerides Dataset

Calum Turner ^{1,2} and Raj Thilak Rajan ²

Abstract—This technical note accompanies a dataset providing the time-varying positions of 1584 satellites in a simulated megaconstellation modelled on Phase 1 of SpaceX’s Starlink. This note explains the context, creation, format, and potential uses of the dataset. The code used to create these data is publicly available.

I. CONTEXT

The Starlink mega-constellation is a satellite internet constellation currently under construction by SpaceX (Space Exploration Technologies) in Low Earth Orbit. Launches of operational satellites began in 2019, and as of 1st January 2021 roughly one third of all active satellites in orbit belong to the Starlink constellation [1]. January 2021 was the most recent update of the Union of Concerned Scientists’ Satellite Database, but at the time of writing, July 21, 2021, news reports suggest that almost 1,500 Starlink satellites are in orbit. This proliferation of satellites in orbit has prompted concern from astronomers [2] and space environmentalists [3] and has led to a spate of research on the Starlink constellation. The designs of megaconstellations are ambiguous and in a state of flux [4], and the design of Starlink in particular is evolving rapidly. This dataset represents Phase 1 of Starlink, a single shell of satellites at an altitude of 550 km consisting of 22 planes of satellites, each at an inclination of 53°. This constellation design is based on the information in an FCC filing dated April 17, 2020, and the parameters describing the constellation design are shown in Table IV.

II. NOTES ON THE DATASET

The orbits represented in this dataset are simple Keplerian ellipses, and can be uniquely defined at any point by six parameters. Five of these parameters specify an ellipse with a given size and orientation with respect to a reference frame, and the sixth reflects the displacement of an orbiting body along this elliptical path. For Earth

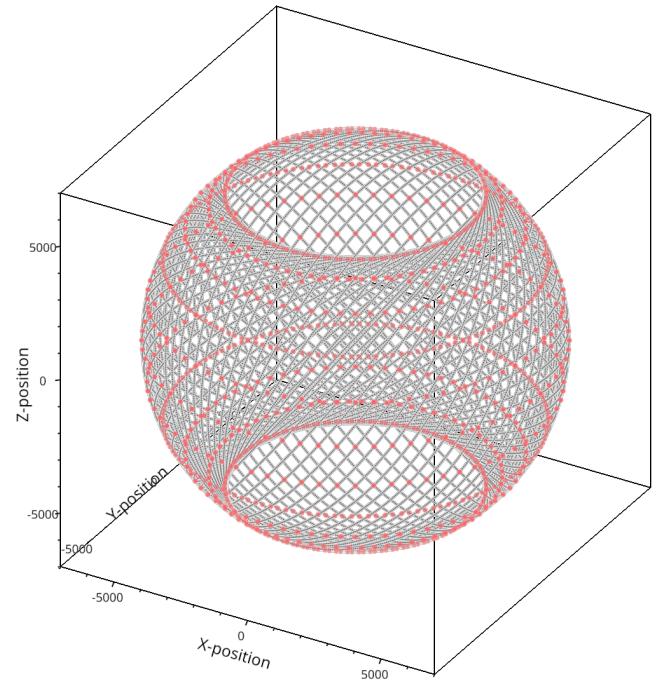


Fig. 1. Satellite orbits (shown in grey) and initial positions (shown in red) for the Starlink Megaconstellation. Both the orbital planes and satellites within the planes are equally spaced.

orbit, these parameters are shown in Table I. The orbital elements are illustrated in Figure 2 and captured for every agent at every timestep, as shown in Table V. The orbits were propagated using a built-in Polisastro function `TWOBODY.PROPAGATION.VALLADO`, which propagates orbits using implementations of the algorithms in [5]. This method also outputs the position and velocity of each satellite in Cartesian coordinates.

A. Identifying Satellites

Following the methodology of Chaudhry & Yanikomeroglu [6] Each satellite has a unique identifier with the format `sXXYYY` where XX is plane number and YYY is satellite number. For example, the first satellite in the first plane has the identifier `s01001`.

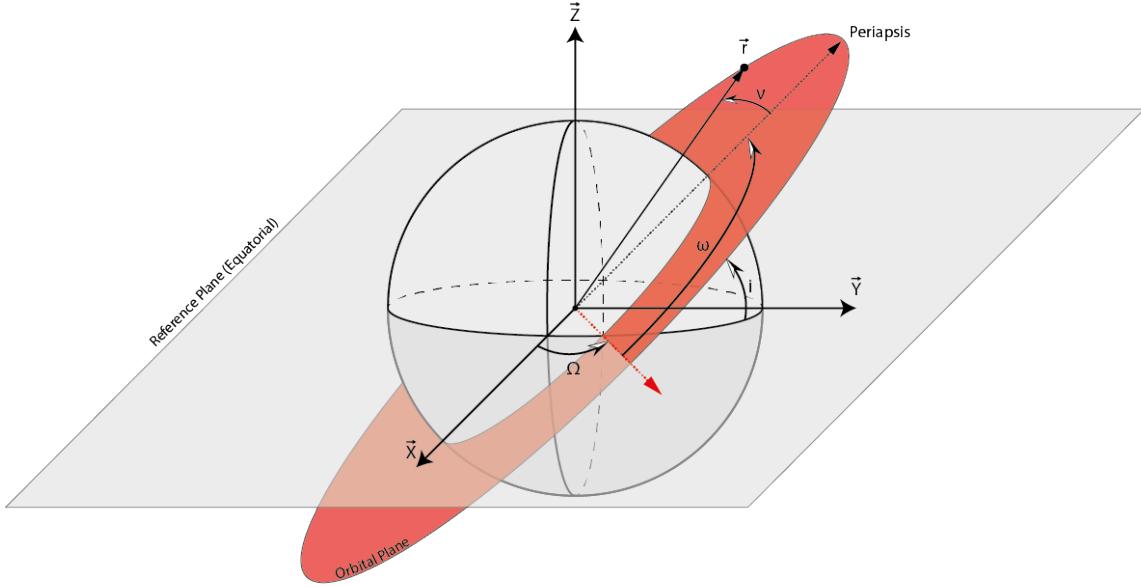


Fig. 2. Simplified sketch of the classical orbital parameters. Ω is the Right Ascension of Ascending Node (RAAN). ω is the argument of periapsis, i is the inclination and ν is the true anomaly. The Semimajor axis a and the eccentricity e are not shown in this diagram.

B. Reference Frame

The reference frame for the positions and velocities of the simulated megaconstellation satellites is the Geocentric Celestial Reference System (GCRS) [7] with default parameters shown in Table II. Satellite s01001 has initial position $[a, 0, 0]$ where a is the semimajor axis of the orbit.

C. Simulation Parameters

The parameters used to run the simulation are shown in Table III, where T is the total time of the simulation and ΔT is the duration of one timestep.

III. COMMENTS

The positions of megaconstellation satellites can be used to address various research topics, such as designing megaconstellation network topologies (see [4], for example) or classifying intersatellite links (see [6]). The code used to create this dataset can be readily modified to create ephemerides for other mega-constellations such as OneWeb or Kuiper, and is publicly available under a permissive MIT license at [this link](#). As well as the potential uses of this dataset, it is important to note its limitations:

- Despite sharing the same constellation design, the ephemerides of the simulated satellites do not necessarily reflect the actual orbital positions of Starlink satellites.

- The simulated megaconstellation consists of a single shell of satellites with the same altitude, whereas proposed megaconstellations will consist of several shells
- Orbital perturbations such as the J2 effect or aerodynamic drag are not taken into account.

The data is stored as a .csv file with the format shown in Table V. The data was exported from a Pandas DataFrame with multi-level indexing, and the first two columns of the .csv file are indexes for each individual satellite and each individual timestamp. If working with the original DataFrame, this allows the data for either a single satellite or a single timeframe to be easily isolated. The full dataset, consisting of 583 timesteps (1 orbital period), is provided alongside a smaller dataset of 10 timesteps made available for the purposes of testing code.

ACKNOWLEDGMENTS

The code used to create this dataset made use of Astropy¹, a community-developed core Python package for Astronomy [8], [9]. It also made use of Poliastro², a community-developed astrodynamics package [10]. This work was conducted at TU Delft and was supported by the Dutch-PIPP (Partnerships for Space Instruments & Applications Preparatory Programme), funded by NWO

¹<http://www.astropy.org>

²<https://www.poliastro.space/>

(Netherlands Organisation for Scientific Research) and NSO (Netherlands Space Office).

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TABLE I
CLASSICAL ORBITAL ELEMENTS

Parameter	Symbol	Description
SEMIMAJOR AXIS	a	Determines the size of the elliptical orbit
ECCENTRICITY	e	Determines the eccentricity of the ellipse
INCLINATION	i	Determines the inclination for the orbital plane with respect to the equatorial plane
RIGHT ASCENSION OF ASCENDING NODE	Ω	Determines the orientation of the orbital plane with respect to a reference direction
ARGUMENT OF PERIGEE	ω	Determines the angular distance of the perigee from the equatorial plane
TRUE ANOMALY	ν	Determines an orbiting bodies angular displacement in the orbital plane measured from periapsis

TABLE II
REFERENCE FRAME PARAMETERS

Parameter	Value
Observation Time	J2000.000
Position of the observer relative to the barycenter	[0, 0, 0] m,
Velocity of the observer relative to the barycenter	[0, 0, 0] m,

TABLE III
SIMULATION PARAMETERS

Parameter	Value
Number of Timesteps	573
ΔT	10 seconds
T	5730 seconds

TABLE IV
STARLINK PHASE 1 PARAMETERS

Parameter	Value
Altitude	550 km
Number of Planes	72
Satellites per Plane	22
Inclination i	53°
Orbital Period T	1.59 hours
Total Satellites	1584

TABLE V
DATA FORMAT

Index	Satellite ID	Identifiers			Classical Orbital Elements						Position			Velocity			
		Time	Plane No.	Sat. No.	Time	a	e	i	RAAN	$ArgP$	ν	\vec{r}_x	\vec{r}_y	\vec{r}_z	\vec{v}_x	\vec{v}_y	\vec{v}_z
s01001	0.0	1	1	0	6928	0	53°	0°	0°	0°	0.0	6928.0	0.0	0.0	0.0	4.56	6.06
s01001	10.0	1	1	10	6928	0	53°	0°	0°	0.63°	6927.58	45.65	60.58	-0.083	4.56	6.06	
:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	
s01001	5730.0	1	1	5730	6928	0	53°	0°	0°	359.45°	6927.68	-40.27	-53.44	0.07	4.56	6.06	
s01002	0.0	1	2	0	6928	0	53°	0°	0°	16.36°	6647.37	1174.65	1558.81	-2.14	4.38	5.81	
:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	
s01002	5730.0	1	2	5730	6928	0	53°	0°	0°	375.81°	6665.91	1135.95	1507.46	-2.07	4.39	5.83	
:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	
:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	
s01022	0.0	1	22	5730	6928	0.0	53	0.0°	0.0°	703.08°	6628.20	-1213.24	-1610.02	2.21	4.37	5.79	
s02001	0.0	2	1	0	6928	0.0	53	5.0°	0.0°	0.0°	6901.64	603.81	0.0	-0.40	4.55	6.06	
:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	
:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	
s72022	0.0	72	22	0	6928	0	53°	355.0°	0°	343.64°	6519.69	-1749.53	-1558.81	2.51	4.18	5.81	
:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	
s72022	5730.0	72	22	5730	6928	0	53°	355.0°	0°	703.08°	6497.24	-1786.30	-1610.02	2.58	4.16	5.79	