STUDENTS' SPACE ASSOCIATION
THE FACULTY OF POWER AND AERONAUTICAL ENGINEERING
WARSAW UNIVERSITY OF TECHNOLOGY

PRELIMINARY DESIGN REVIEW

MISSION ANALYSIS

pw-sat.pl

August 2015

Abstract

The following document is a part of Preliminary Design Review – a paper describing the Phase B of student satellite project called PW-Sat2. Several analyses where conducted to determine communication sessions duration and frequency, eclipse duration and maximum sun exposure for 7 possible destination orbits for PW-Sat2.

Revisions

Date	Changes	Responsible
2015-05-04	First Revision of this document	Artur Łukasik
2015-05-18	Orbital decay analyses added	Artur Łukasik
2015-05-18	Editorial changes	Dominik Roszkowski
2015-05-21	Paragraph 6.5 introduction added, Table 8-1 extended	Artur Łukasik
2015-05-29	Editorial changes	Dominik Roszkowski
2015-08-16	Small editorial changes	Dominik Roszkowski

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Abbreviated terms

ADCS	Attitude Determination and Control System
AGI	Analytical Graphics, Inc's
AP	Argument of Perigee
AR	Acceptance Review (as defined in [RD. 1])
CNES	Centre national d'études spatiales (National Centre for Space Studies)
COMM	Communication subsystem
DT	Deployment Team (mechanical team, responsible for sail system and solar arrays opening mechanism)
ECC	Eccentricity
EOL	End Of Life
EPS	Electrical Power System
ESA	European Space Agency
ESEO	European Students Earth Orbiter
FRR	Flight Readiness Review (as defined in [RD. 1])
GMAT	General Mission Analysis Tool
GS	Ground Station
IADC	Inter-agency space debris coordination committee
INC	Inclination
ITAR	International Traffic in Arms Regulations
LEO	Low Earth Orbit
LTAN	Local Time of Ascending Node
MA	Mission Analysis
NASA	National Aeronautics and Space Administration
PDR	Preliminary Design Review (as defined in [RD. 1])
RAAN	Right Ascension of the Ascending Node
SC	Spacecraft
SKA	Studenckie Koło Astronautyczne (Students' Space Association)
SMA	Semi-Major Axis
SSETI	Student Space Exploration and Technology Initiative
SSO	Sun-Synchronous Orbit
STELA	Semi-analytic Tool for End of Life Analysis
STK	Systems Tool Kit

SW	Software
TBC	To Be Continued
TBD	To Be Defined
w.r.t	with respect to
WUT	Warsaw University of Technology

1 Introduction

1.1 Purpose and scope

This document describes the activities of the Mission Analysis team of PW-Sat2 satellite project during phase B. Main activity of phase B mission analysis team were analyses performed for 7 different candidate orbits for PW-Sat2 which were selected from the available launch opportunities. It should be noted that this document serves both as technical documentation and the general description of organizational and supporting activities performed by Mission Analysis team during phase B.

1.2 Document outline

The document is structured as follows:

- Chapter 1 contains an introduction to the document
- Chapter 2 provides the applicable and reference documents
- Chapter 3 provides the revision of phase A activities
- Chapter 4 provides the update of the phase A launch opportunities search for PW-Sat2
- Chapter 5 provides the description of the software tools used and the progress in license acquisition
- Chapter 6 provides the results of the analyses conducted for candidate orbits for PW-Sat2
- Chapter 7 describes the operators internships in BRITE-PL ground station
- Chapter 8 provides planned activities for phase C

1.3 Document contributions

This document and any results described were prepared solely by PW-Sat2 project team members. As of this revision, this document is planned to be delivered to external entities for review, particular entities are yet TBD.

2 REFERENCES

2.1 PROJECT DOCUMENTS

Table 2-1 List of applicable project documents

Ref.	Title	Code	Version	Date
[PD. 1]	PW-Sat2 – Preliminary Requirements Review – Mission Analysis	PW-Sat2_10_PRR_MA_EN	1.0.1 EN	2014-07-02
[PD. 2]	PW-Sat2 – Preliminary Design Review - Overview	PW-Sat2_00_PDR_Overview	1.0	2015-05-24

2.2 REFERENCE DOCUMENTS

Table 2-2 List of applicable reference documents

Ref.	Title	Version	Date
[RD. 1]	ECSS-M-ST10C – “Space project management.”	Rev.1	2009.03.06
[RD. 2]	Website: *https://logiciels.cnes.fr/content/stela?language=en*		2015.04.06
[RD. 3]	Website: *http://www.stoff.pl/*		2015.04.06
[RD. 4]	Website: *http://help.agi.com/stk/index.html*		2015.04.06
[RD. 5]	Lyle R., Stabekis P., *Spacecraft Aerodynamic Torques*, *NASA SP-8058*, NASA Electronics Research Center, Jan 1971		
[RD. 6]	Lamy et al., *Resonance Effects on lifetime of Low Earth Orbit Satellites*, 23rd ISSFD, 2012		
[RD. 7]	Montenbruck, Gill, *Satellite Orbits*, Springer, Germany, 2001		
[RD. 8]	*GMAT User Guide R2014a*, NASA GSFC, 2014 Access from website: *http://gmat.sourceforge.net/docs/R2014a/help-a4.pdf*	R2014A	2015.05.18
[RD. 9]	IADC-02-01, *Space Debris Mitigation Guidelines*, 2007	Rev. 1	Sep. 2007

3 REVISION OF PREVIOUS WORK

3.1 TEAM OBJECTIVES

During Phase A the following tasks were defined for the Mission Analysis Team [PD. 1]:

1. Finding a way to launch the satellite into orbit
2. Mission and orbit analysis in Mission Analysis software
    2.1. Contact with software distributors
    2.2. Organization of training mission analysis software
    2.3. Mission modeling
        2.3.1. Modeling of solar panels' exposure to light
        2.3.2. Modeling of communication session with ground station
        2.3.3. Calculation of suitable time to test sun sensor
3. Implementation a of detailed mission plan
4. Preparation of the satellite operators' team (OPER)
    4.1. Radio amateur training organization
    4.2. Obtaining of radio amateur licenses
    4.3. Process mission plan to a set of telecommands
    4.4. Develop contingency plans for emergency response of individual sub-systems
    4.5. Risk analysis for satellite mission

3.2 PHASE A ACTIVITIES

As described in [PD. 1] Phase A activities included:

- Looking for launch opportunity
- Looking for educational licenses of mission analysis software.
- Risk Analysis for PW-Sat2 mission

3.3 Revision

For clarity the tasks were provided by the new unique code which was not the case in Phase A documentation. The order of tasks was preserved from the list in chapter 3.1 of this document.

Table 3-1 Team Objectives Task codes, description and comments

Task code	Description	Comment
	Tasks derived from the phase A	
PRR_MA_1	Finding a way to launch the satellite into orbit	First search for launch opportunities was conducted during the phase A activities and he updated information are presented in this document. Next activity in scope of this task is planned for phase, it is planned to find new launch opportunities and update previous results taking into account changes in project schedule.
PRR_MA_2	Mission and orbit analysis in Mission Analysis software	This is a general task divided into a smaller sub-tasks
PRR_MA_2.1	Contact with software distributors	Contact with software distributors was made during phase A and continued in phase B the detailed update is presented in the chapter 5.1 of this document.
PRR_MA_2.2	Organization of training mission analysis software	This task is scheduled for phase C.
PRR_MA_2.3	Mission modeling	This is a general task divided into a smaller sub-tasks
PRR_MA_2.3.1	Modeling of solar panels' exposure to light	This task's activities are presented in the chapter 0 of this document.
PRR_MA_2.3.2	Modeling of communication session with ground station	This task's activities are presented in the chapter ▯ of this document.
PRR_MA_2.3.3	Calculation of suitable time to test sun sensor	This task is scheduled for phase C when the mission plan will be available.
PRR_MA_2.3.4	**(New)** Orbital decay analysis	This task's activities are presented in the chapter 6.5 of this document.
PRR_MA_3	Implementation a of detailed mission plan	This task is scheduled for phase C.
PRR_MA_4	Preparation of the satellite operators' team (OPER)	This task is scheduled for phase C, however some activities were presented in chapter 7 of this document.
PRR_MA_4.1	Radio amateur training organization	This task is scheduled for phase C.
PRR_MA_4.2	Obtaining of radio amateur licenses	This task is scheduled for phase C.
PRR_MA_4.3	Process mission plan to a set of telecommands	This task is scheduled for phase C when the mission plan will be available.
PRR_MA_4.4	Develop contingency plans for emergency response of individual sub-systems	This task is scheduled for phase C when the mission plan will be available.
PRR_MA_4.5	Risk analysis for satellite mission	This task activities were started in Phase A and are described in [PD. 1]. Further activities and their schedule are still TBD due to lack of manpower and lower priority.

		However, ongoing risk management is performed by the project management in a non-formalized matter.

4 LAUNCH OPPORTUNITIES UPDATE

Initial search for the launch opportunities was conducted in a scope of phase A activities as described in [PD. 1], chapter 3. Since the time of the search preparation some of the offers became outdated as the projects AR has been postponed to no earlier than February 2016. During phase B, contact with the launch providers was maintained and updated accordingly as shown in the table below (Table 4-1). The more comprehensive update is planned for the beginning of phase C when the new request for offers according to the updated schedule will be issued to launch providers.

For the purpose of making the choice of the most suitable offer the priorities were set in phase A that were revised and updated during phase B:

1. Orbit higher than 400 km - for lower orbits CubeSats orbits naturally decay very fast so there will be no possibility to examine sail influence on orbital decay.
2. Cost
3. Additional services included in the price (such as tests, legal assistance)
4. Reliability of the rocket

It is also worth noting that as the project progresses and become more technically mature the main driving factor for the launch date choice is no longer the project schedule, but the ability to secure financial resources for launch. Launch providers that PW-Sat2 team contacted, stated that on average the time from the beginning of negotiation to the launch takes 1-1.5 years. Although much work has been put into search for such resources, as of the date of this revision being issued, no such resources were secured whatsoever.

Table 4-1 Launch providers' offers

Company	Rocket	Country	Possible orbits	Possible launch dates	P-Pod	Tests	Included in price	Price
ISILaunch	Dnepr, PSLV, LM, Soyuz	Netherlands	Various, some SSO	2015-2016	ISIPOD included in price	Qualification tests included	• Documentation assistance • "Interface meeting" • customs/export help	120-145 000 €
Spaceflight services	Falcon 9, Soyuz	USA	• SSO (450-550 / 600-830 / 500-600) • HEO (1500 x 39000) • LEO (400 / 500 x 27000) • From decision to launch: o Russian 2-1.5 yrs. o Falcon 9: 2-1.5 yrs. o ISS – 1 yr.	2016: Q1-400km 52° | ISS Q2-500km 98.7° Q3-400km 52° | ISS Mid-620km 98.7° Q4-500km 44° 2017: Q1-500km 98.7° Q3-400km 52° | ISS Q3-550km 98.7° Q3-550km 31° 2018: Q1-475km 28.5° Q3-550km 98.7°	Included in price	Not included in price	• Help with passing the requirements. • Certification for the rocket providers and safety tests. • Integration on a rocket • P-Pod • Visa help	< 185 000 €

United Start Launch	Start1	USA	SSO 500 km (10:30am) / 400-500 i=70-90°	2016-2018	?	Not included	• Documentation assistance • customs/export help	90000€ (up to 2 kg)
Arianespace	Vega / Soyuz	France	No details at the moment (last contact in March 2014)					
JAMSS	H-2	Japan	Do not have a schedule for 2015 yet (last contact in March 2014)					200 000€
CGWIC	LM-2D	China	SSO 600 km	3Q 2015	Not included in price	Cosmodrome tests laboratory: • cosmodrome tests • integration with the P-Pod and rocket	• Interface meeting • Integration with rocket • Ejection tests • Visa assistance • Travel and accommodation	150 000 €
EADS Astrium	*No details*	ESA	ISS Orbit	*No details*	Standard service			180 000 €
Kosmotras	Dnepr	Russia	No offer for CubeSats					

5 SOFTWARE TOOLS FOR MISSION ANALYSIS

To complete task PRR_MA_2 - *Mission and orbit analysis in mission analysis software* (as defined in chapter 3.1) the PW-Sat2 Mission Analysis team required specialized software and such software was not available on WUT. Team performed a study of available software solutions and contacted two companies providing this kind of solutions to acquire student licenses:

- Systems Tool Kit (STK), Analytical Graphics Inc
- FreeFlyer, A.I. Solutions

Because of the problems in acquisition of free licenses and high prices of normal licenses, MA team studied also the possibility to use free/open-source software available in the internet:

- General Mission Analysis Tool (GMAT), NASA
- Semi-analytic Tool for End of Life Analysis (STELA), CNES
- Orbitron, Sebastian Stoff
- Open-SESSAME Framework, Space Systems Simulation Laboratory (SSSL), Virginia Tech
- SPUTNIX Satellite Simulator, S. O. Karpenko

Some of these tools which were used by the team are described in more detail in the following chapters.

5.1 ACQUISITION OF ANALYSIS TOOLS LICENSES

5.1.1 SYSTEMS TOOL KIT, ANALYTICAL GRAPHICS INC

Students' Space Association had already had some previous experience in using Analytical Graphics, Inc's Systems Tool Kit (AGI STK) software during ESEO and SSETI-Express projects[1]. As PW-Sat2 team remained in touch with SKA's alumni who took part in these projects, the first choice of mission analysis software was STK. Team contacted the representatives of AGI in Poland in January 2014 to ask for student licenses for the STK package with all additional features. Various formal and organizational reasons on WUT's side, made it virtually impossible for the Team to fulfill the requirements of AGI's Educational Alliance program. With help of Polish representatives of AGI,

[1] SKA took part in both SSETI-Express and ESEO projects under ESA's supervision. In both projects SKA teams were responsible, among other, for operations.

some effort has been done to bypass the Educational Alliance program requirements, however with little success, as of the date of this revision.

By the March of 2015 the AGI's policy regarding free version of STK license changed and from that time on it is available for non-commercial use for unlimited time. The free version of STK was used to perform analyses for PW-Sat2 phase B which resultant data are described in chapter 6.

5.1.2 FreeFlyer, A.I. Solutions

In March 2014, PW-Sat2 team contacted A.I. Solutions asking for student licenses for FreeFlyer software. However due to ITAR regulations it company was not able to offer student licenses for students outside the USA.

In February 2015 the ITAR regulations were loosened and A.I. Solutions reach out to PW-Sat2 team to confirm if the team is still interested in using FreeFlyer as it might be possible to provide the student licenses outside the USA. As for this day team remains in touch with A.I Solutions representatives.

5.2 SW tools used for phase B analyses

5.2.1 STK

STK is a comprehensive tool with capabilities greatly exceeding PW-Sat2 needs. MA team used STK to perform several analyses:

- Communication Sessions duration and frequency analysis
- Eclipses duration and frequency analysis

Although STK can utilize advanced perturbations models including atmospheric drag this feature is not available in a free license.

5.2.2 GMAT

GMAT is a NASA tool in a development phase to become their main, versatile tool for mission analysis. It is licensed on NASA Open Source Agreement v1.3. GMAT in a current version (2014a) already includes advanced perturbations modeling which made it useful for MA team for early orbital decay predictions. However, GMAT uses direct numerical integration of equations of motion and because of that is slower than semi-analytical tools and as such less feasible for long term orbital decay simulations. Sample simulation of orbital decay took approx. 40 min to complete on a personal computer available for MA team[2] and the amount of generated data was huge and required further time-consuming processing.

5.2.3 STELA

Semi-analytic Tool for End of Life Analysis has been designed by CNES to support the French Space Operations Act [RD. 2]. Its interface and functionality is focused on analyzing if the given satellite breaches the EOL requirements imposed by the French Space Act. One of the possible analyses to be performed by STELA is the LEO orbit degradation analysis. Tool allows, also, performing statistical analysis for the unstable orbits running the simulation multiple times with a user-defined spread of the selected parameters. STELA is a semi-analytic tool which means that it can run much faster than tools which numerically integrates the equations. This makes STELA especially useful for long-term orbital decay analyses. PW-Sat2 MA team used STELA for orbital decay analyses described in section 6.5.

5.2.4 ORBITRON

Orbitron is a satellite tracking system for radio amateur and observing purposes [RD. 3]. It features SGP4/SDP4 propagator and allows inputting data in TLE format. One of the Orbitron functionalities is estimation of the time and duration of the communication sessions for the user-defined ground station with a given min. elevation angle. This featured became very useful for preliminary communication sessions predictions.

[2] Simulation duration is given rather to justify decisions made by the team choosing the most suitable software, taking into account available hardware, than to give any indication of SW performance as such. To give a reliable information on GMAT performance comprehensive tests should be performed which is out of the scope of this project.

6 SELECTED ORBITS ANALYSIS

From the very beginning of the PW-Sat2 project it was clear that the destination orbit is not defined and the satellite was designed to perform universally well on any LEO. This also imposed a requirement that all the analyses should be performed for different possible orbits. Representative orbits were selected, based on the most frequently occurring orbit types in the launch opportunities offers (see chapter 4).

6.1 SELECTED ORBITS DESCRIPTION

7 different orbits were selected as representatives for detailed analyses:

- 575km 65deg orbit
- 600km 52deg orbit
- SSO400km, LTAN: 10:00 h
- SSO500km, LTAN: 10:00 h
- SSO600km, LTAN: 10:00h
- SSO700km, LTAN: 10:00 h
- SSO780km, LTAN: 10:00h

Details of selected orbits orbital parameters are presented in a table below:

Table 6-1Orbital parameters of the selected representative orbits

Orbit	SMA [km]	ECC [-]	INC [°]	RAAN [°]	AP [°]	Period [s]
575km65deg	6953.14	0.00	65.00	111.74	0.00	5770.00
600km52deg	6978.14	0.00	52.00	111.74	0.00	5801.23
SSO400km	6778.14	0.00	97.12	111.74	0.00	5553.62
SSO500km	6878.14	0.00	97.49	111.74	0.00	5676.98
SSO600km	6978.14	0.00	97.88	111.74	0.00	5801.23
SSO700km	7078.14	0.00	98.28	111.74	0.00	5926.38
SSO780km	7158.14	0.00	98.61	111.74	0.00	6027.14

Starting epoch for all analyses was 12 Feb 2016, 11:00:00 UTC and for communication and eclipse analyses ending date was 12 Feb 2017, 11:00:00 UTC. The same starting epoch was chosen for the orbital decay analyses. All the diagrams shown in paragraphs below are also available in bigger format in *Appendix A: Diagrams close-ups*

6.2 STK ANALYSES PARAMETERS

Even though PW-Sat2 mission is designed to last 2 months (TBD), longer simulation time of one year was chosen to cover different possible configurations of the SC w.r.t. Earth and Sun. Longer simulation time allowed to get more general results as both the final destination orbit and launch epoch are yet TBD. For communication and eclipse analyses J4Perturbation model was used which does not take aerodynamic drag into account and thus orbit does not decay with time. Simulation parameters were as follows:

- Starting epoch: 12 Feb 2016 11:00:00.000 UTCG
- End epoch: 12 Feb 2017 11:00:00.000 UTCG
- Step size: 60 sec
- Propagator: J4Perturbation[3]

6.3 COMMUNICATION SESSIONS ANALYSIS

In STK communication sessions are modeled as accesses between the SC and Ground Station and term 'access' will be used here interchangeably with 'communication session'.

For all the simulations GS on the Faculty of Electronics and Information Technology of WUT was defined as PW-Sat2 GS with parameters as follows:

- Location: Warsaw, Latitude: 52.2188° East, Longitude: 21.0107° North
- Altitude above sea level: 130m
- Minimum elevation angle for satellite visibility: 30°.
- Omni-directional antenna

Communication sessions analyses were divided into two parts:

- Communication sessions duration, average duration, duration spread
- Communication sessions frequency, max time without communication

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[3] Quoting STK Online Help for STK 10.1.3 [RD. 4]: *The J4 Perturbation (second-order) propagator accounts for secular variations in the orbit elements due to Earth oblations. This propagator does not model atmospheric drag or solar or lunar gravitational forces. The J4 propagator includes the first- and second-order effects of J2 and the first-order effects of J4. The J3 coefficient, which produces long period periodic effects, is not included in either propagator. J4 is approximately 1000 times smaller than J2 and is a result of Earth oblations. Since the second-order J2 and the first-order J4 secular effects are very small, there is little difference between the orbits generated by the two propagators.*

6.3.1 COMMUNICATION SESSIONS DURATION ANALYSIS

Simulation results were the Modified Julian Dates of the access start and end. From these data access duration was calculated. Accesses with duration shorter than 60 s where omitted in further analysis because 60 s was considered as too short time for communication with the SC. Summary of the results is shown in the following table, with the total access time (for accesses longer than 60 s) as a fraction of whole simulation time and mean access time (taking into account also only accesses longer than 60 s). Additional data is shown in the following paragraphs.

Table 6-2 Communication sessions duration analysis.

Orbit	Total Access Time (Duration >60 s) [%]	Mean Access (Duration >60 s) [s]
575km65deg	0.636 %	199
600km52deg	0.919 %	231
SSO400km	0.248 %	141
SSO500km	0.371 %	168
SSO600km	0.496 %	201
SSO700km	0.639 %	231
SSO780km	0.763 %	254

6.3.1.1 575km 65deg orbit

Histogram below shows access duration distribution for the 575km 65deg orbit:

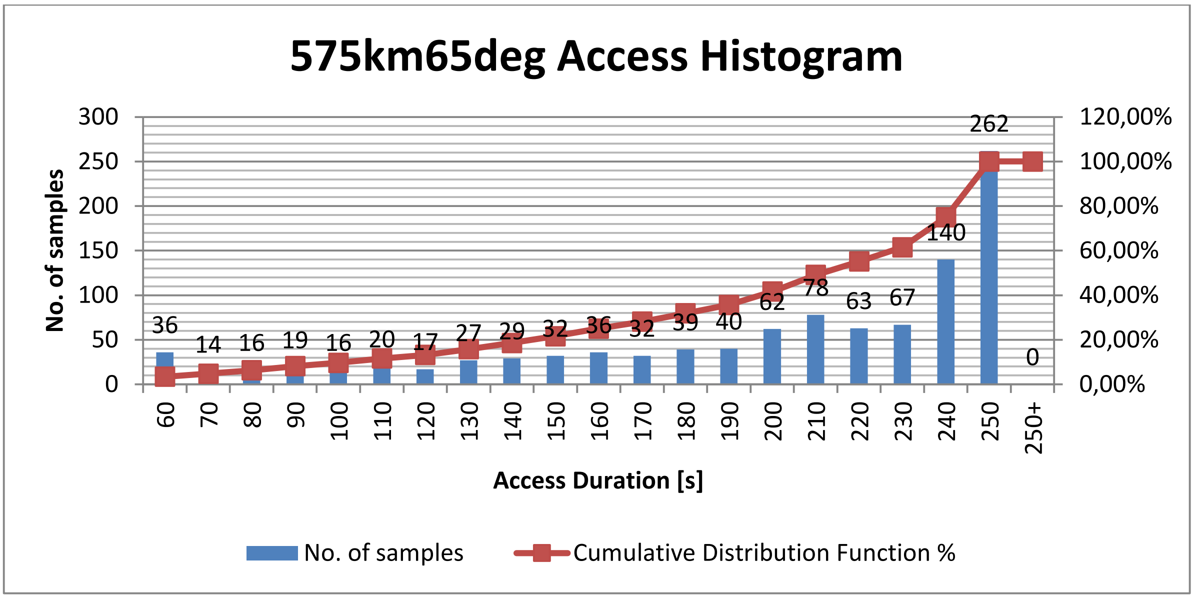

Figure 6-1 575km65deg Access Histogram

Data on the histogram show all accesses, including those shorter than 60 s. 38.47 % of accesses are between 230 s and 250 s long and only 3.44 % is shorter than 60 s.

6.3.1.2 600km 52deg orbit

Histogram below shows access duration distribution for the 600km 52deg orbit:

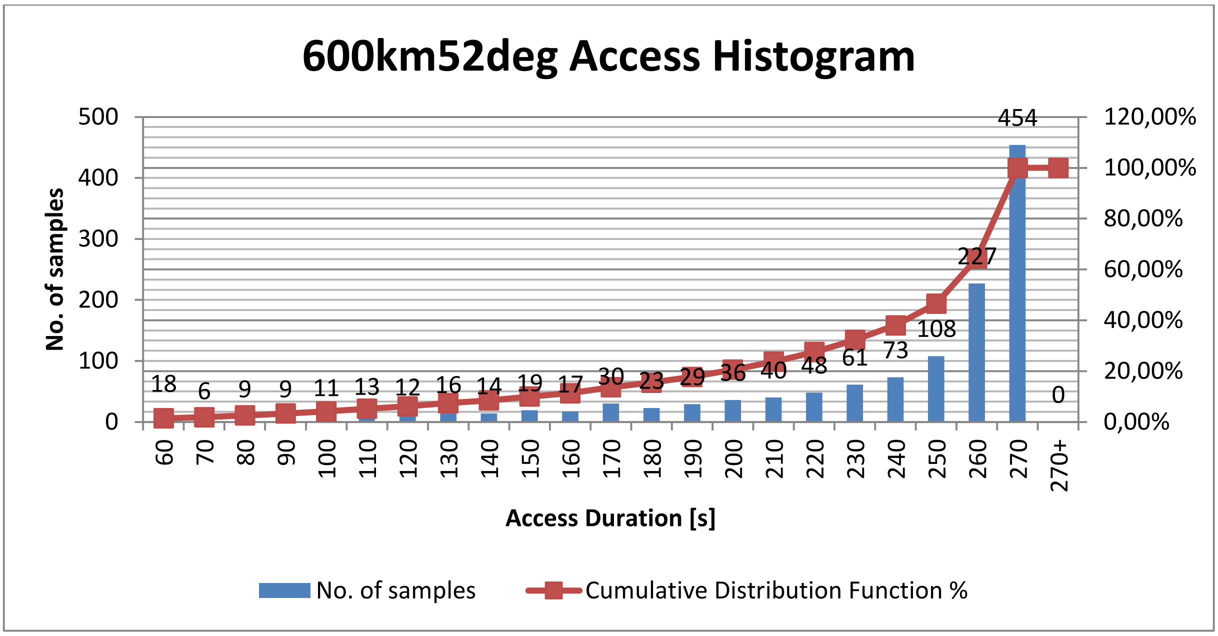

Figure 6-2 600km52deg Access Histogram

Data on the histogram show all accesses, including those shorter than 60 s. 53.50 % of accesses are between 250 s and 270 s long and only 1.41 % is shorter than 60 s.

6.3.1.3 SSO 400km orbit

Histogram below shows access duration distribution for the SSO 400km orbit:

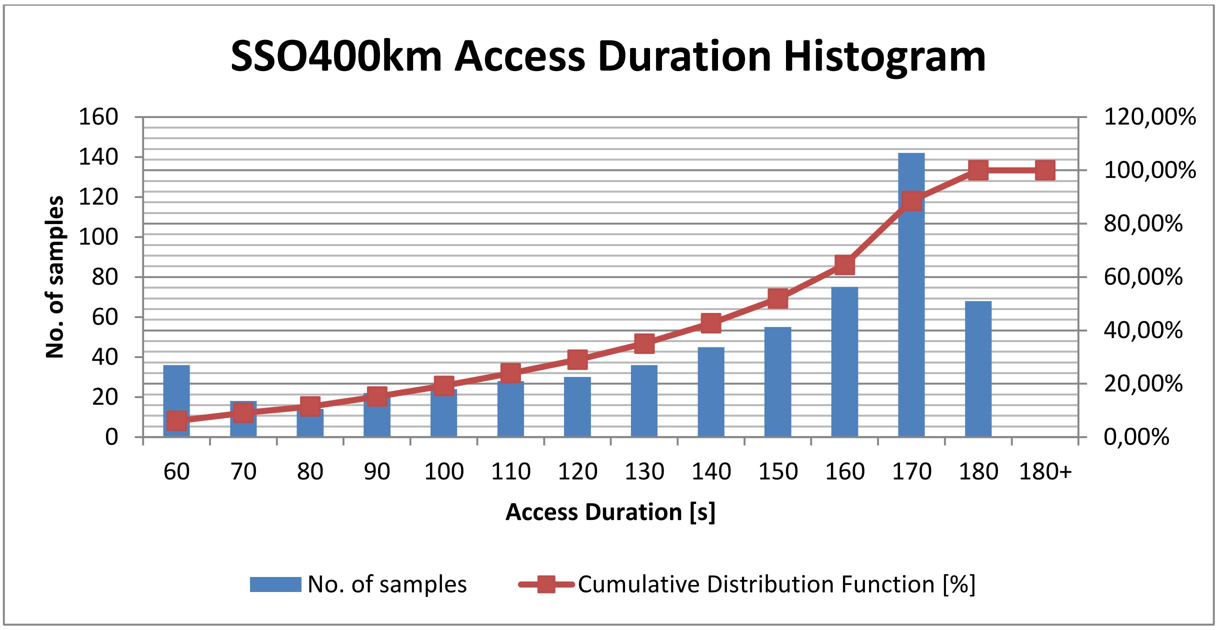

Figure 6-3 SSO400km Access Duration Histogram

Data on the histogram show all accesses, including those shorter than 60 s. 48.06 % of accesses are between 160 s and 180 s long and only 6.07 % is shorter than 60 s.

6.3.1.4 SSO 500km orbit

Histogram below shows access duration distribution for the SSO 500km orbit:

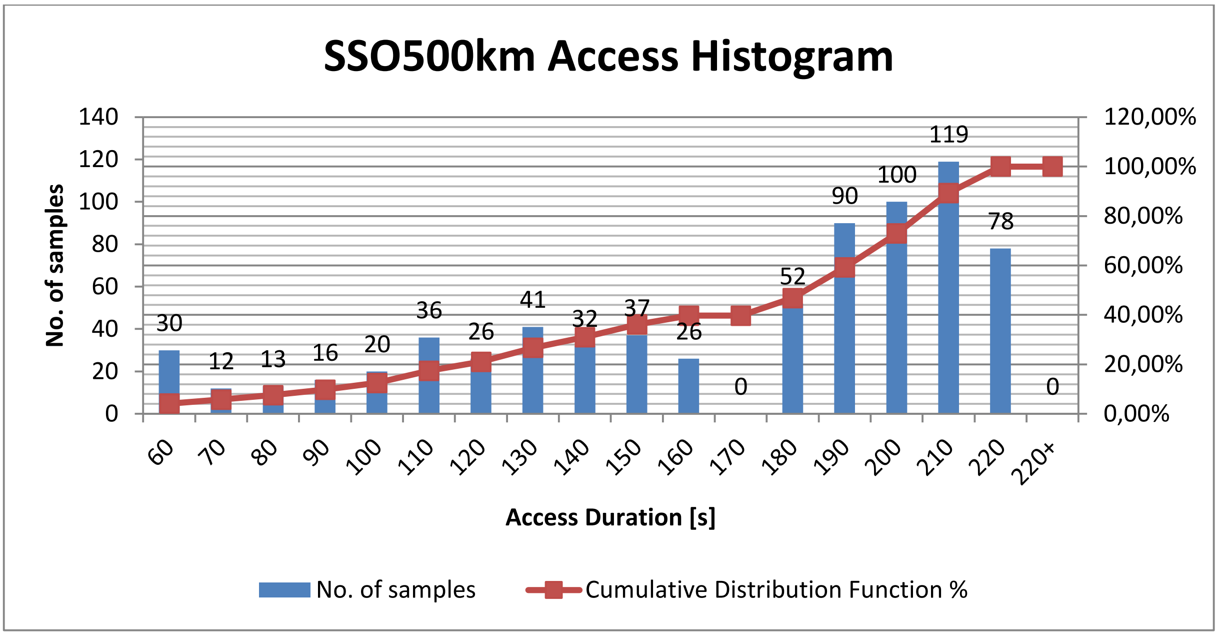

Figure 6-4 SSO500km Access Histogram

Data on the histogram show all accesses, including those shorter than 60 s. 53.16 % of accesses are between 180 s and 220 s long and only 4.12 % is shorter than 60 s.

6.3.1.5 SSO 600km orbit

Histogram below shows access duration distribution for the SSO 600km orbit:

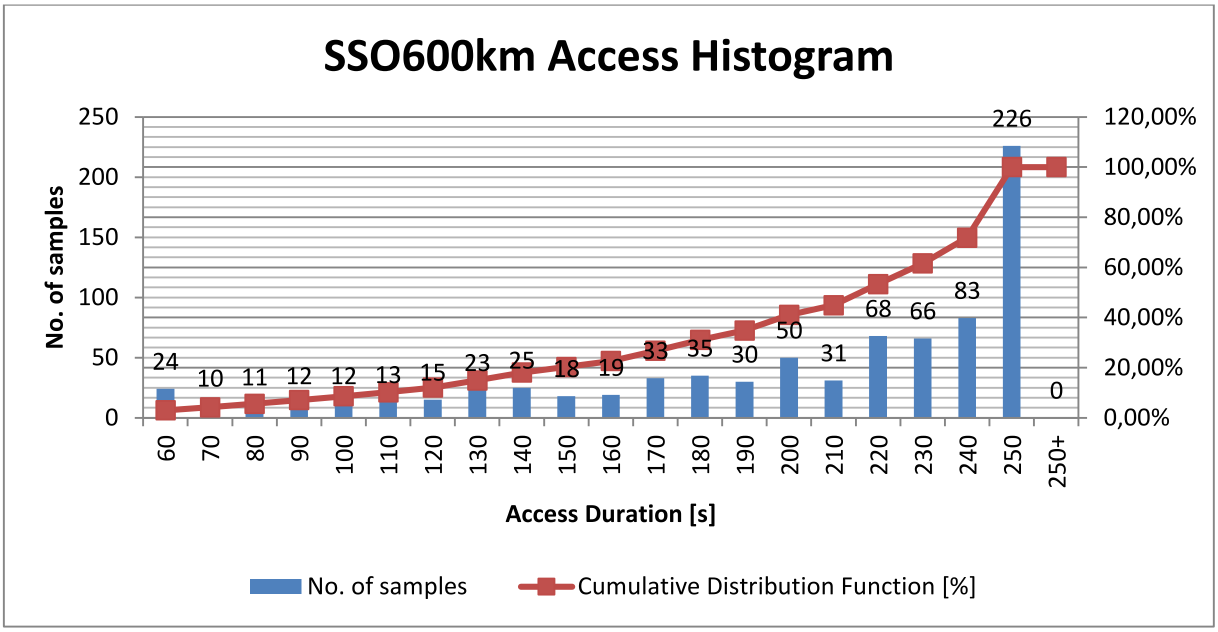

Figure 6-5 SSO600km Access Histogram

Data on the histogram show all accesses, including those shorter than 60 s. 55.10 % of accesses are between 210 s and 250 s long and only 2.99 % is shorter than 60 s.

6.3.1.6 SSO 700km orbit

Histogram below shows access duration distribution for the SSO 700km orbit:

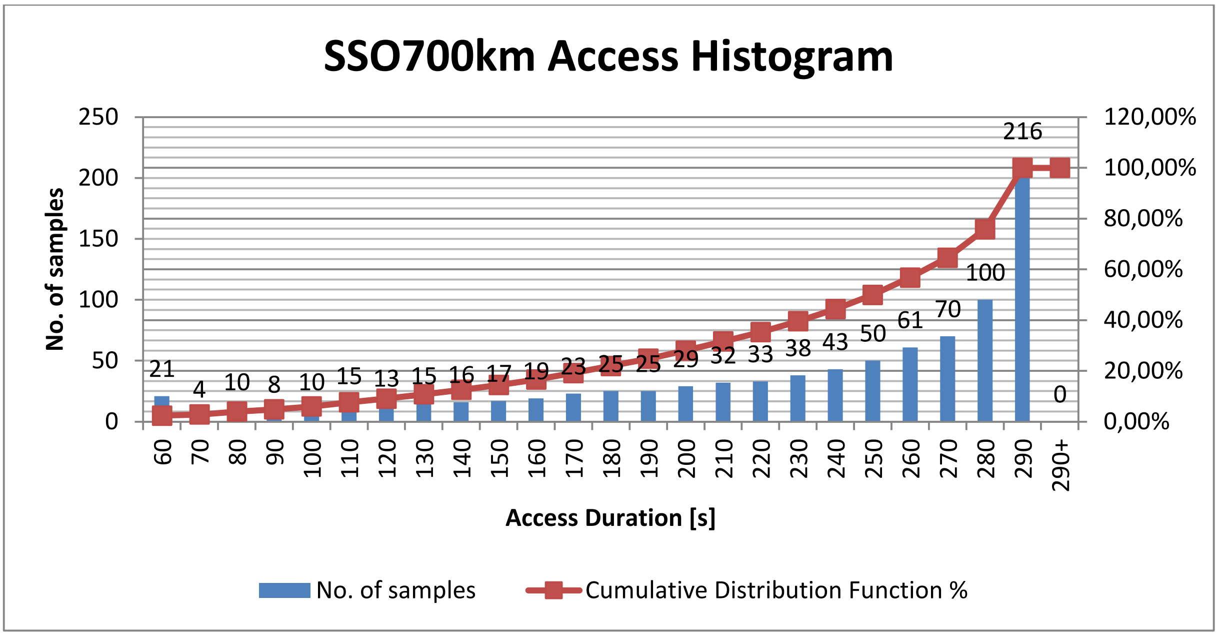

Figure 6-6 SSO700km Access Histogram

Data on the histogram show all accesses, including those shorter than 60 s. 50.06 % of accesses are between 250 s and 290 s long and only 2.35 % is shorter than 60 s.

6.3.1.7 SSO 780km orbit

Histogram below shows access duration distribution for the SSO 780km orbit:

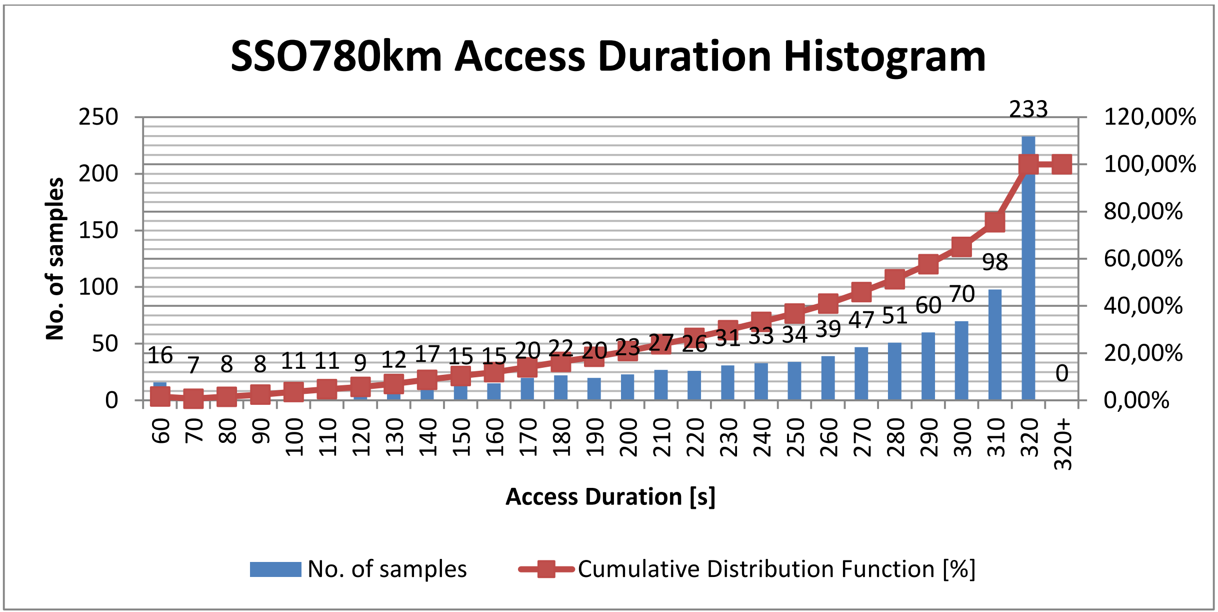

Figure 6-7 SSO780km Access Duration Histogram

Data on the histogram show all accesses, including those shorter than 60 s. 53.17 % of accesses are between 270 s and 320 s long and only 1.66 % is shorter than 60 s.

6.3.2 Communication sessions frequency and gaps

Second part of the communication sessions analysis focused on the frequency of the communication sessions and duration of gaps between accesses. ‘Gap’ is understood here as a time between two subsequent communication sessions, that is the time with no communication. Similarly to the previous chapter, accesses shorter than 60 s where omitted and the gap durations before and after such omitted access where summed. Summary of the results is shown in the table below. Additional data is shown in the following paragraphs.

Table 6-3 Communication sessions gaps duration analysis

Orbit	Max Access Gap (Duration >60 s) [s]	Mean Access Gap (Duration >60 s) [s]
575km65deg	62391	31096
600km52deg	74694	24890
SSO400km	134446	56660
SSO500km	85164	45077
SSO600km	53256	40347
SSO700km	48453	36031
SSO780km	49213	33139

6.3.2.1 575km 65deg orbit

Histogram below shows access gaps duration distribution for the 575km 65deg orbit:

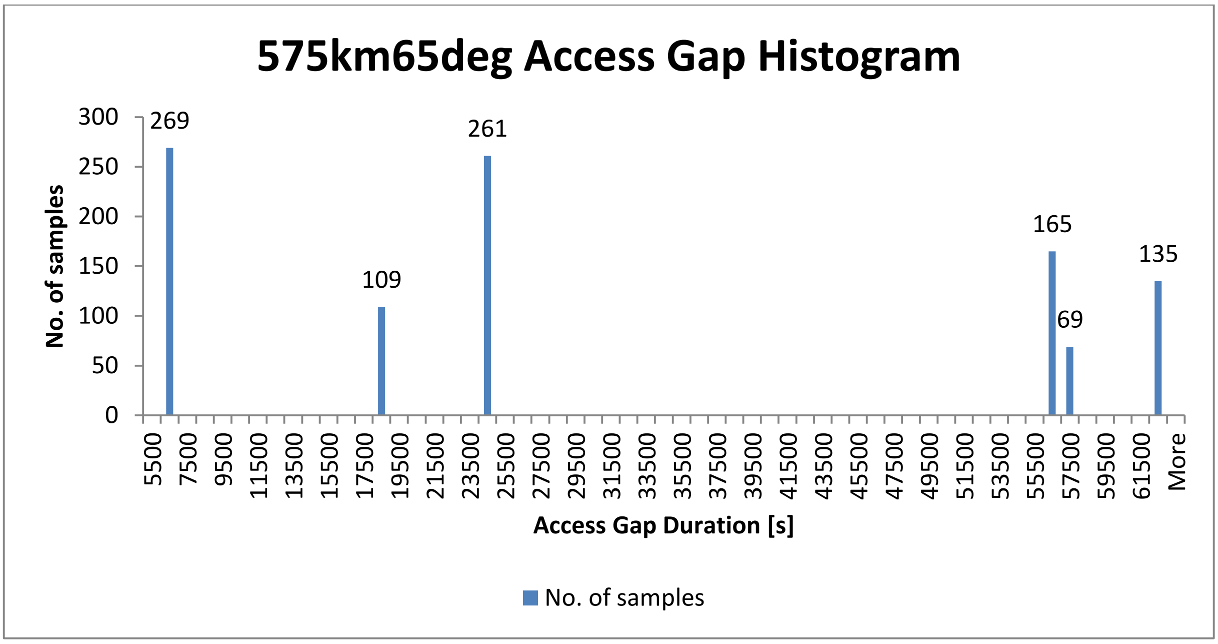

Figure 6-8 575km65deg Access Gap Histogram

Access gap durations are grouped around a few values, however never exceed 24 h (86400 s).

6.3.2.2 600km 52deg orbit

Histogram below shows access gaps duration distribution for the 600km 52deg orbit:

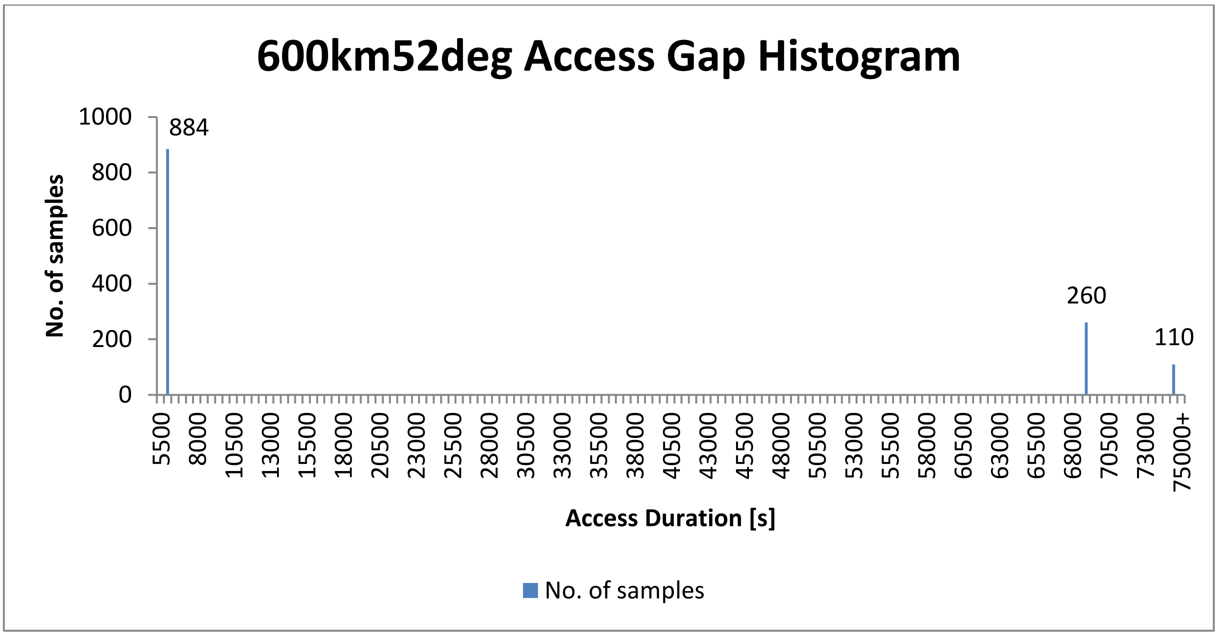

Figure 6-9 600km52deg Access Gap Histogram

Access gap durations are grouped around a few values, however never exceed 24 h (86400 s).

6.3.2.3 SSO 400km orbit

Histogram below shows access gaps duration distribution for the SSO 400km orbit:

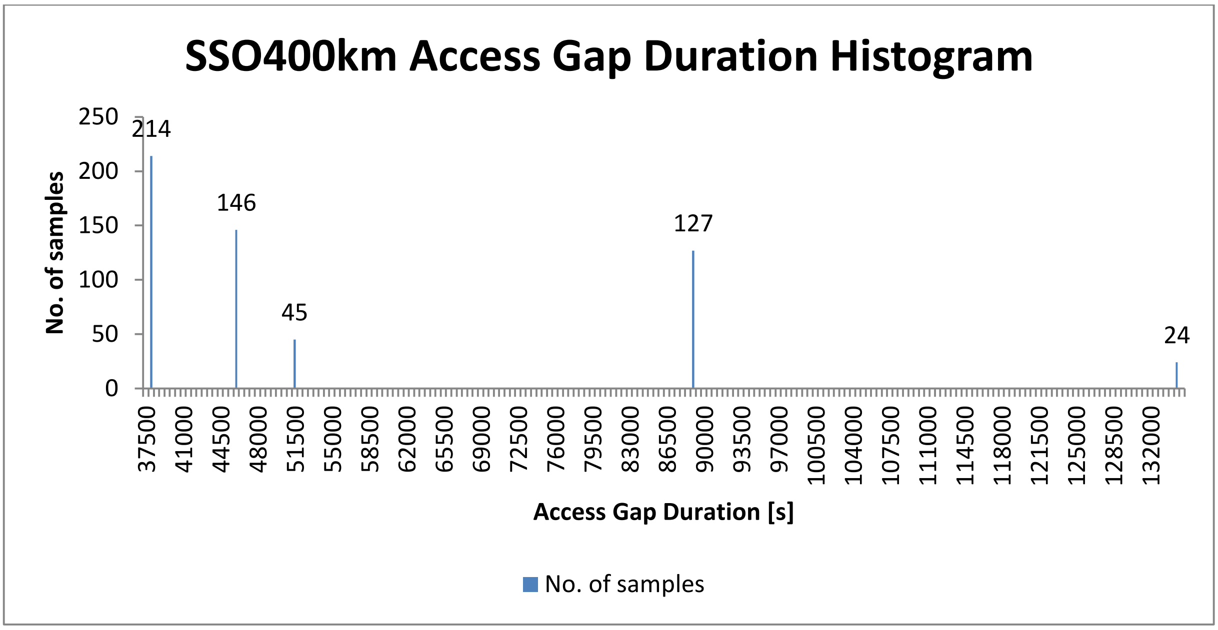

Figure 6-10 SSO400km Access Gap Duration Histogram

Access gap durations are grouped around a few values, 24 times exceeding 24 h (86400 s) and lasting between 134000 s and 134500 s (over 37 h).

6.3.2.4 SSO 500km orbit

Histogram below shows access gaps duration distribution for the SSO 500km orbit:

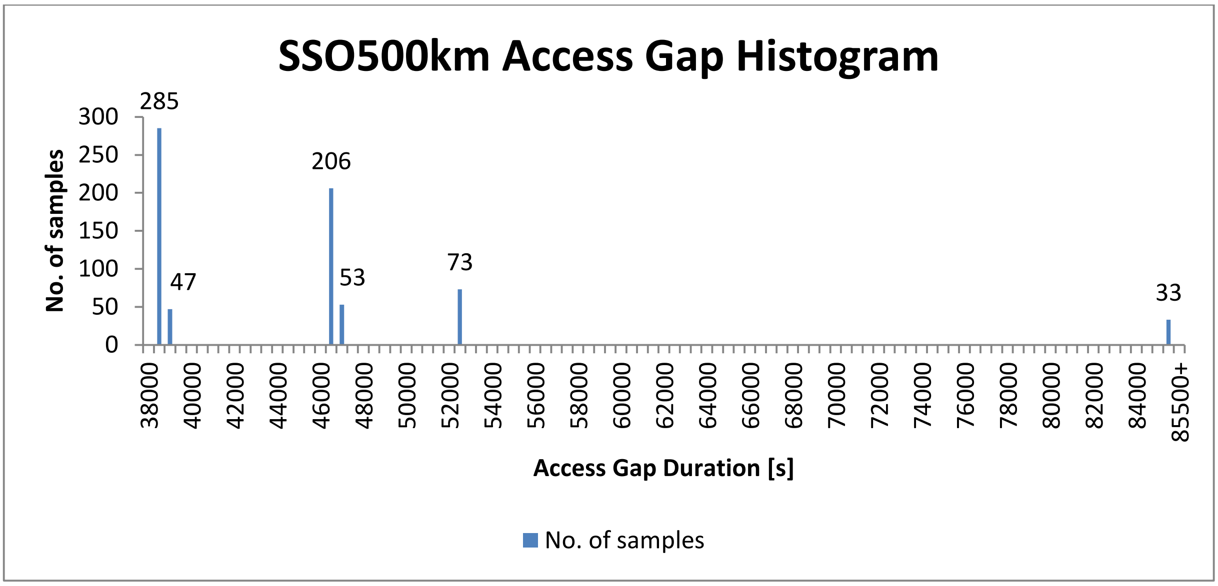

Figure 6-11 SSO500km Access Gap Histogram

Access gap durations are grouped around a few values, however never exceed 24 h (86400 s) and 95.27 % are shorter than 52500 s (less than 15 h).

6.3.2.5 SSO 600km orbit

Histogram below shows access gaps duration distribution for the SSO 600km orbit:

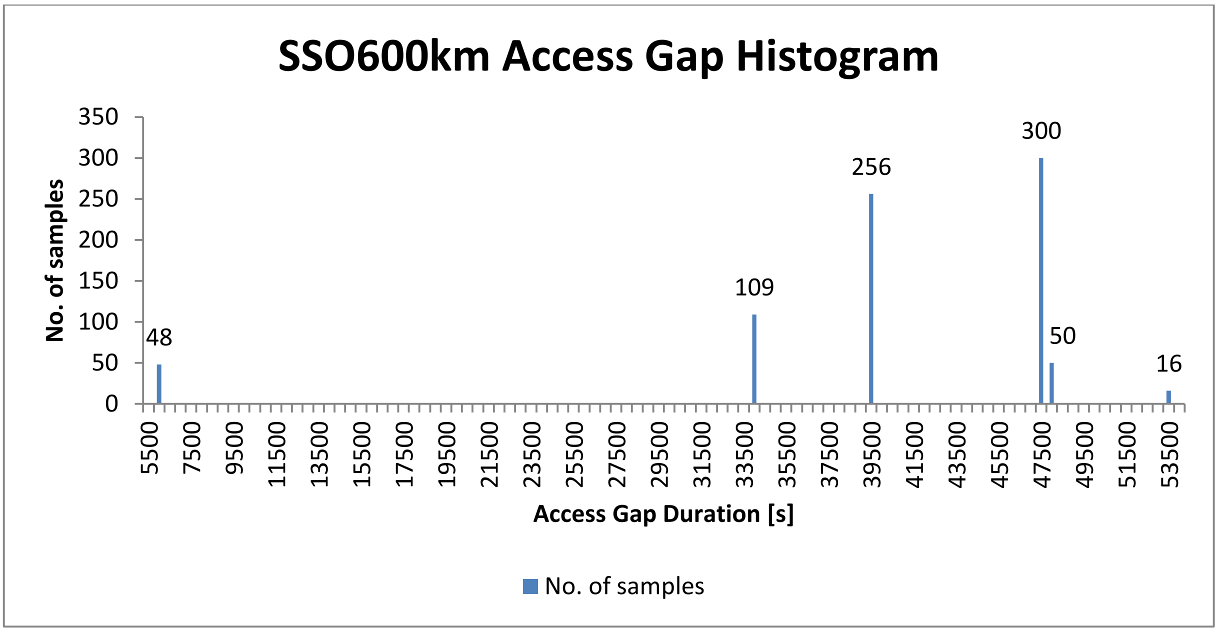

Figure 6-12 SSO600km Access Gap Histogram

Access gap durations are grouped around a few values, however never exceed 24 h (86400 s) and 91.78 % of samples are between 33500 s and 48000 s.

6.3.2.6 SSO 700km orbit

Histogram below shows access gaps duration distribution for the SSO 700km orbit:

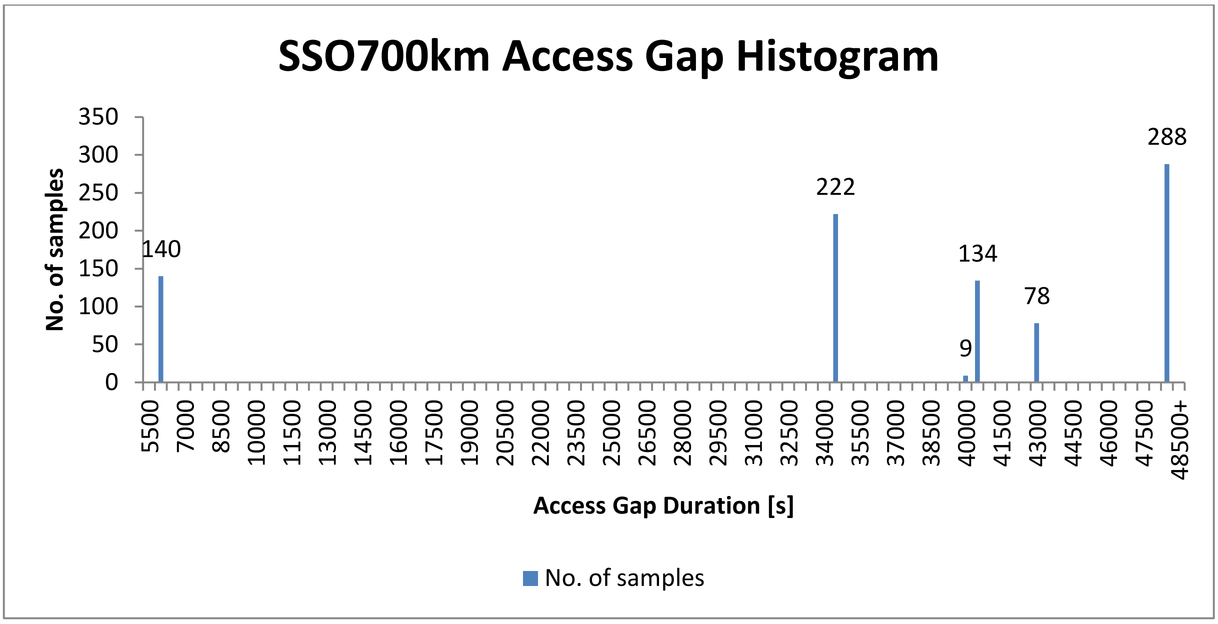

Figure 6-13 SSO700km Access Gap Histogram

Access gap durations are grouped around a few values, however never exceed 24 h (86400 s) and 83.93 % of samples are between 34500 s and 48500 s.

6.3.2.7 SSO 780km orbit

Histogram below shows access gaps duration distribution for the SSO 780km orbit:

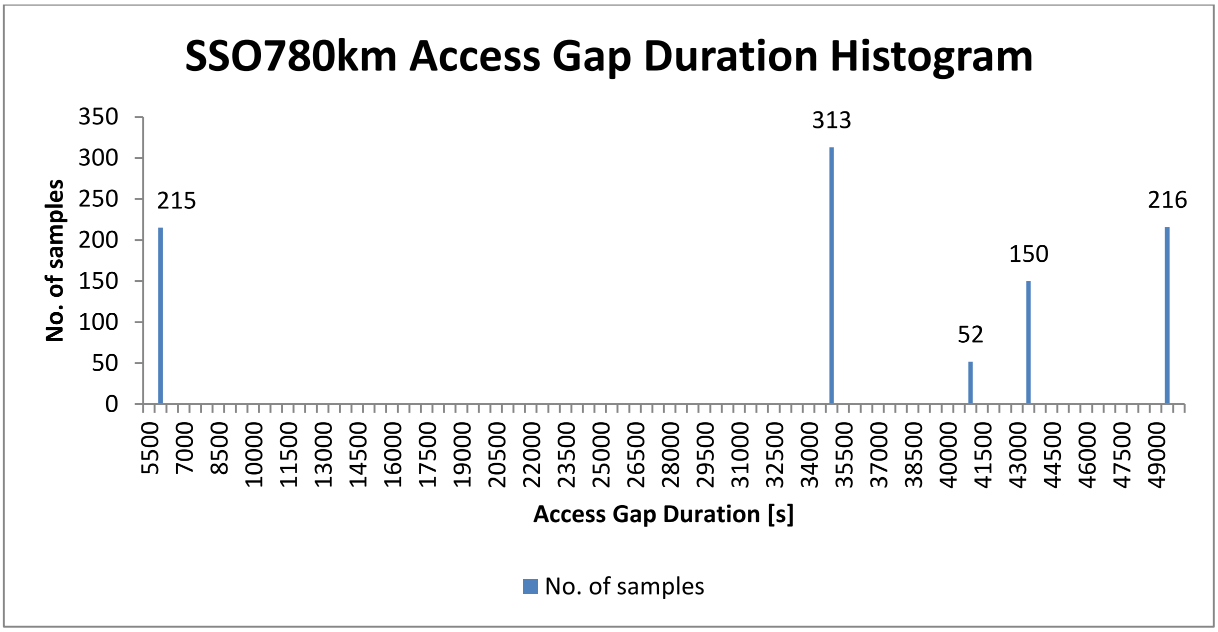

Figure 6-14 SSO780km Access Gap Duration Histogram

Access gap durations are grouped around a few values, however never exceed 24 h (86400 s).

6.4 ECLIPSES AND SUNLIGHT EXPOSURE ANALYSIS

STK has a functionality to calculate the eclipse time and duration for the SC. This data will be taken into consideration in the design of SC Electrical Power System and Thermal Control System. In this chapter eclipse is understood as the sum of SC time in Earth's penumbra and umbra regions. For sun exposure calculations only umbra time was considered as 'eclipse'.

6.4.1 ECLIPSE DURATION ANALYSIS

The table below presents the summary of the results, where 'Eclipse Time' is a total time SC spends in eclipse as a fraction of the whole time of simulation. Detailed data for each orbit is presented in the following paragraphs.

Table 6-4 Eclipse duration analysis results

Orbit	Eclipse Time [%]	Max Eclipse [s]	Mean Eclipse [s]
575km65deg	28.68 %	2134	1858
600km52deg	31.30 %	2131	1908
SSO400km	37.60 %	2113	2089
SSO500km	36.24 %	2086	2058
SSO600km	35.01 %	2064	2032
SSO700km	33.90 %	2047	2010
SSO780km	33.07 %	2035	1993

6.4.1.1 575km 65deg orbit

Histogram below shows eclipses duration distribution for the 575km 65deg orbit:

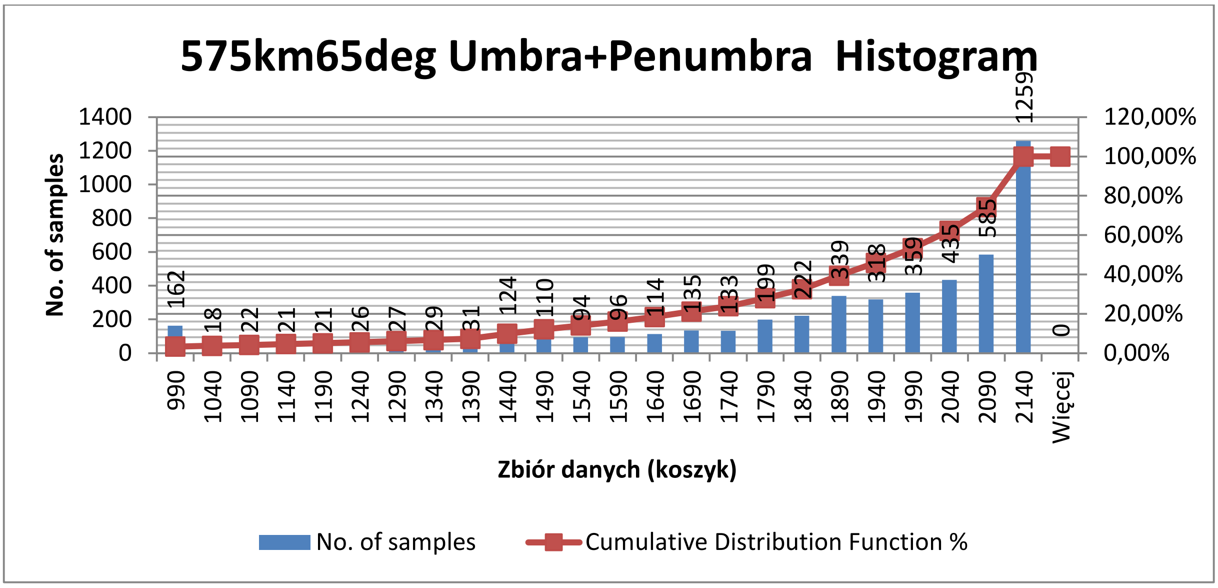

Figure 6-15 575km65deg Umbra+Penumbra histogram

Eclipse duration never exceeds 2134 s (35 min 36 s) and over 50 % of samples is between 1940 s and 2134 s.

6.4.1.2 600km 52deg orbit

Histogram below shows eclipses duration distribution for the 600km 52deg orbit:

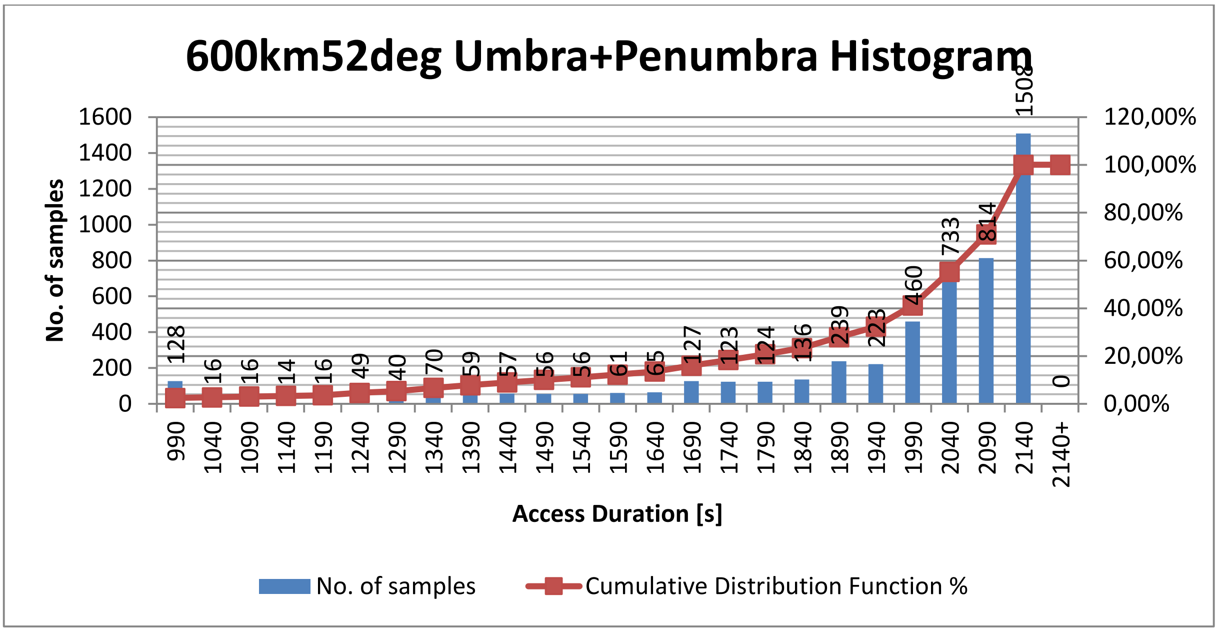

Figure 6-16 600km52deg Umbra+Penumbra Histogram

Eclipse duration never exceeds 2131 s (35 min 33 s) and over 58 % of samples is between 2040 s and 2131 s.

6.4.1.3 SSO 400km orbit

Histogram below shows eclipses duration distribution for the SSO 400km orbit:

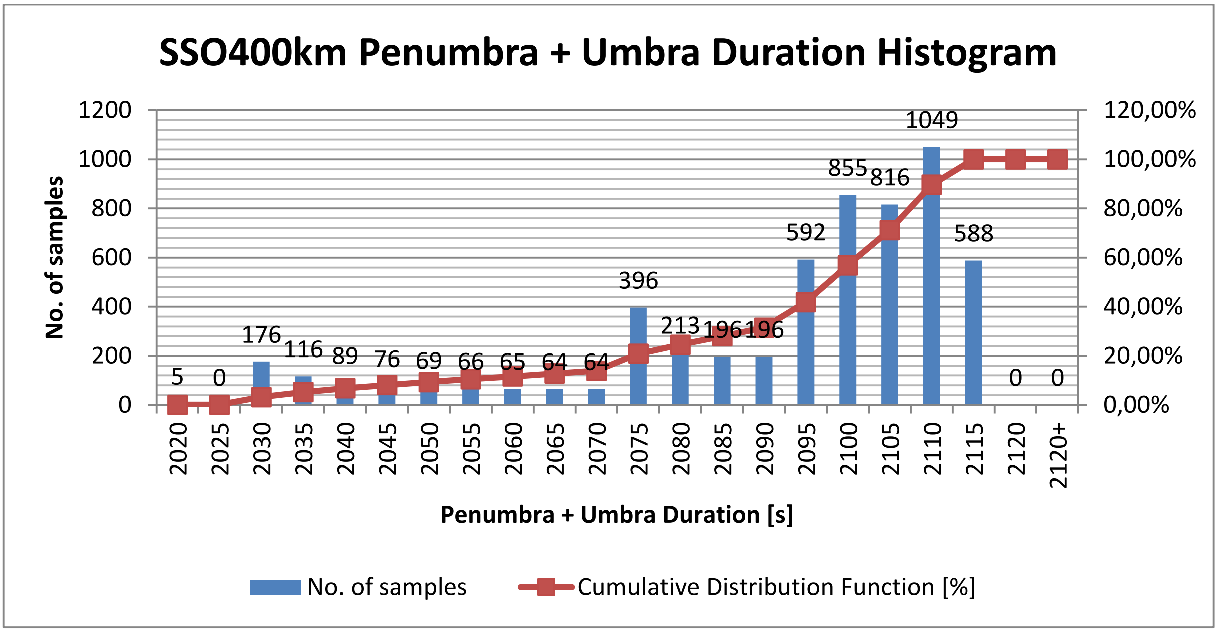

Figure 6-17 SSO400km Penumbra + Umbra Duration Histogram

Eclipse duration never exceeds 2113 s (35 min 13 s) and over 58 % of samples are between 2095 s and 2113 s.

6.4.1.4 SSO 500km orbit

Histogram below shows eclipses duration distribution for the SSO 500km orbit:

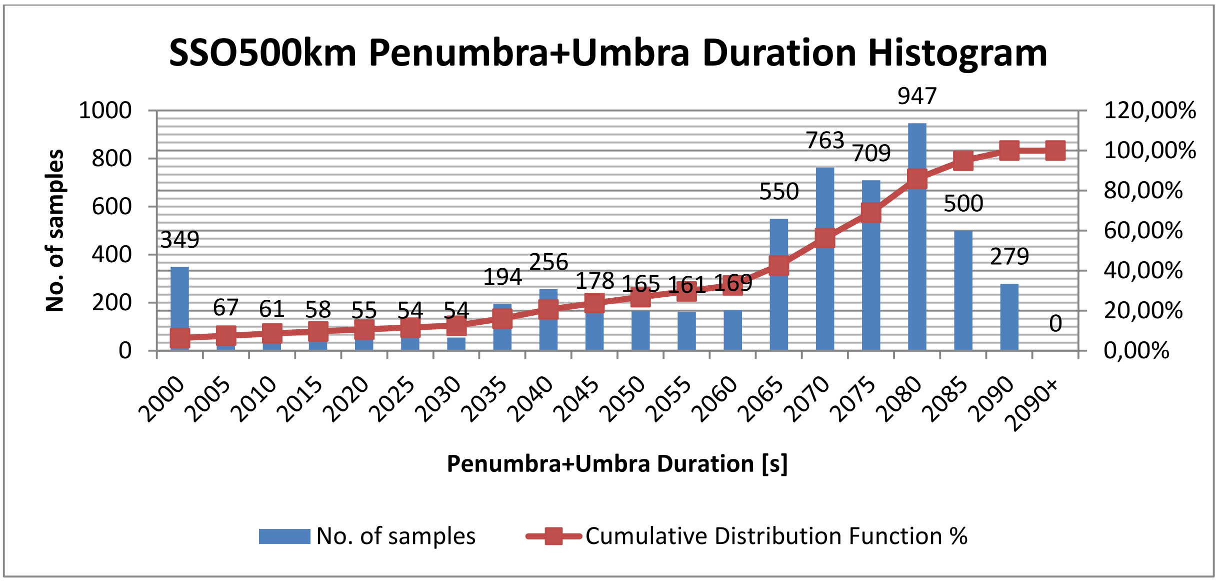

Figure 6-18 SSO500km Penumbra+Umbra Duration Histogram

Eclipse duration never exceeds 2086 s (34 min 46 s) and over 57 % of samples are between 2065 s and 2086 s.

6.4.1.5 SSO 600km orbit

Histogram below shows eclipses duration distribution for the SSO 600km orbit:

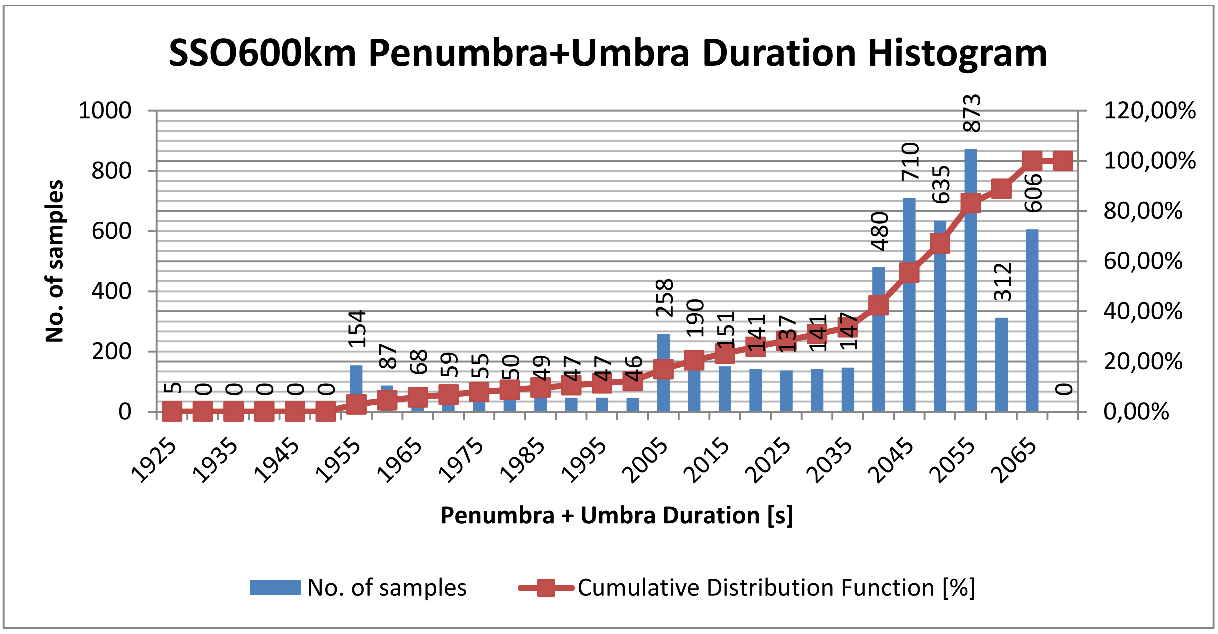

Figure 6-19 SSO600km Panumbra+Umbra Duration Histogram

Eclipse duration never exceeds 2064 s (34 min 24 s) and over 57 % of samples is between 2040 s and 2064 s.

6.4.1.6 SSO 700km orbit

Histogram below shows eclipses duration distribution for the SSO 700km orbit:

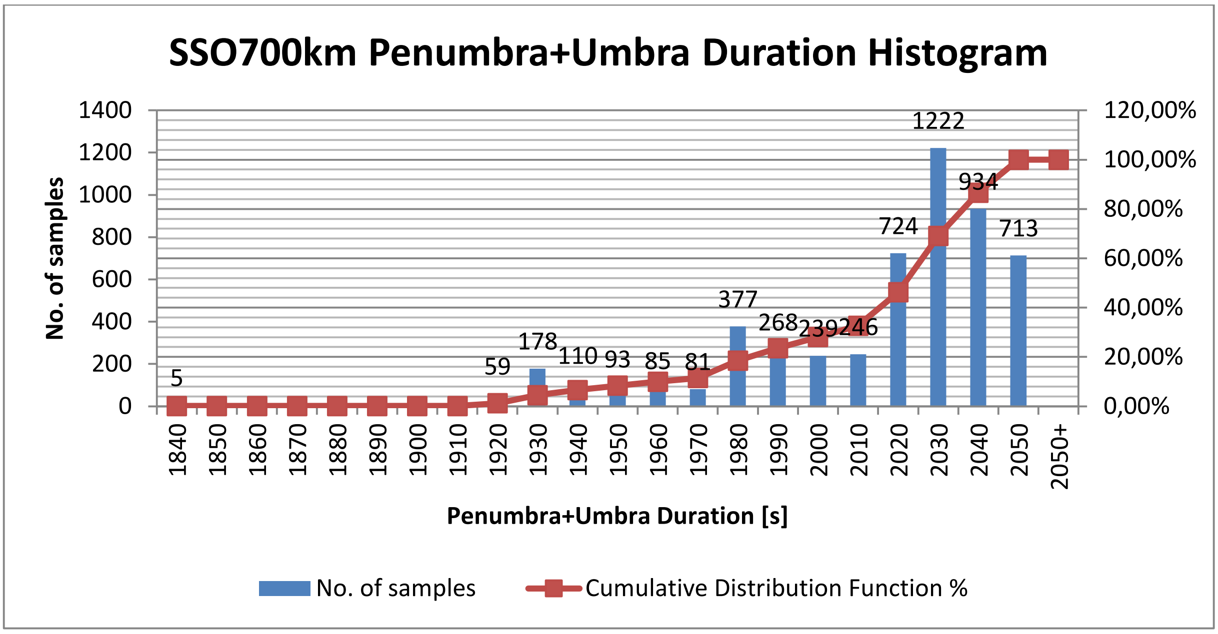

Figure 6-20 SSO700km Penumbra+Umbra Duration Histogram

Eclipse duration never exceeds 2047s (34 min 7 s) and over 53 % of samples is between 2020 s and 2047 s.

6.4.1.7 SSO 780km orbit

Histogram below shows eclipses duration distribution for the SSO 780km orbit:

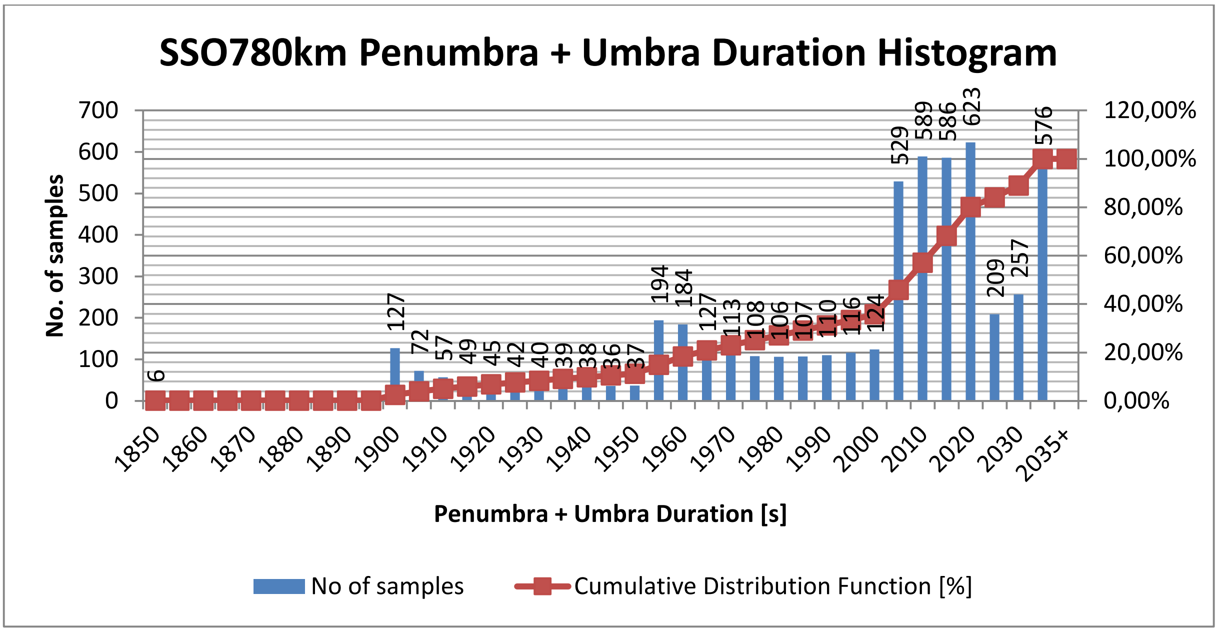

Figure 6-21 SSO780km Penumbra + Umbra Duration Histogram

Eclipse duration never exceeds 2035 s (33 min 55 s) and over 64 % of samples is between 2000 s and 2035 s.

6.4.2 SUN EXPOSURE DURATION ANALYSIS

Table below presents the results of the sun exposure analysis, where 'No. of Sun exposures > 1.1 Period' is the parameter indicating if there are orbital cycles in which satellite will not cross Earth's umbra region at all, which is interesting from the thermal control point of view. This parameter is a simple count of Sun exposure periods which are longer than 1.1 times orbital period.

Table 6-5 Sun exposure duration analysis results

Orbit	Max Exposure time [s]	No. of Sun exposures > 1.1 Period
575km65deg	1047315	4
600km52deg	680071	3
SSO400km	3534	0
SSO500km	3698	0
SSO600km	3858	0
SSO700km	4014	0
SSO780km	4139	0

6.4.2.1 575km 65deg orbit

Histogram below shows eclipses duration distribution for the 575km 65deg orbit:

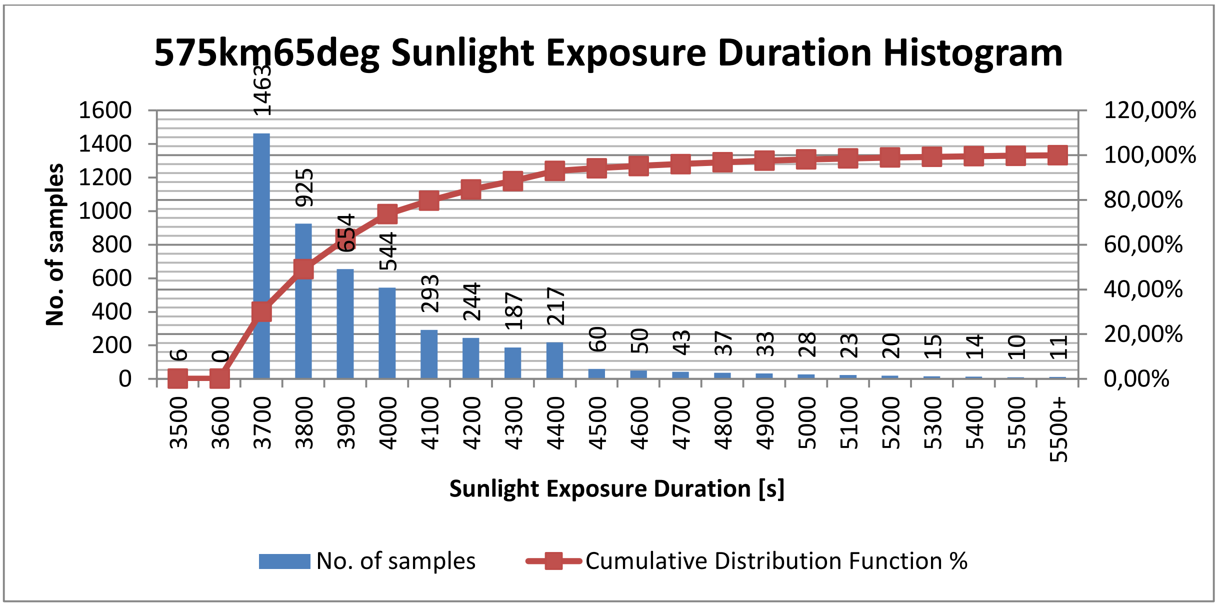

Figure 6-22 575km65deg Sunlight Exposure Duration Histogram

Maximum exposure duration is 1047315 s (over 12 days), however 90 % of samples are below 4400 s.

6.4.2.2 600km 52deg orbit

Histogram below shows eclipses duration distribution for the 600km 52deg orbit:

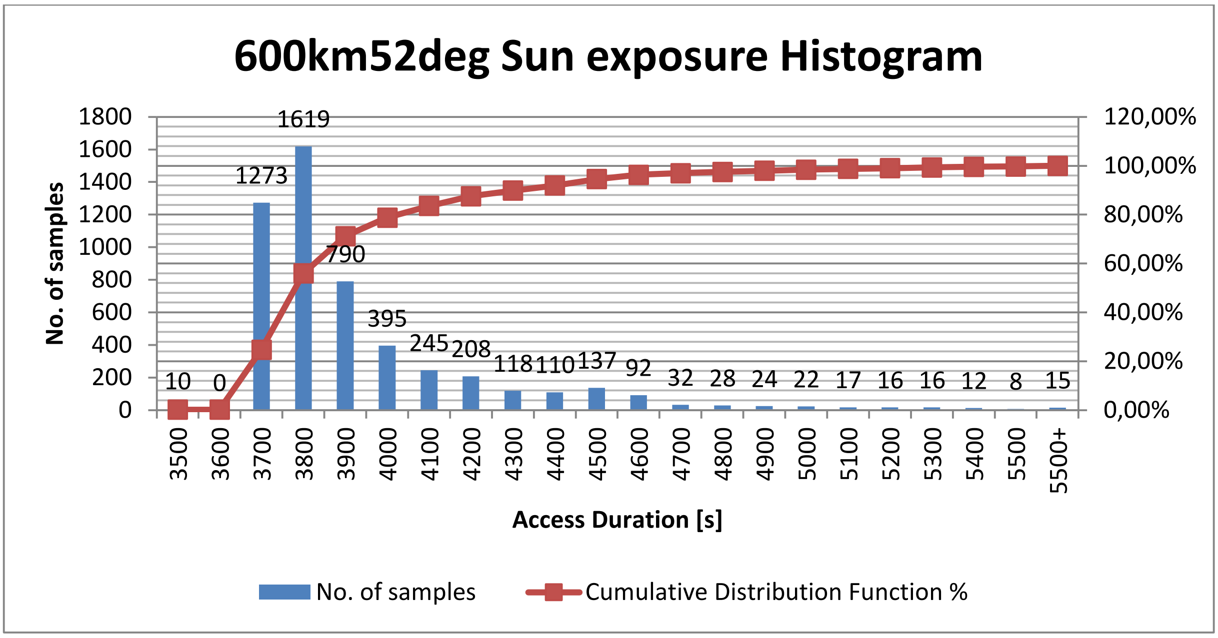

Figure 6-23 600km52deg Sun exposure Histogram

Maximum exposure duration is 680071 s (almost 8 days), however 90 % of samples are below 4400 s.

6.4.2.3 SSO 400km orbit

Histogram below shows eclipses duration distribution for the SSO 400km orbit:

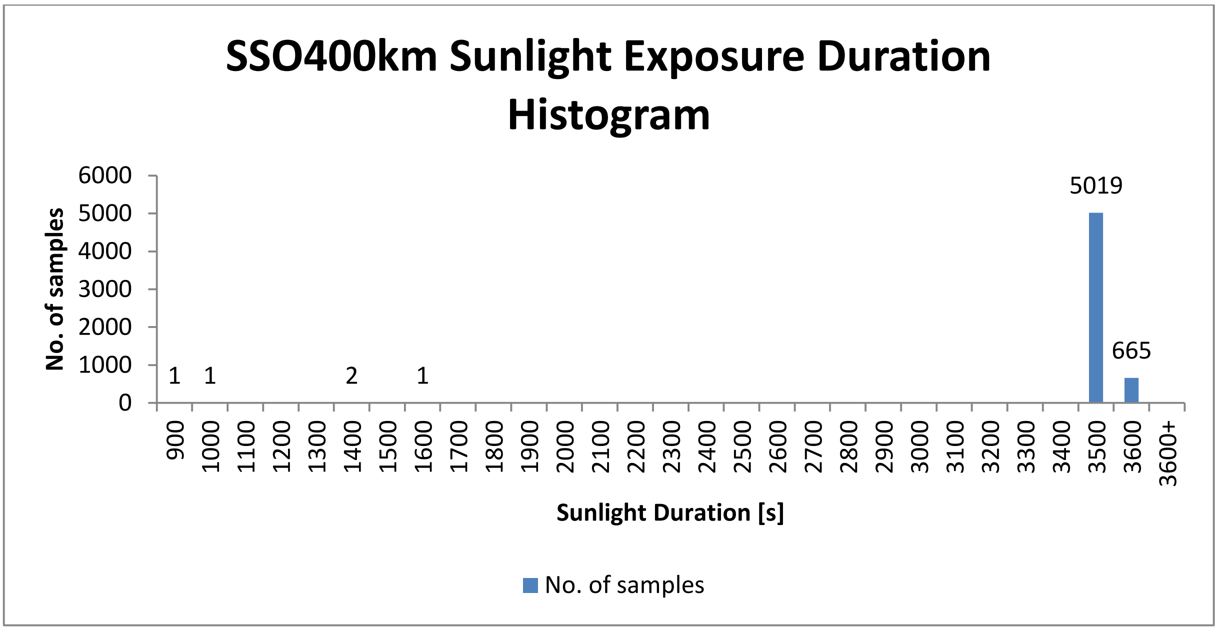

Figure 6-24 SSO400km Sunlight Exposure Duration Histogram

Maximum exposure duration is 3534 s (less than 1 h), and 99.91 % of samples are below between 3400 s and 3543 s.

6.4.2.4 SSO 500km orbit

Histogram below shows eclipses duration distribution for the SSO 500km orbit:

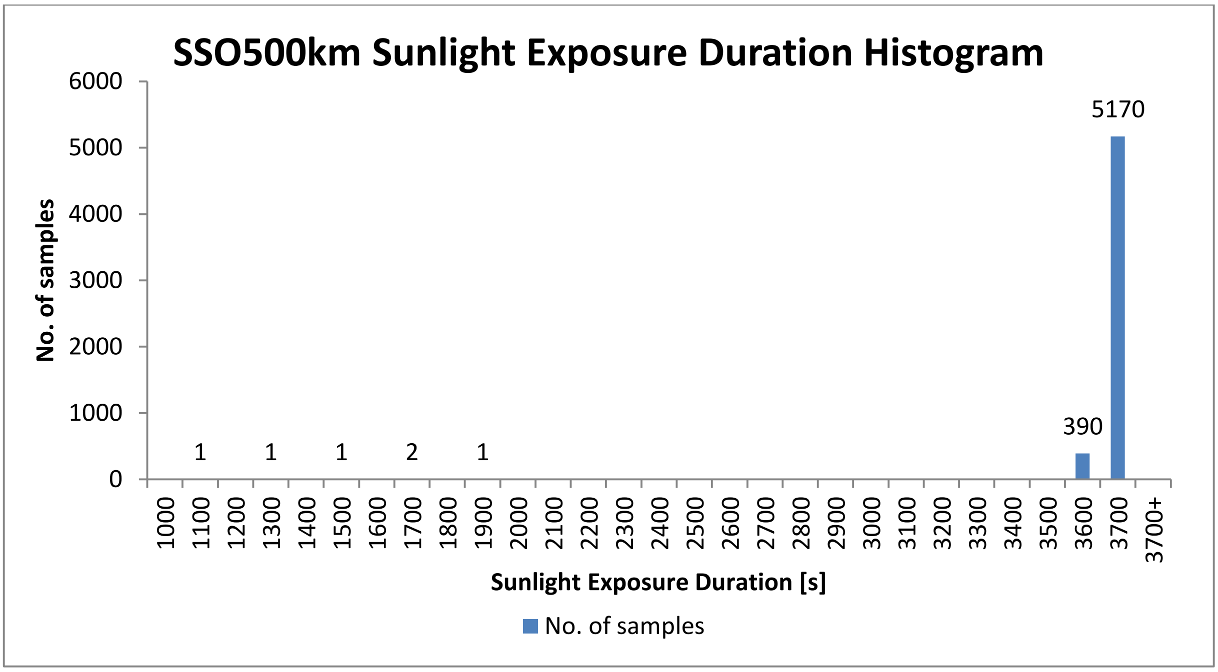

Figure 6-25 SSO500km Sunlight Exposure Duration Histogram

Maximum exposure duration is 3698 s (1 h 1min 38 s), and 99.89 % of samples are between 3500 s and 3698 s.

6.4.2.5 SSO 600km orbit

Histogram below shows eclipses duration distribution for the SSO 600km orbit:

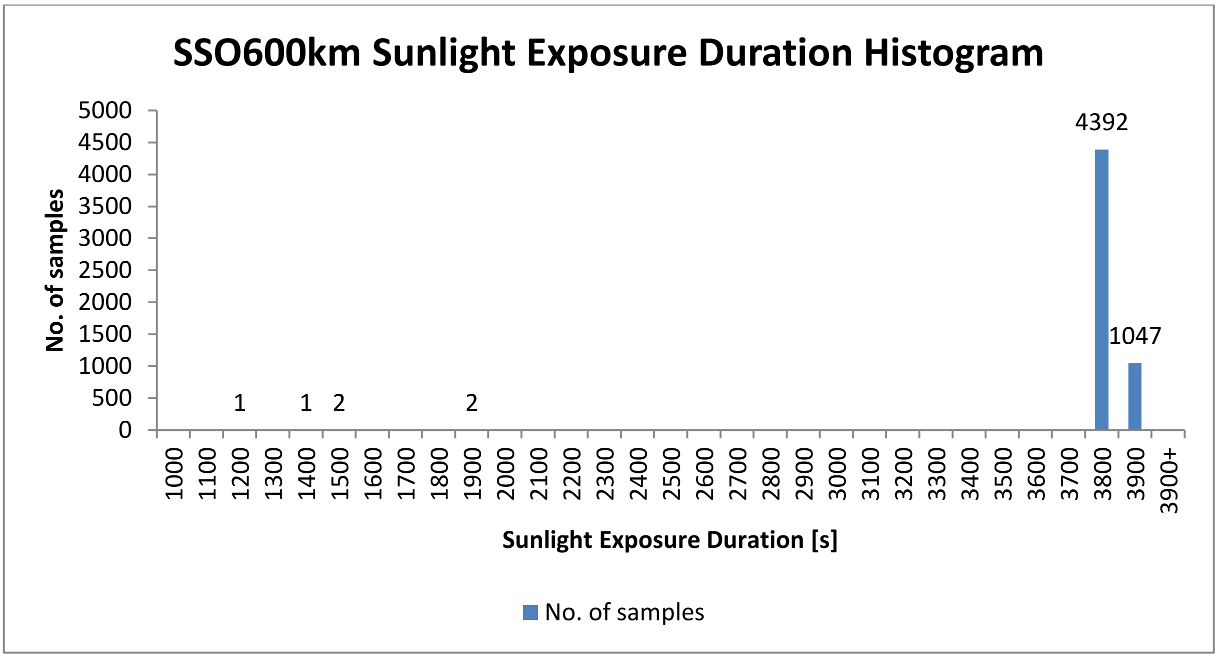

Figure 6-26 SSO600km Sunlight Exposure Duration Histogram

Maximum exposure duration is 3858 s (over 29 h), however 99.89 % of samples are between 3700 s and 3858 s.

6.4.2.6 SSO 700km orbit

Histogram below shows eclipses duration distribution for the SSO 700km orbit:

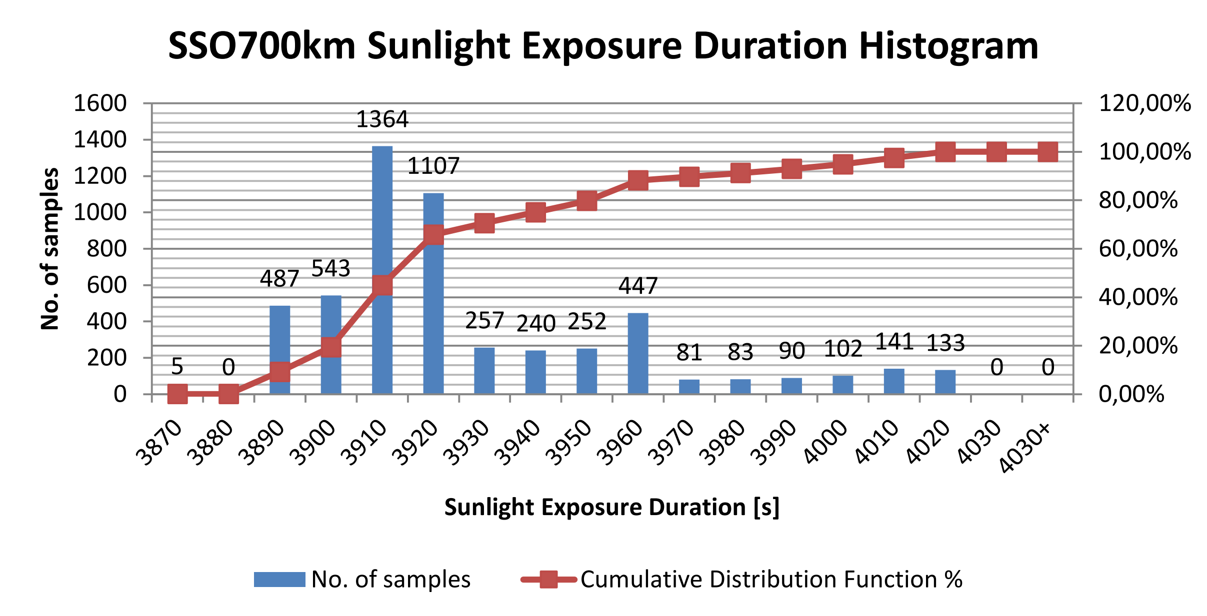

Figure 6-27 SSO700km Sunlight Exposure Duration Histogram

Maximum exposure duration is 4014 s (1 h 6 min 54 s), however 88.09 % of samples are between 3880 s and 3960 s.

6.4.2.7 SSO 780km orbit

Histogram below shows eclipses duration distribution for the SSO 780km orbit:

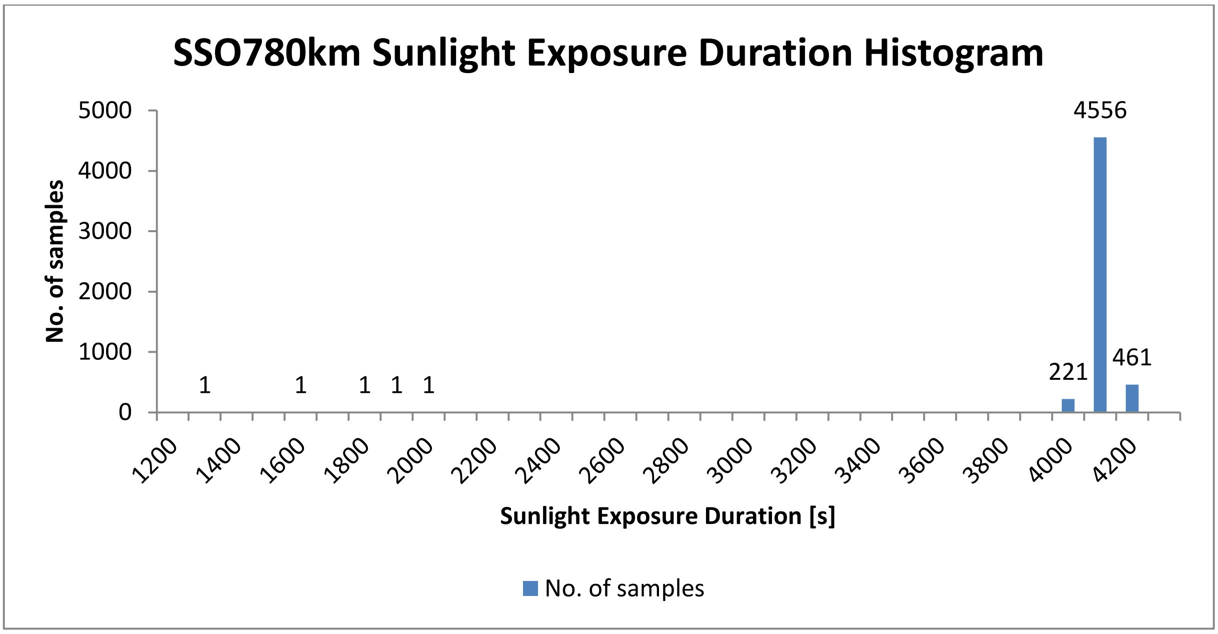

Figure 6-28 SSO780km Sunlight Exposure Duration Histogram

Maximum exposure duration is 4139 s (1 h 8 min 59 s), and 99.9 % of samples are between 3900 s and 4139 s.

6.5 ORBIT DECAY ANALYSIS

PW-Sat2 main mission is the test of the drag sail to decrease satellites' lifetime in compliance with IADC *Space Debris Mitigation Guidelines* [RD. 9].

> A spacecraft or orbital stage should be left in an orbit in which, using an accepted nominal projection for solar activity, atmospheric drag will limit the orbital lifetime after completion of operations. A study on the effect of post-mission orbital lifetime limitation on collision rate and debris population growth has been performed by the IADC. This IADC and some other studies and a number of existing national guidelines have found 25 years to be a reasonable and appropriate lifetime limit. (paragraph 5.3.2)

Orbit decay analyses are performed to estimate the performance of the drag sail on different considered orbits. These analyses where conducted using STELA software introduced in section 5.2.3. Detailed information about the satellite parameters (mass, final sail area), orbit parameters and launch date are yet TBD hence the statistical analyses where conducted instead of single-point analyses. STELA allows user to choose which parameter will be fixed and which will have some magnitude of distribution during statistical analysis. It randomizes all non-fixed parameters (in user-defined bounds) and calculates orbit lifetime for randomized initial conditions. It continues to do so until the predefined number of executions is reached. The end result of this analysis is orbit lifetime distribution.

This paragraph is divided into the following sections:

- In Section 0 STELA Mean Area Tool calculations of PW-Sat2 mean area in different SC configurations are described.
- Section 0 presents the single-parameter variation analyses. These analyses were conducted for one of the possible orbits (780km SSO) to determine how orbit lifetime depends on every single parameter.
- Section 0 is a description of the analysis of drag area influence on the orbit-lifetime for different orbits.
- Section 6.5.4 demonstrates the results of the multi-parameter variation analyses for all considered orbits
- Section 6.5.5 outlines the iterative analyses aiming to find the maximum SMA for SSO orbits, keeping the orbit lifetime shorter than 25 years for 2U CubeSat without any drag augmentation device, considering worst and best case scenarios w.r.t. solar activity.

6.5.1 DRAG AREA CALCULATIONS

Obviously, one of the most influential parameters in orbital lifetime analyses for LEO is drag area. In case of satellites with big, flat structures (as in case of PW-Sat2) the drag area is strongly dependant on the SC orientation w.r.t the velocity vector. For SCs with very low mass to area ratio on LEO orbits, like PW-Sat2 the main orientation perturbation is drag torque (see Figure 6-29). Precise analysis of drag torque is very complicated and requires detailed information on SC surface properties which are not available without comprehensive material properties research, especially during the SC design phase [RD. 5]. Therefore mean drag area was calculated for a set of different orientations of SC w.r.t. velocity vector and further analyses where conducted for different values of mean area. STELA Mean Area Tool allows to build a simple 3D model of the satellite and to decide on the SC attitude w.r.t velocity vector in one of the three modes:

- Random Tumbling
- Spin (with user-defined spin axis)
- Fixed Orientation

3D model of PW-Sat2 with sail deployed is presented on Figure 6-30, Figure 6-31 and Figure 6-32.

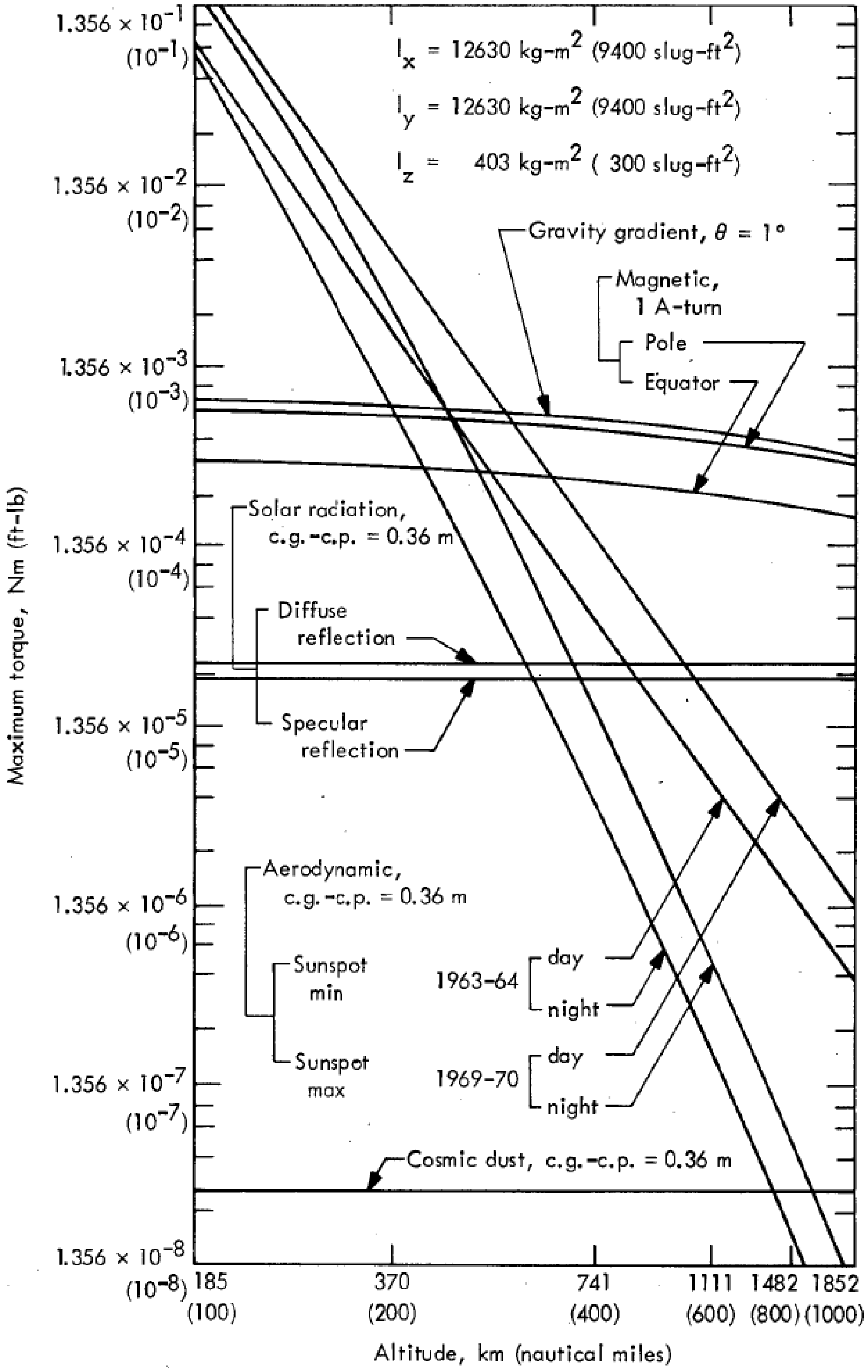

Figure 6-29 Relative magnitudes of the enviornmental torques on an Earth satellite [RD. 5]

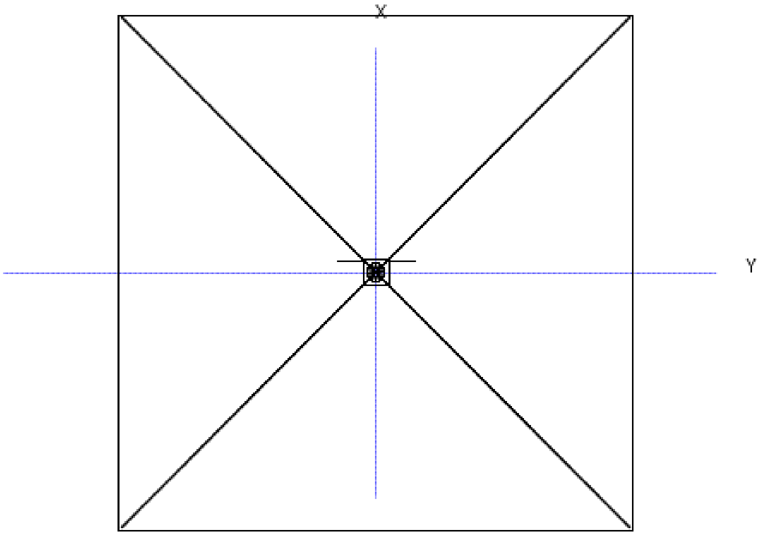

Figure 6-30 PW-Sat2 3D model created in STELA Mean Area Tool, XY-view

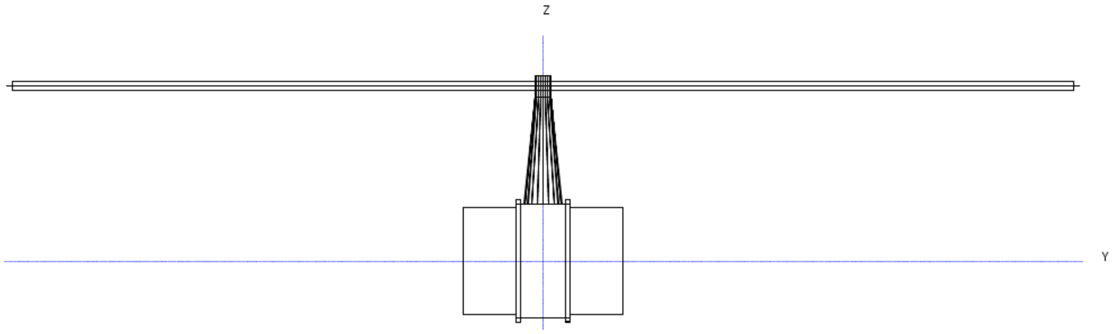

Figure 6-31 PW-Sat2 3D model created in STELA Mean Area Tool, ZY-view

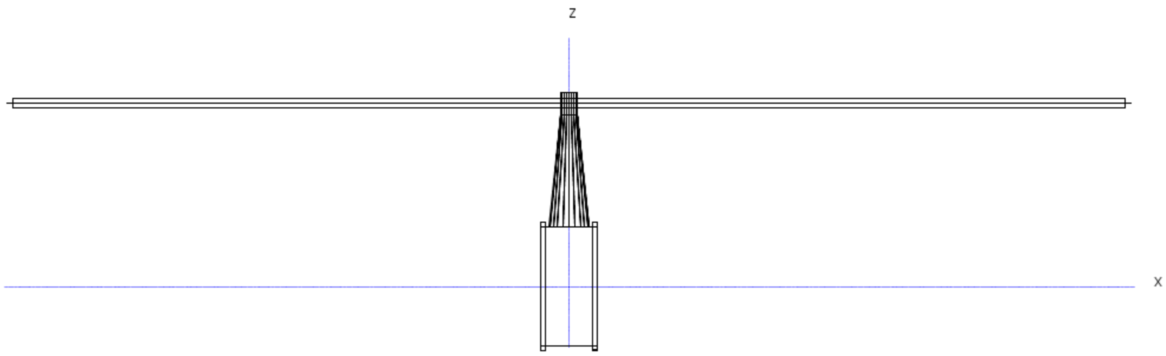

Figure 6-32 PW-Sat2 3D model created in STELA Mean Area Tool, ZX-view

Calculations were conducted for 3 configurations (CubeSat 2U, CubeSat 2U with deployed solar arrays, PW-Sat2 with deployed sail and solar arrays) for several orientations:

a) Random tumbling
b) Fixed orientation, velocity aligned with X-axis
c) Fixed orientation, velocity aligned with Y-axis
d) Fixed orientation, velocity aligned with Z-axis
e) Spin around axis at angle (5˚, 10˚, 15˚, 30˚, 45˚, 60˚, 90˚ -rotation around X-axis) to Z-axis, velocity aligned with Z-axis, (only for deployed sail configuration), see Figure 6-33.
f) Spin around axis at angle (2.5˚) to Z-axis, velocity aligned with X-axis.

Note that spin around axis at 45˚ to Z-axis with velocity aligned with Z-axis means that the satellite oscillate between positions in which sail is perpendicular and parallel to the velocity vector. Case f) is the oscillation of sail plane w.r.t velocity vector from 0˚ (sail plane parallel to velocity vector) to 5˚.

Spin axis orientation in case e) is showed on Figure 6-33:

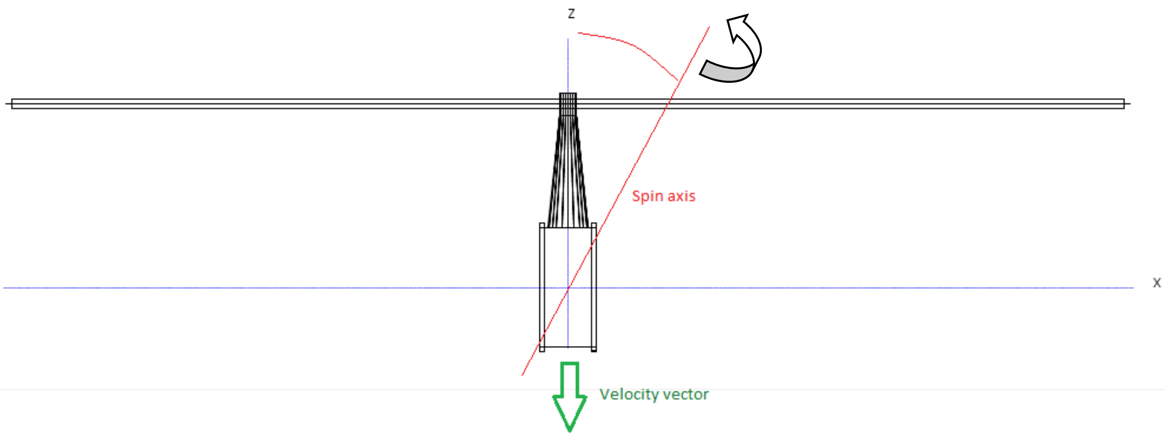

Figure 6-33 XZ-view of the 3D model with spin axis and velocity vector depicted (case e))

Results of the mean drag area are presented in Table 6-6.

Table 6-6 Mean drag area for different configurations and orientations of PW-Sat2

Mean Area [m²]	a) Random Tumbling	b) Fixed. Obs: X-axis	c) Fixed. Obs: Y-axis	d) Fixed. Obs: Z-axis	e) Rotation around axis at angle to Z-axis (obs: Z-axis)							f)
					5˚	10˚	15˚	30˚	45˚	60˚	90˚	
2U CubeSat	0.0267	0.0216	0.0216	0.0100	-	-	-	-	0.0256	-	0.0201	-
+Solar Arrays	0.0411	0.0617	0.0215	0.0102	-	-	-	-	0.0397	-	0.0201	-
+Sail	2.0150	0.0775	0.0321	4.0763	3.9708	3.8804	3.7325	3.0007	2.0256	2.0294	2.5742	0.2266

For the further analyses a) case (random tumbling) was considered as the nominal case and the f) case was considered as the worst case.

6.5.2 SINGLE-PARAMETER VARIATION

To determine the influence of every single parameter on a decay time 8 analyses were conducted for the SSO780km orbit taken as an example. The highest of the considered orbits was chosen so that the possible effects with longer periods might be visible. Further analyses for the rest of the orbits will be conducted in phase C, if these orbits will remain considered as applicable. Nominal simulation parameters for single-parameter variation analyses are presented in a Table 6-7 (for each simulation analyzed parameter varies from the nominal value by the dispersion value):

Table 6-7 Single-parameter variation analyses nominal configuration

Parameter	Nominal value	Dispersion[4]
Launch date	2016/13/02, 09:00:00UTC	Uniform (2016/13/02 - 2017/13/02)
RAAN	111.738	Uniform 0˚-360˚
Mean anomaly (M)	0	Uniform 0˚-360˚
Mass	3.2 kg	Uniform 2.6-3.2kg
Coefficient of drag (Cd)	STELA Default file	Uniform +/- 20 %
Reflectivity coefficient (Cr)	1.5	Uniform +/- 20 %
Drag area	2.01495686 m2	N.A.
Reflectivity Area	2.01495686 m2	N.A.
Solar activity, F10.7 index	140	Gaussian[5]: $\sigma = 53.47$; $\bar{x} = 126.27$
Geomagnetic activity, AP index	15	Gaussian: $\sigma = 15.51$; $\bar{x} = 13.56$

Influence of drag area on orbit lifetime is discussed in a separate paragraph 0.

[4] Dispersion is applicable only in a simulation of a particular parameter influence, for other parameters there is no dispersion then.

[5] σ - standard deviation; $\bar{x}$ = mean value

Drag coefficient variation with altitude from STELA default file is presented on Figure 6-34. In drag coefficient variation analysis the whole file is multiplied by a random number (in this case a number from 80 % - 120 % range, see Table 6-7).

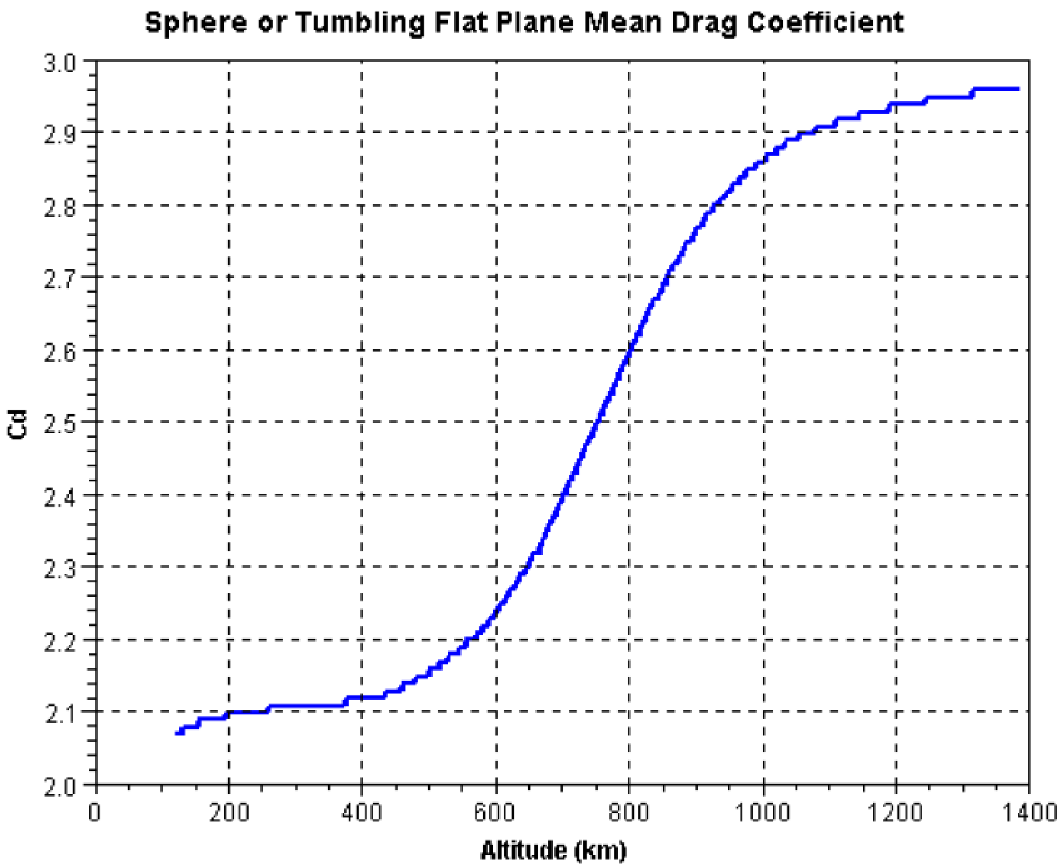

Figure 6-34 Drag coefficient variation with altitude, from STELA default file [RD. 2]

6.5.2.1 Launch Date

Orbit lifetime variation with launch date is presented on a Figure 6-35.

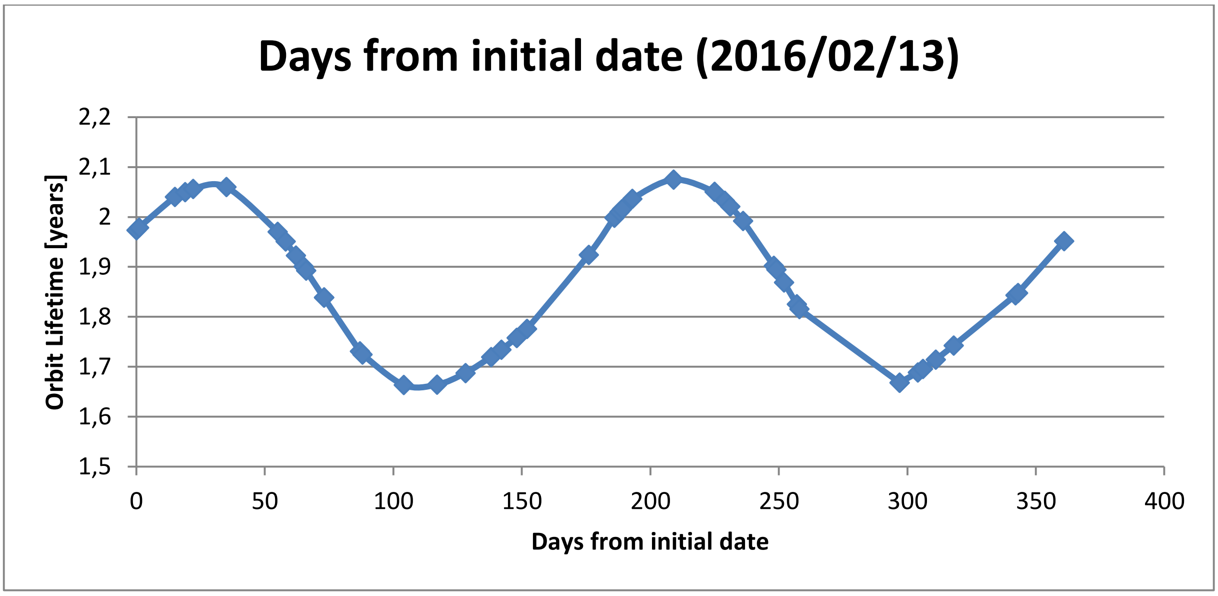

Figure 6-35 Orbit lifetime vs launch date

For nominal analysis parameters and launch date dispersion between 2016/02/13 and 2017/02/13, orbit lifetime oscillates between 2.0747 and 1.6636 years, therefore the relative difference[6] is 19.81 %

[6] Relative difference $(\Delta T_{orbit})_{relative}$ of values x and y is defined as follows: $(\Delta T_{orbit})_{relative} = \frac{|x-y|}{\max(|x|,|y|)}$

6.5.2.2 Right Ascension of the Ascending Node

Orbit lifetime variation with RAAN is presented on a Figure 6-36.

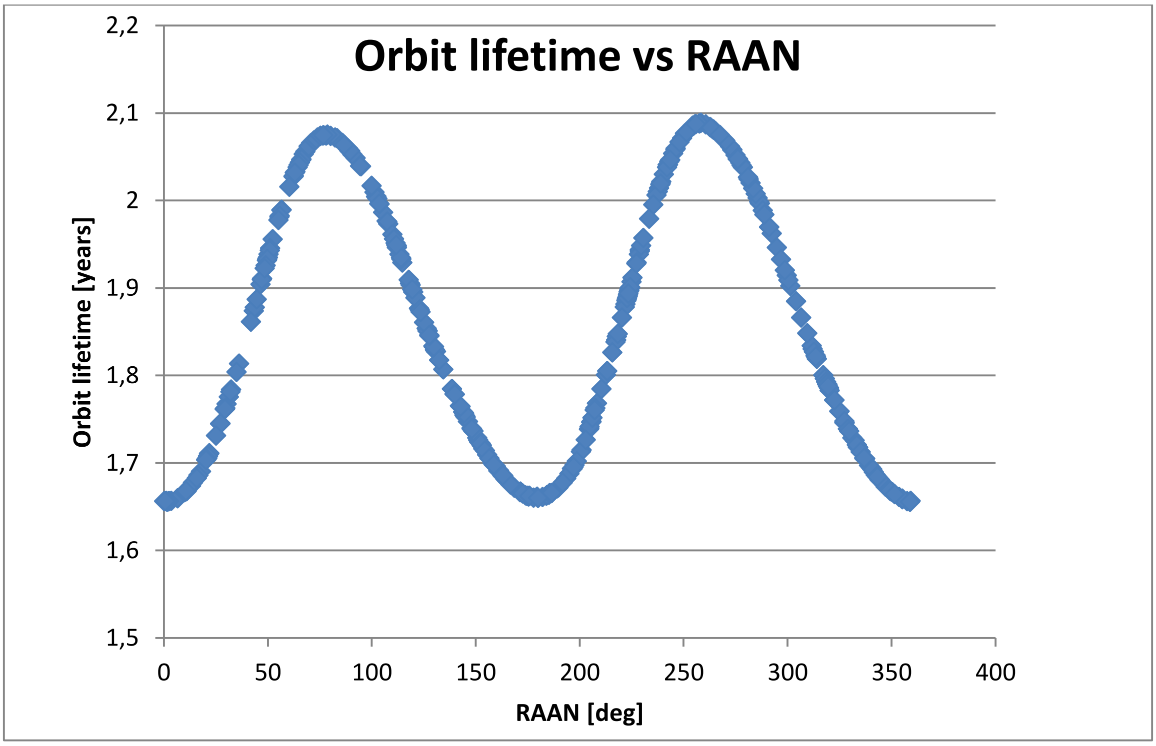

Figure 6-36 Orbit lifetime vs RAAN

For nominal analysis parameters and RAAN dispersion between 0˚ and 360˚, orbit lifetime oscillates between 2.0890 and 1.6556 years, therefore the relative difference is 20.75 %

6.5.2.3 Mean Anomaly

Orbit lifetime variation with mean anomaly is presented on a Figure 6-37.

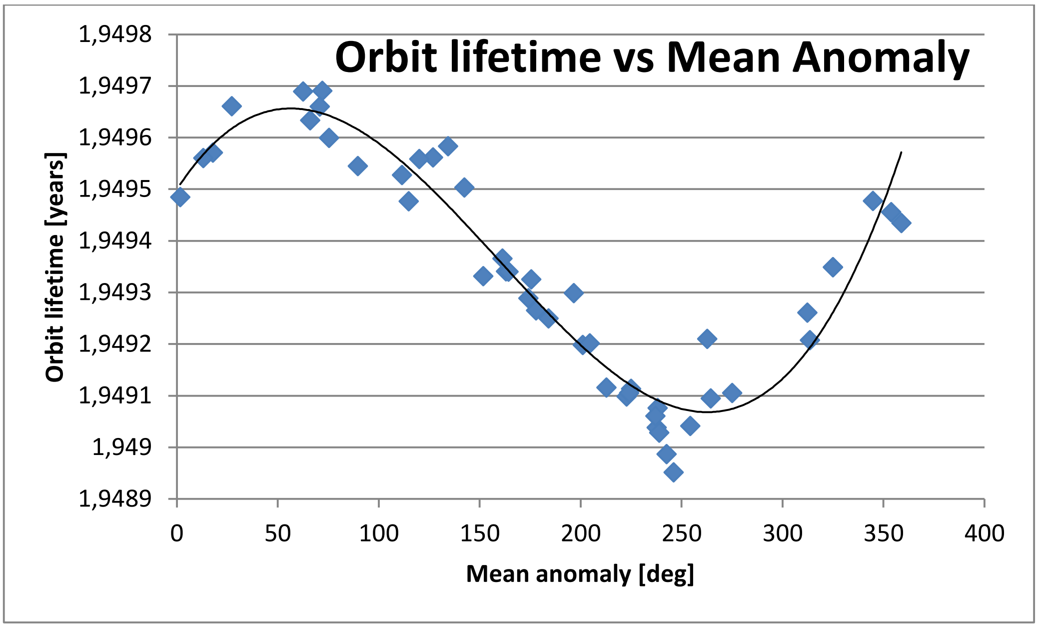

Figure 6-37 Orbit lifetime vs mean anomaly

For nominal analysis parameters and mean anomaly dispersion between 0˚ and 360˚, orbit lifetime oscillates between 1.9497 and 1.99490 years, therefore the relative difference is 0.04 %

6.5.2.4 Mass

Orbit lifetime variation with mean anomaly is presented on a Figure 6-38.

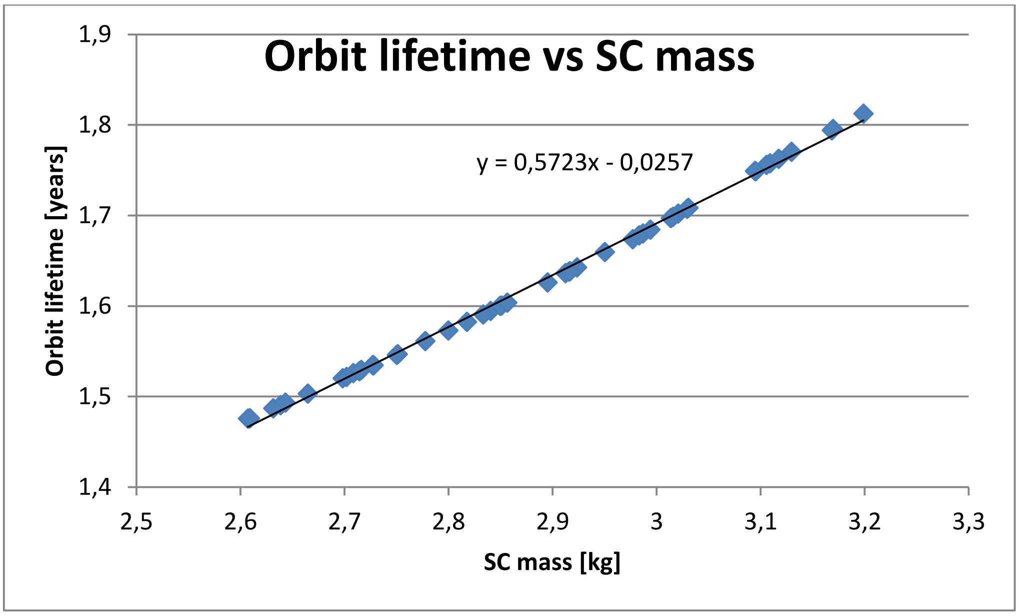

Figure 6-38 Orbit lifetime vs SC mass

For nominal analysis parameters and SC mass dispersion between 2.6 and 3.2 it can be seen on Figure 6-38 that orbit lifetime is linearly dependent on SC mass:

$$T_{orbit} = 0.5723\left[\frac{years}{kg}\right] \times m_{SC} + 0.0257\ [years] \quad \textbf{(1)}$$

Where:

- T_{orbit} is orbit lifetime
- m_{SC} is spacecraft mass

For analyzed distribution range, the relative difference is 18.59 %

6.5.2.5 Coefficient of drag

Orbit lifetime variation with coefficient of drag (Cd) is presented on a Figure 6-39

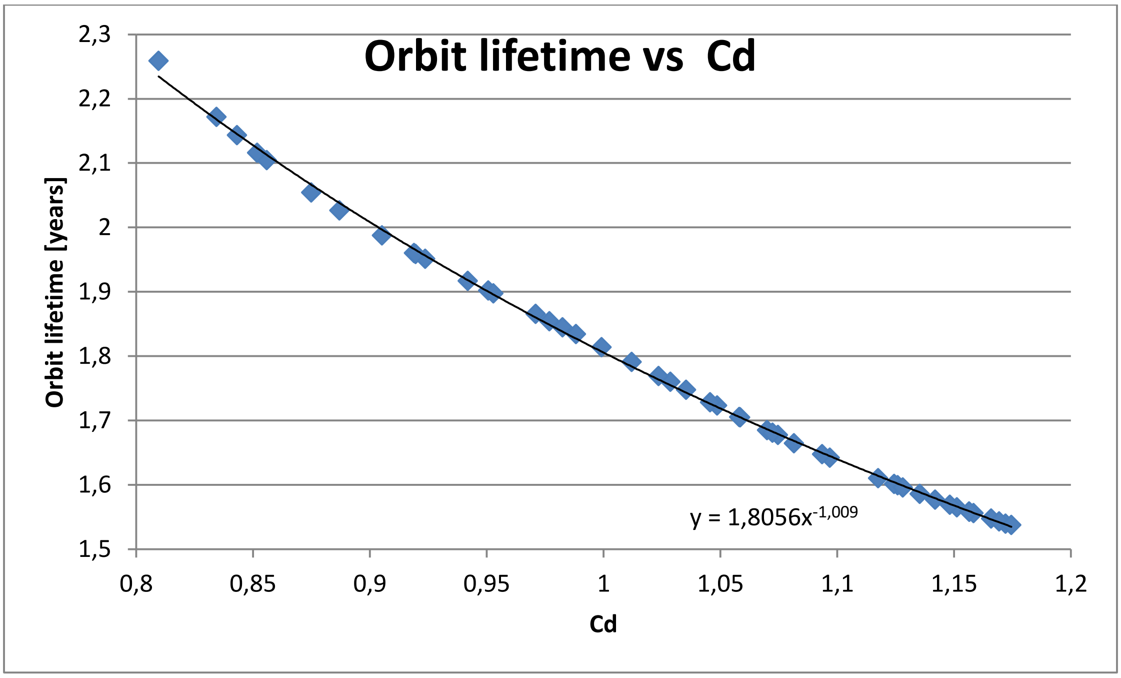

Figure 6-39 Orbit lifetime vs Cd

For nominal analysis parameters and SC coefficient of drag dispersion between 0.8096 and 1.1745 it can be seen on Figure 6-39 that orbit lifetime is power-function dependent on coefficient of drag:

$$T_{orbit} = 1.8056 \times C_d^{-1.009}\ [years] \qquad \textbf{(2)}$$

Where:

- T_{orbit} is orbit lifetime
- C_d is coefficient of drag

For analyzed distribution range, the relative difference is 31.92 %

6.5.2.6 Reflectivity Coefficient

Orbit lifetime variation with reflectivity coefficient is presented on Figure 6-40:

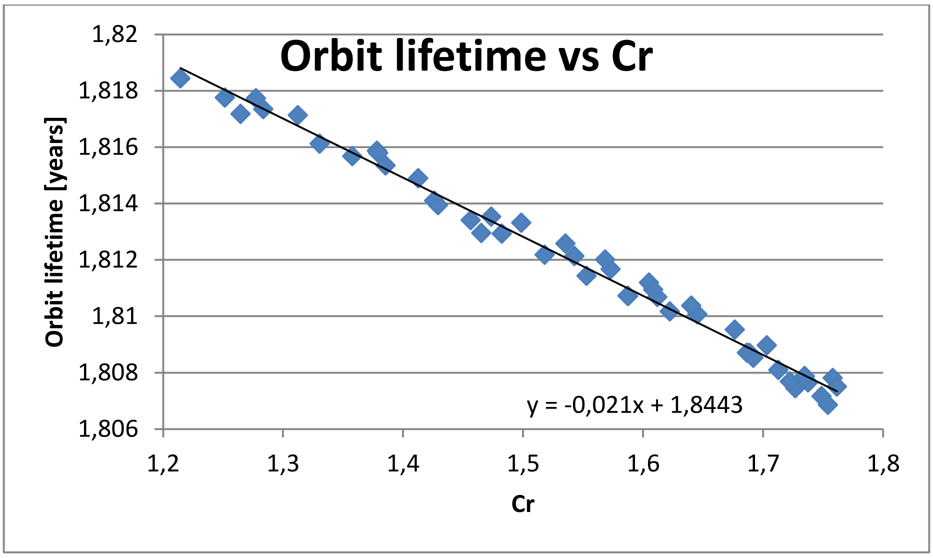

Figure 6-40 Orbit lifetime vs Cr

For nominal analysis parameters and SC reflectivity coefficient dispersion between 1.2144 and 1.7617 it can be seen on Figure 6-40 that orbit lifetime is linearly dependent on SC reflectivity coefficient:

$$T_{orbit} = -0.021[years] \times C_r + 1.8443\ [years] \qquad (3)$$

Where:

- T_{orbit} is orbit lifetime
- C_r is SC reflectivity coefficient

For analyzed distribution range, the relative difference is 0.64 %

6.5.2.7 Solar Activity, F10.7 index

Orbit lifetime variation with F10.7 index is presented on Figure 6-41

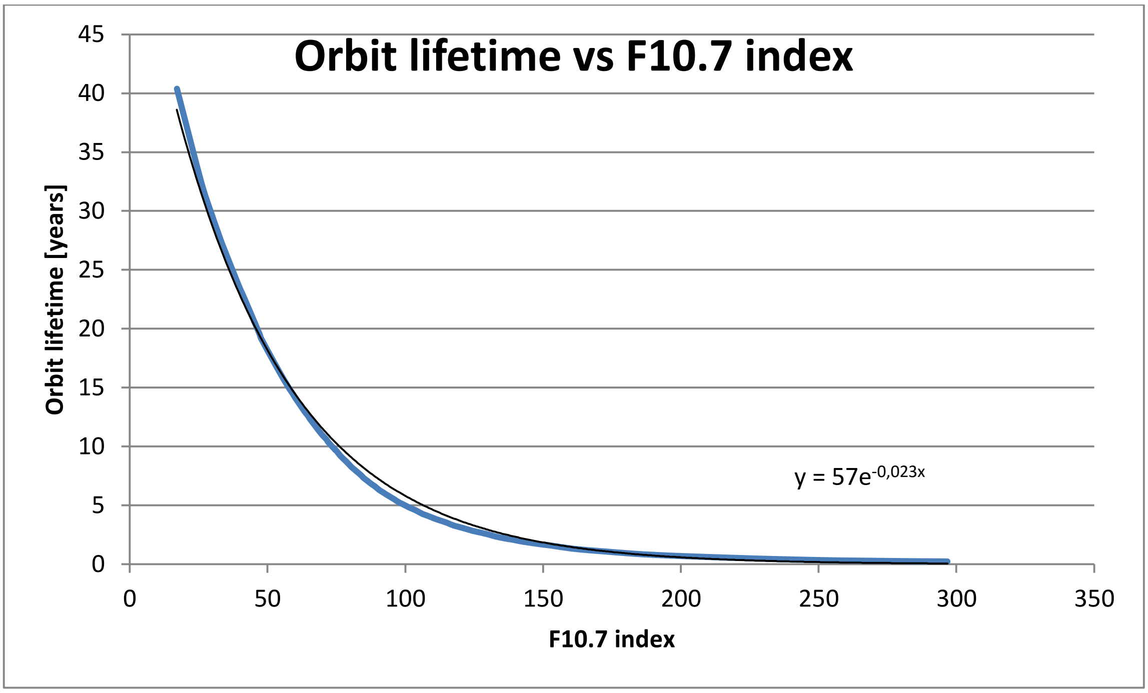

Figure 6-41 Orbit lifetime variation with F10.7 index

For nominal analysis parameters and F10.7 index dispersion between 17.0793 and 296.7797 it can be seen on Figure 6-41 that orbit lifetime is exponentially dependent on F10.7 index:

$$T_{orbit} = 57 \times \exp(-0.023 \times F_{10.7}) \; [years] \qquad \textbf{(4)}$$

Where:

- T_{orbit} is orbit lifetime
- $F_{10.7}$ is F10.7 index

For analyzed distribution range, the relative difference is 99.43 %

6.5.2.8 Geomagnetic Activity, AP index

Orbit lifetime variation with AP index is presented on Figure 6-42

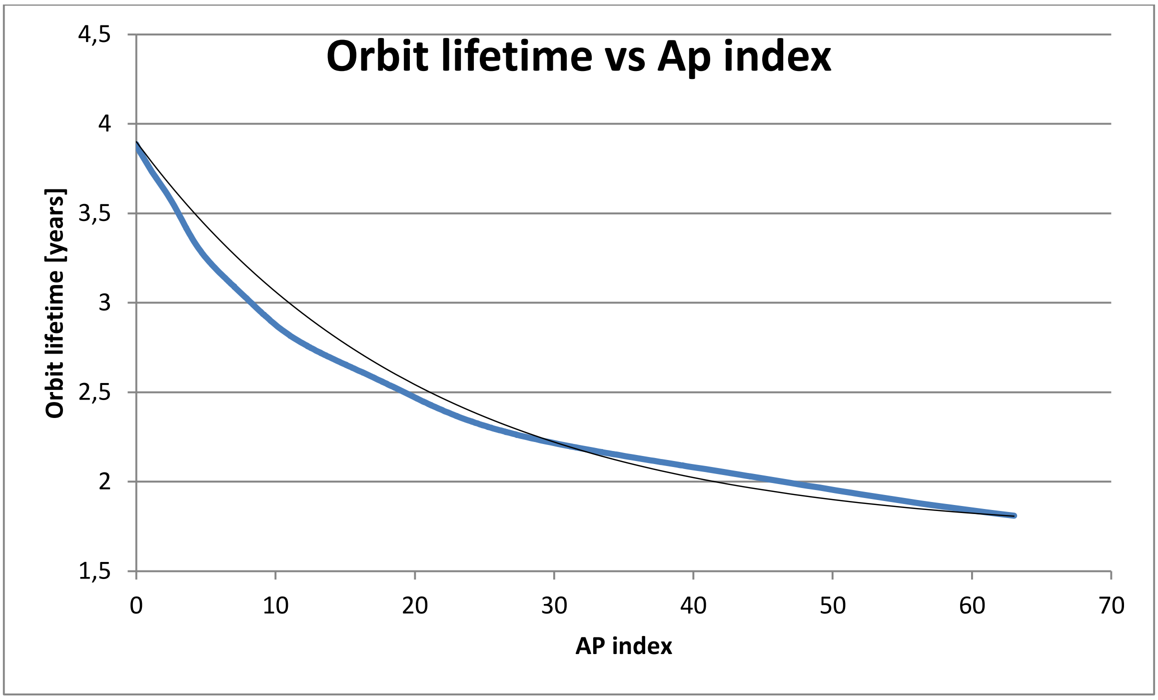

Figure 6-42 Orbit lifetime variation with AP index

For nominal analysis parameters and AP index dispersion between 0 and 63.0196 it can be seen on Figure 6-41 that orbit lifetime is exponentially dependent on AP index:

$$T_{orbit} = 2.2 \times \exp(-0.048 \times A_P) + 1.7 \quad [years] \tag{5}$$

Where:

- T_{orbit} is orbit lifetime
- A_P is AP index

For analyzed distribution range, the relative difference is 53.44 %

6.5.2.9 Summary of single-parameter variation analysis

Table 6-8 summarizes the single-parameter variations results:

Table 6-8 Summary of the single-parameter variation analyses

Distributed parameter	Dispersion range	Orbit lifetime dependency
Launch date	Uniform: (2016/13/02 - 2017/13/02)	Oscillation with relative difference of 19.81 %
RAAN	Uniform: 0˚-360˚	Oscillation with relative difference of 20.75 %
Mean anomaly (M)	Uniform: 0˚-360˚	Oscillation with elative difference of 0.04 %
Mass	Uniform: 2.6-3.2kg	Linear with relative difference of 18.59 %
Coefficient of drag (Cd)	Uniform: +/- 20 %	Power function, with relative difference of 31.92 %
Reflectivity coefficient (Cr)	Uniform: +/- 20 %	Linear with relative difference of 0.64 %
Solar activity, F10.7 index	Gaussian: $\sigma = 53.47; \quad \bar{x} = 126.27$	Exponential with relative difference of 99.43 %
Geomagnetic activity, AP index	Gaussian: $\sigma = 15.51; \quad \bar{x} = 13.56$	Exponential with relative difference of 53.44 %

6.5.3 DRAG AREA VARIATION ANALYSES

Similarly to the previous paragraph an analysis of drag area influence on orbital lifetime was conducted for every considered orbit. Nominal parameters other than drag area are the same as in previous analyses. Drag area dispersion is uniform from the range of 0.22657169 - 2.01495686 m^2 (worst case – nominal case). Results for all considered orbits are presented on Figure 6-43 Maximal simulation duration was set to 100 years.

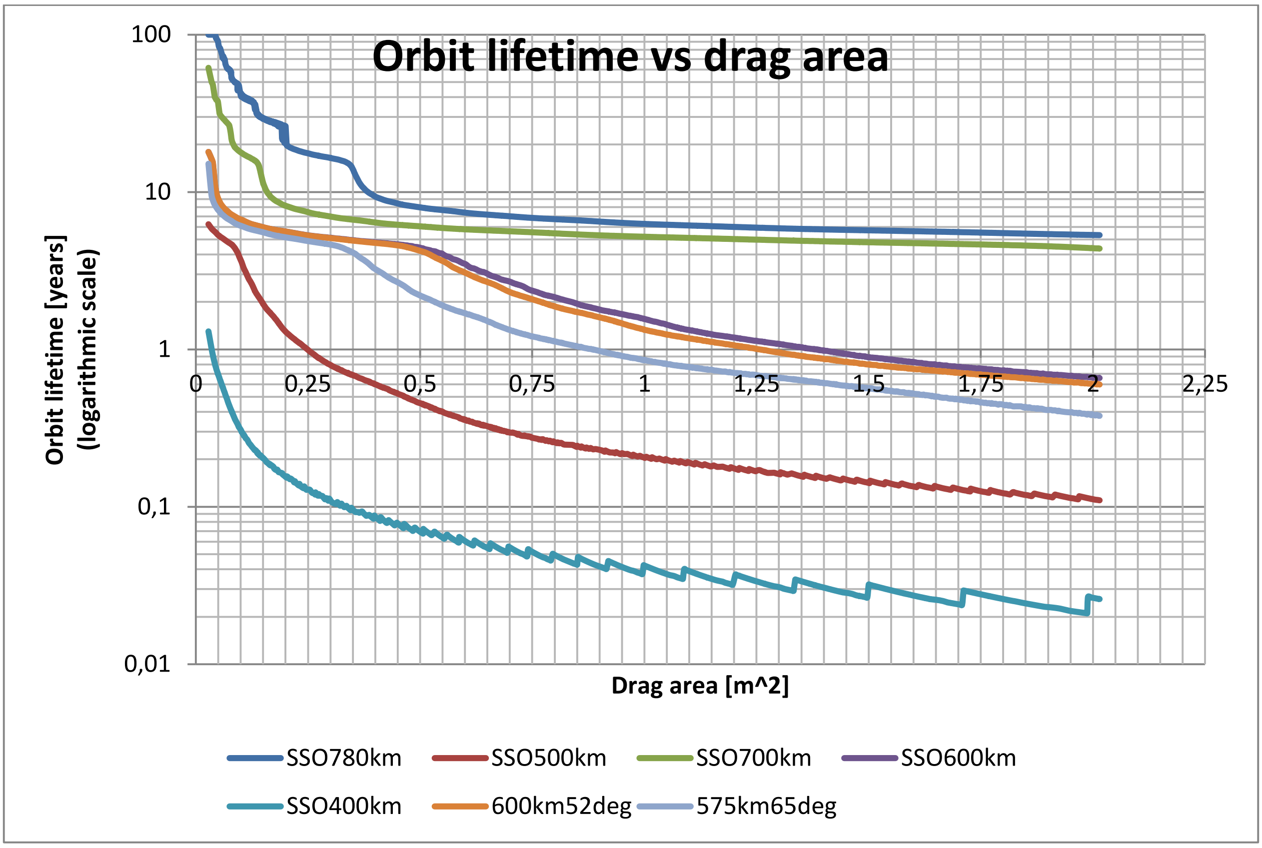

Figure 6-43 Orbit lifetime vs drag area

From the conducted analyses it can be seen that drag area together with solar and geomagnetic activity indices has the strongest influence on orbit lifetime. Orbit lifetime dependency on drag area is very complex. For drag area lower than 0.5 m^2 and orbits higher than 575 km there is a "steps" effect visible, while for the lower orbits and drag area higher than 0.75 m^2 the "saw" effect can be noticed on logarithmic plot. Explanation of these effects is beyond the scope of this analysis, however.

6.5.4 MULTI-PARAMETER VARIATION

For the inclinations outside of the range: [0° ; 40°] ∪ [80°; 110°] ∪ [130°; 180°] the resonance effects between the different perturbation forces may have a strong effect on orbit lifetime. Results are not stable in this range and depend strongly even on small variations of initial parameters. For these orbits it is advisable to use statistical analysis [RD. 2], [RD. 6]. Also many of the PW-Sat2 design features, launch date or orbit parameters are still not precisely defined. For these two reasons statistical analysis was chosen as a way to compare results for all considered orbits. For every orbit there were two cases considered:

- Nominal case with drag area = 2.01495686 m^2
- Worst case with drag area = 0.22657169 m^2

Every analysis was performed with the same parameters and distribution configuration, differing only in nominal orbit parameters as shown in Table 6-9. It should be noted that mass was fixed for every simulation at 3.2 kg value. Contrary to other simulation parameters, mass will be precisely known prior to launch. Final SC mass range is already well-known and the orbit lifetime dependency on mass is clearly linear, so the worst cases scenario of 3.2 kg SC mass was taken and fixed to reduce the number of changing parameters and simplify the analysis.

Table 6-9 Multi-parameter variation analyses configuration

Parameter	Nominal value	Dispersion
Launch date	2016/13/02, 09:00:00UTC	Uniform (2016/13/02 - 2017/13/02)
Semi Major Axis (SMA)	differs for every orbit	Uniform +/- 20km
RAAN	111.738	Uniform 0˚-360˚
Mean anomaly (M)	0	Uniform 0˚-360˚
Inclination (INC)	differs for every orbit	Uniform +/- 1˚
Mass	3.2 kg	Fixed
Coefficient of drag (Cd)	STELA Default file	Uniform +/- 20 %
Reflectivity coefficient (Cr)	1.5	Uniform +/- 20 %
Drag area	two cases were considered	two cases (0.22657169 m^2/2.01495686 m2)
Reflectivity Area	Same as for drag area	Same as for drag area
Solar activity, F10.7 index	In each execution random cycle from STELA default Solar Activity file (see 6.5.5.1)	
Geomagnetic activity, AP index		

6.5.4.1 Nominal case analyses

Following figures (Figure 6-44 to Figure 6-57) show the orbit lifetime distribution and cumulative lifetime distribution functions for conducted analyses for the nominal case for all considered orbits.

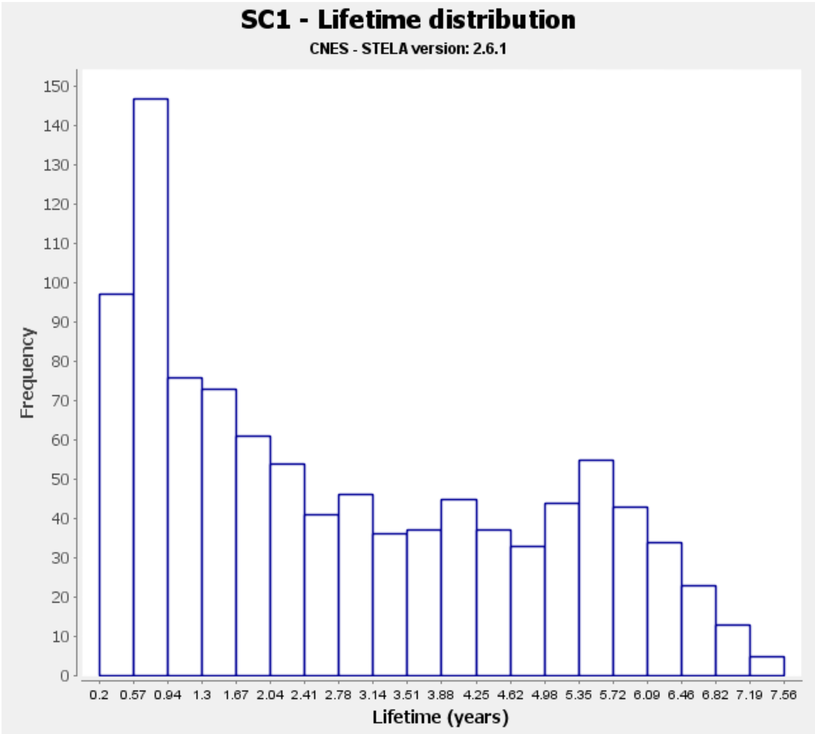

Figure 6-44 SSO780km orbit lifetime distribution for multi-parameter analysis

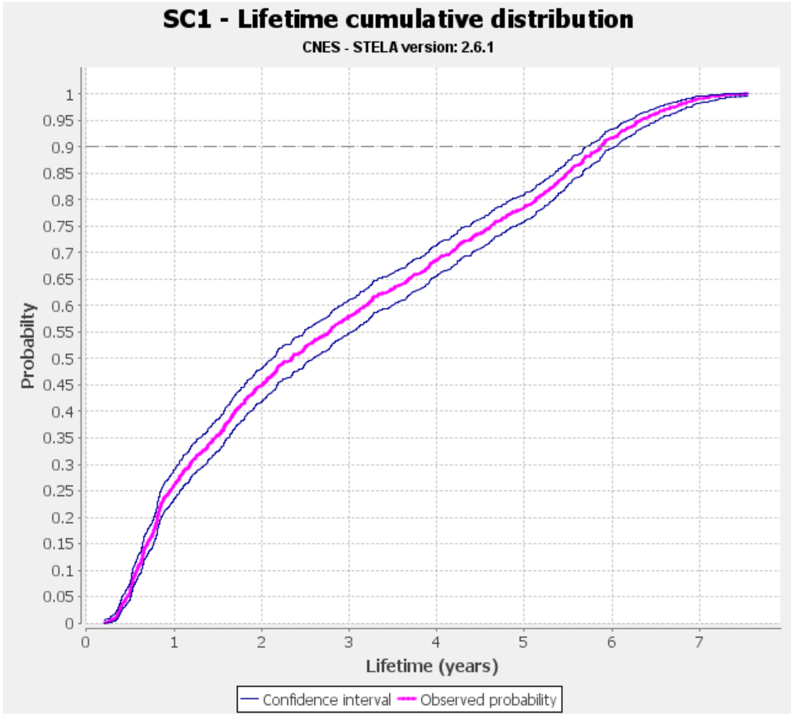

Figure 6-45 SSO780km orbit lifetime cumulative distribution for multi-parameter analysis

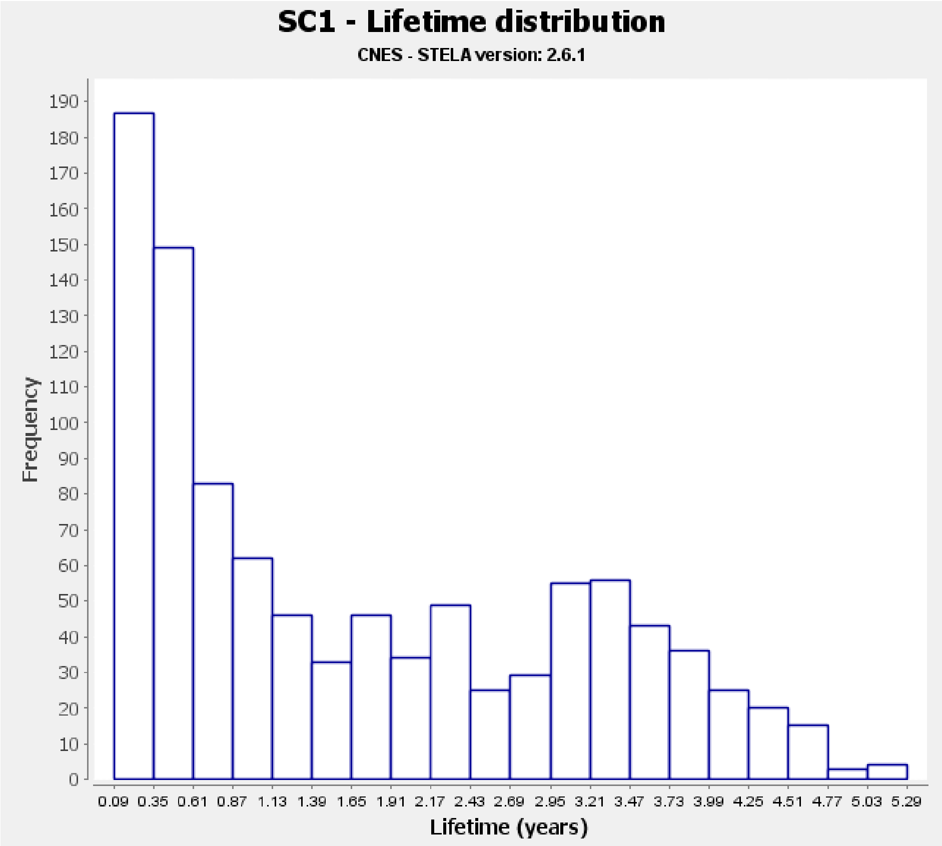

Figure 6-46 SSO700km orbit lifetime distribution for multi-parameter analysis

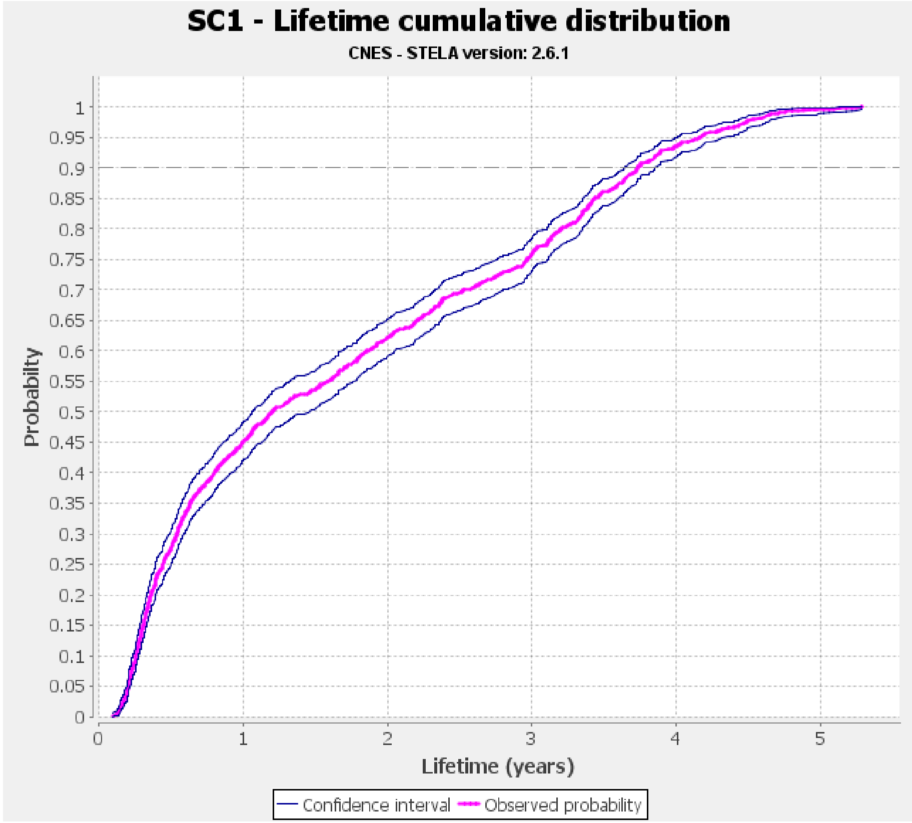

Figure 6-47 SSO700km orbit lifetime cumulative distribution for multi-parameter analysis

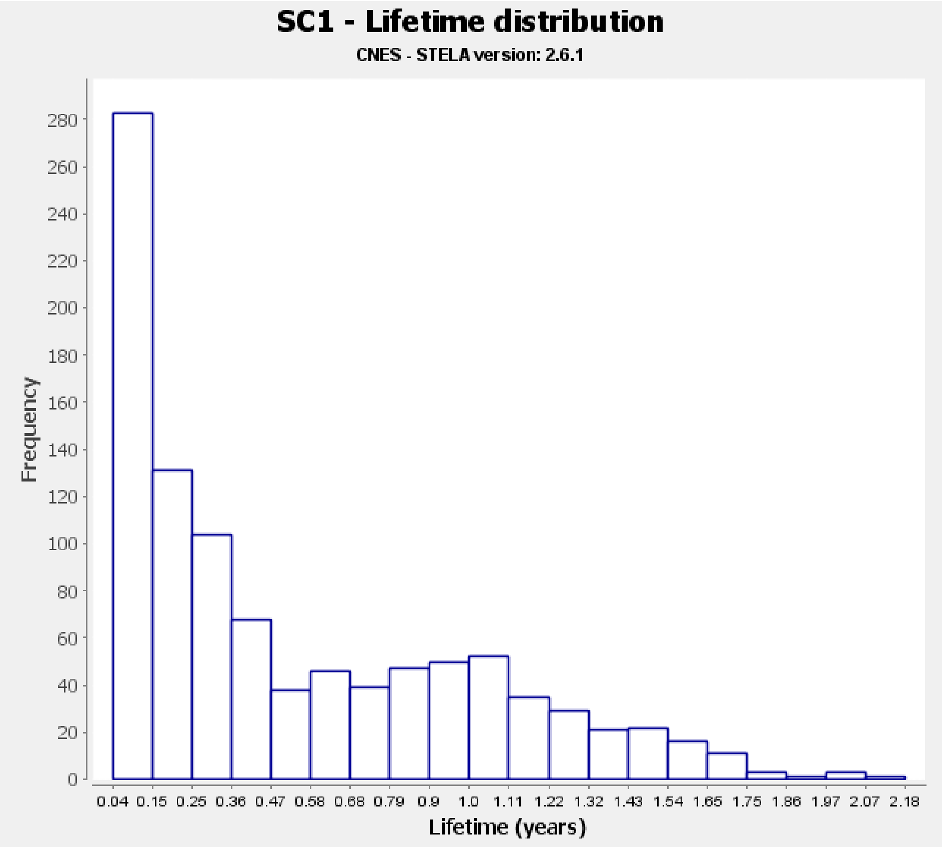

Figure 6-48 SSO600km orbit lifetime distribution for multi-parameter analysis

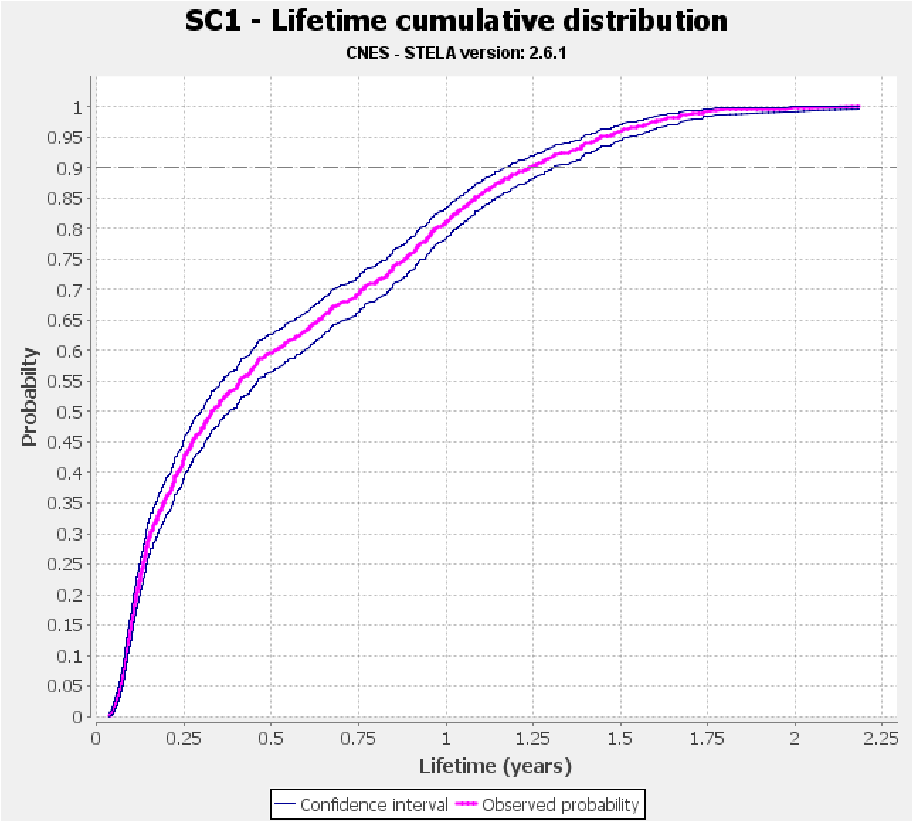

Figure 6-49 SSO600km orbit lifetime cumulative distribution for multi-parameter analysis

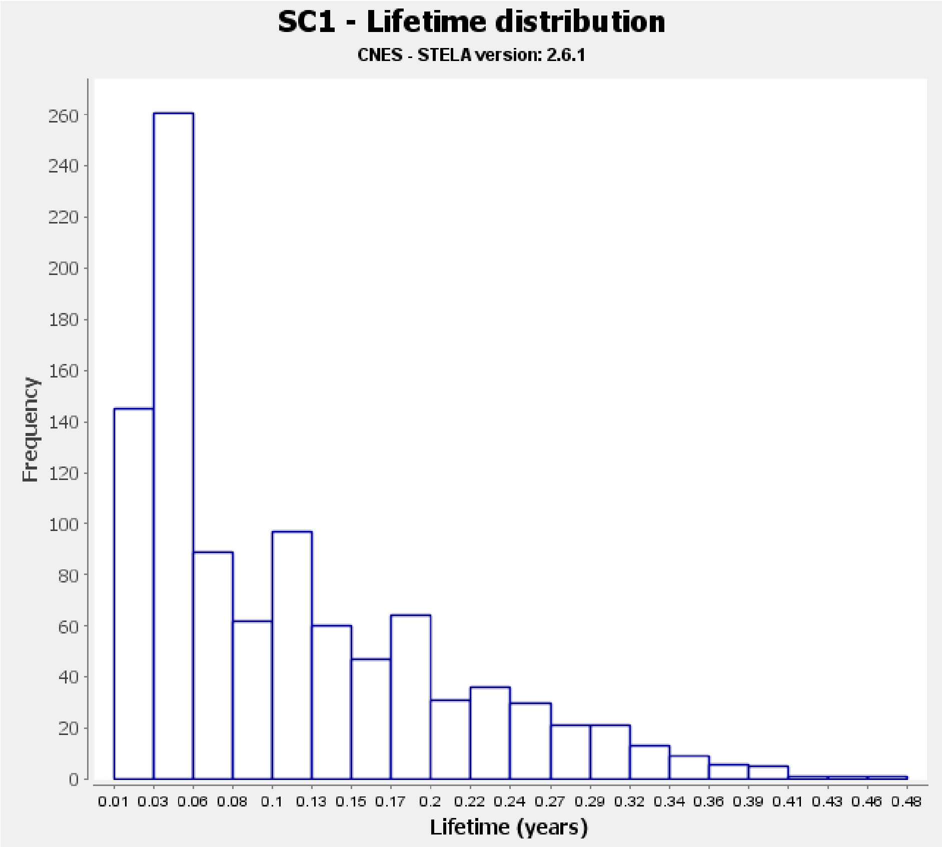

Figure 6-50 SSO500km orbit lifetime distribution for multi-parameter analysis

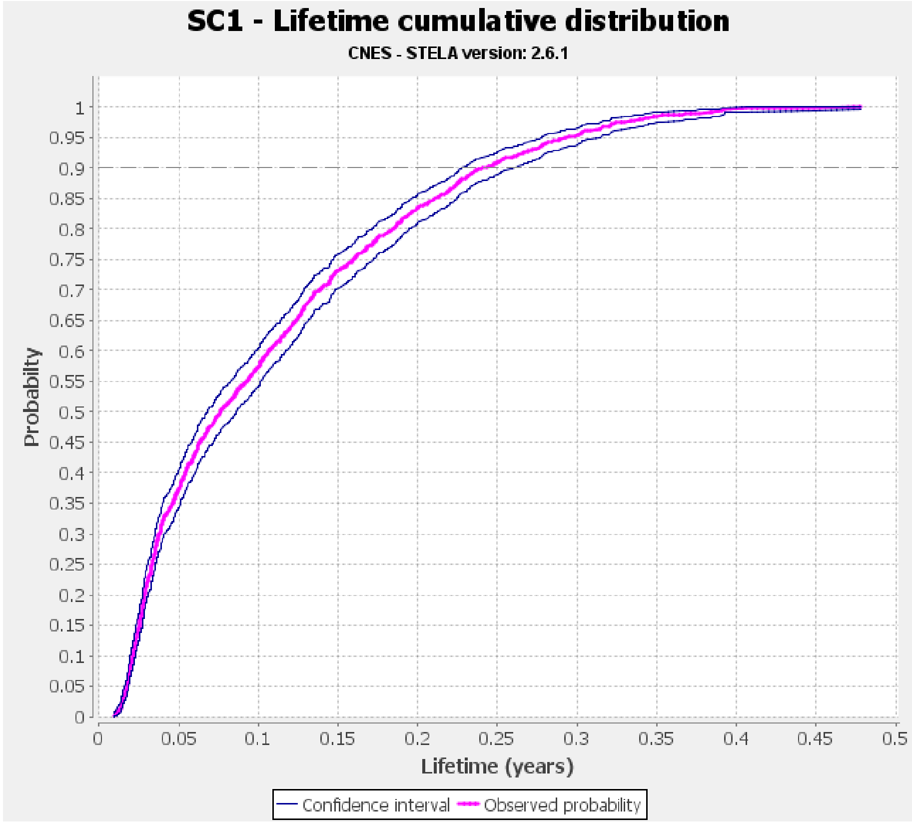

Figure 6-51 SSO500km orbit lifetime cumulative distribution for multi-parameter analysis

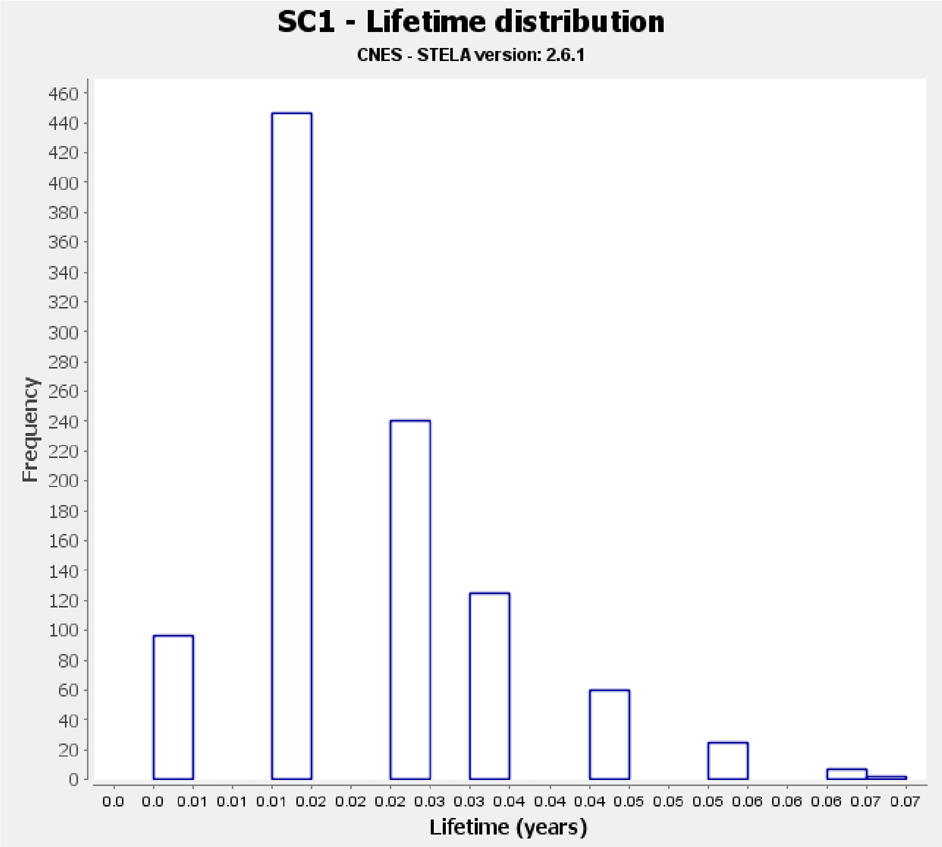

Figure 6-52 SSO400km orbit lifetime distribution for multi-parameter analysis

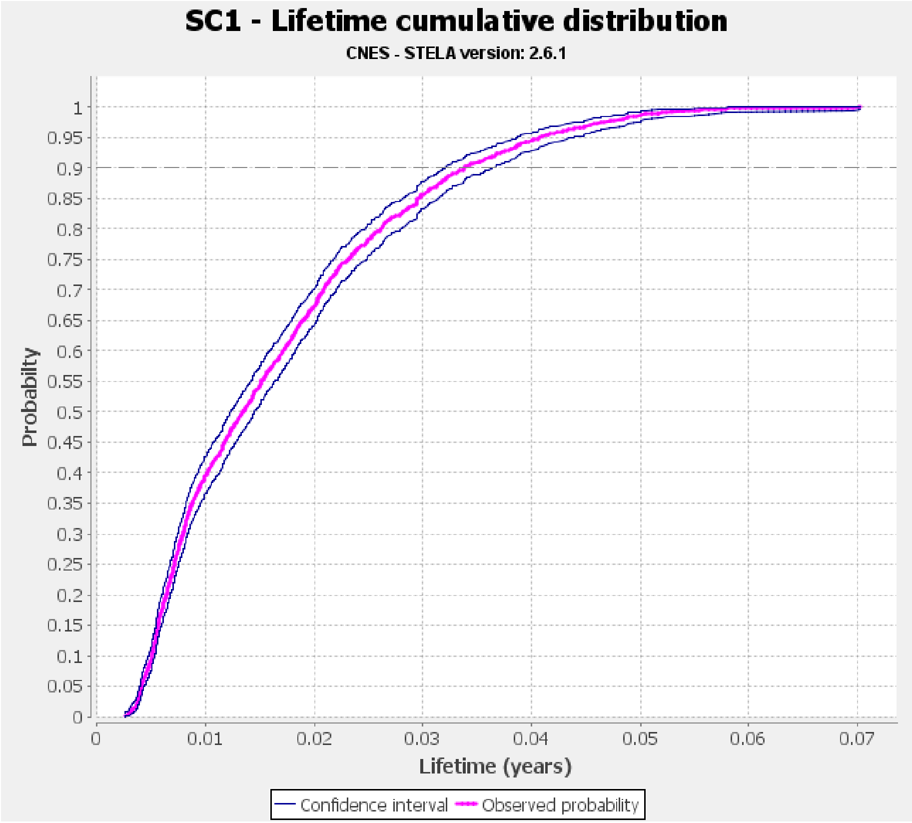

Figure 6-53 SSO400km orbit lifetime cumulative distribution for multi-parameter analysis

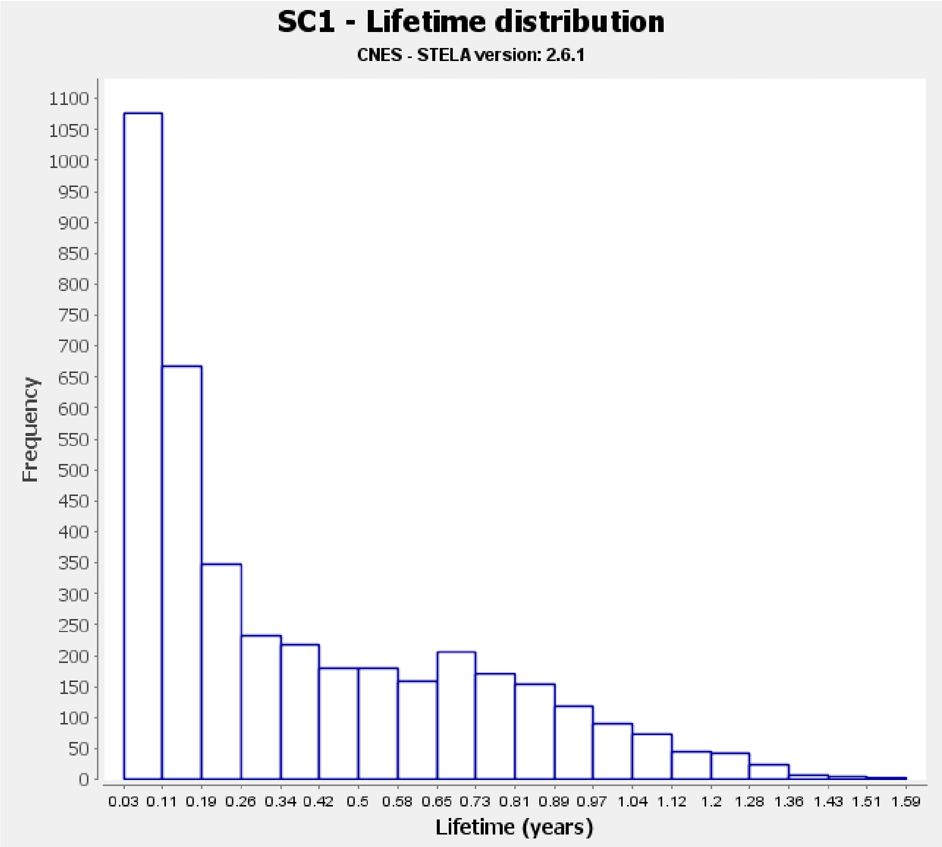

Figure 6-54 575km65deg orbit lifetime distribution for multi-parameter analysis

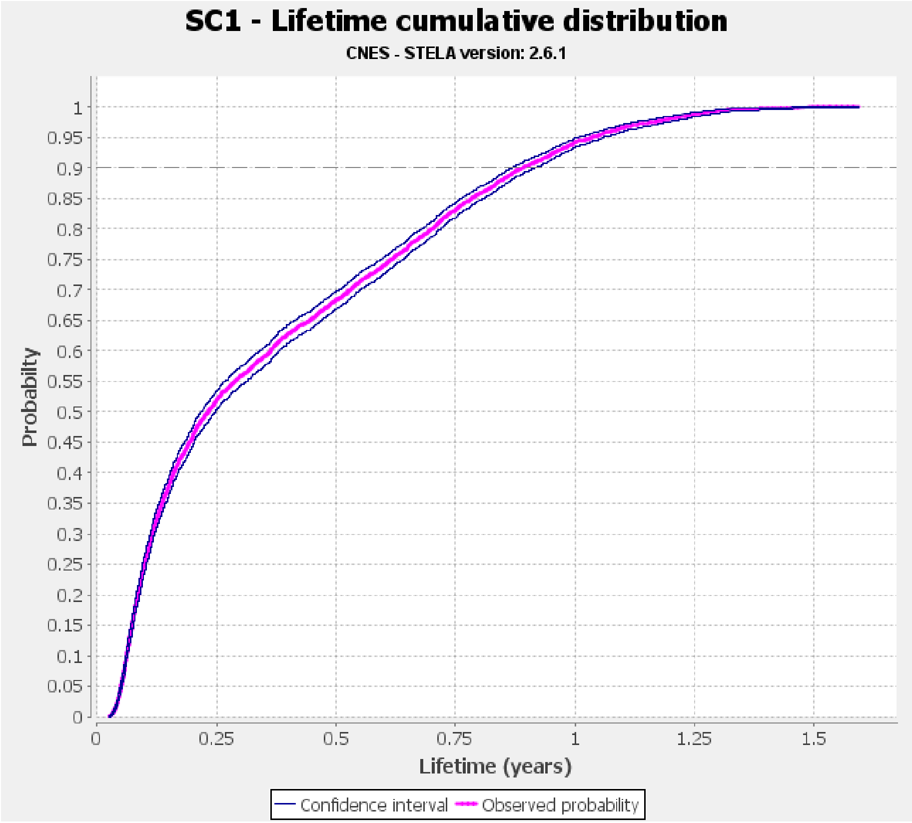

Figure 6-55 575km65deg orbit lifetime cumulative distribution for multi-parameter analysis

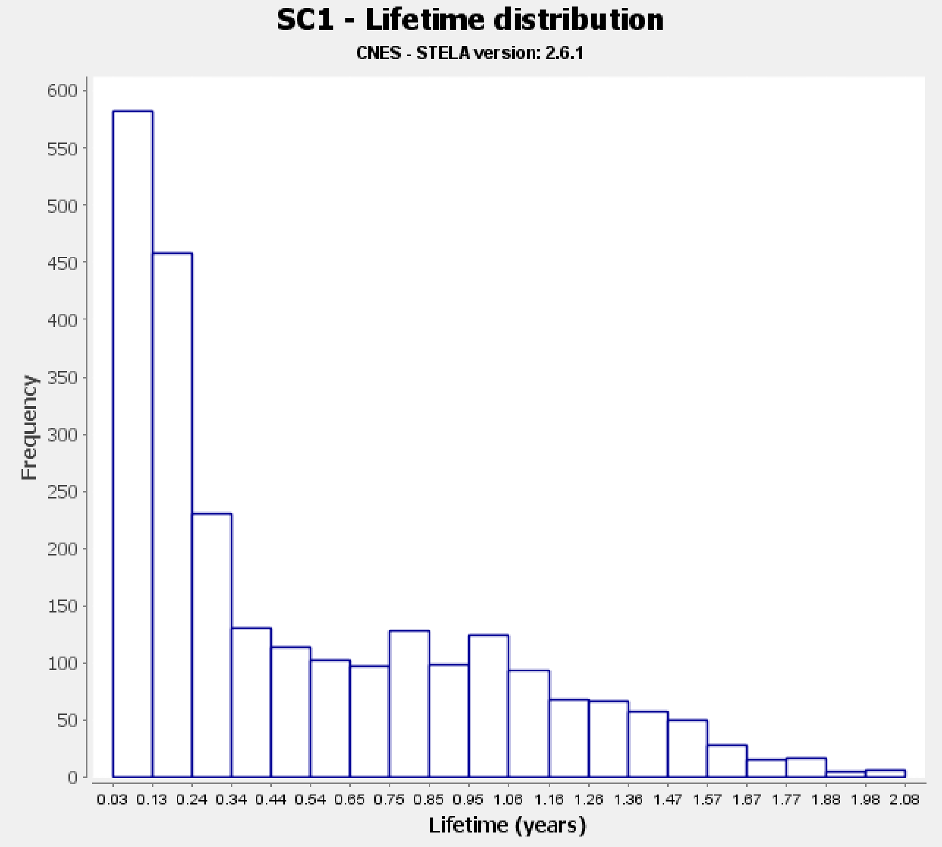

Figure 6-56 600km52deg orbit lifetime distribution for multi-parameter analysis

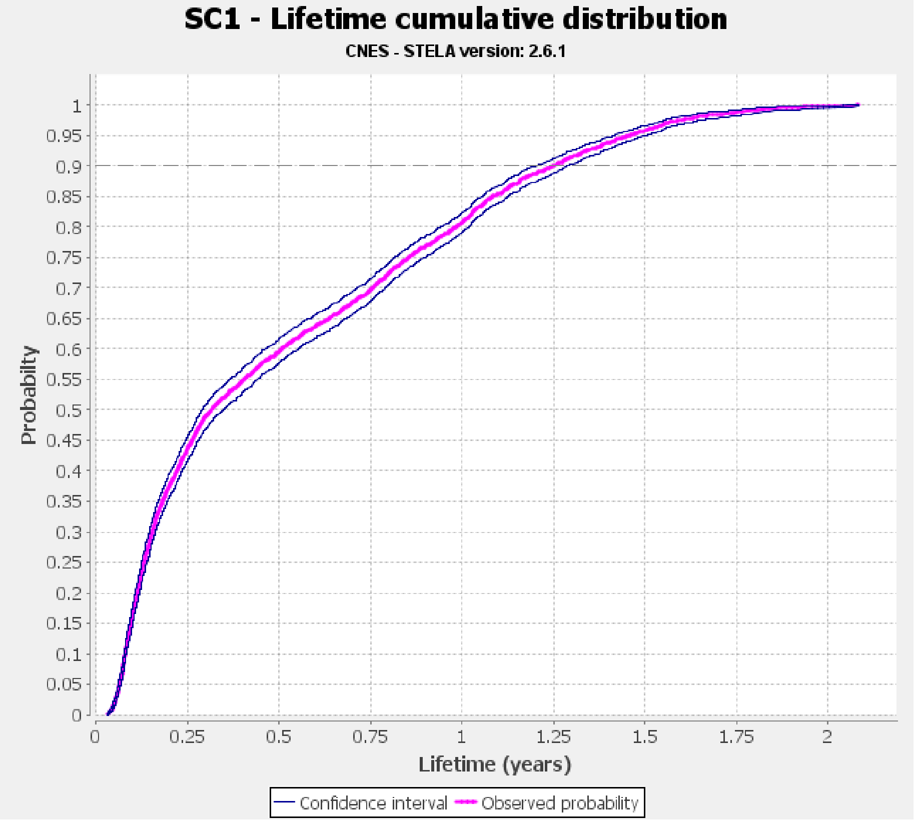

Figure 6-57 600km52deg orbit lifetime cumulative distribution for multi-parameter analysis

6.5.4.2 Worst case analyses

Following figures (Figure 6-58 to Figure 6-71) show the orbit lifetime distribution and cumulative lifetime distribution functions for conducted analyses for the worst case for all considered orbits.

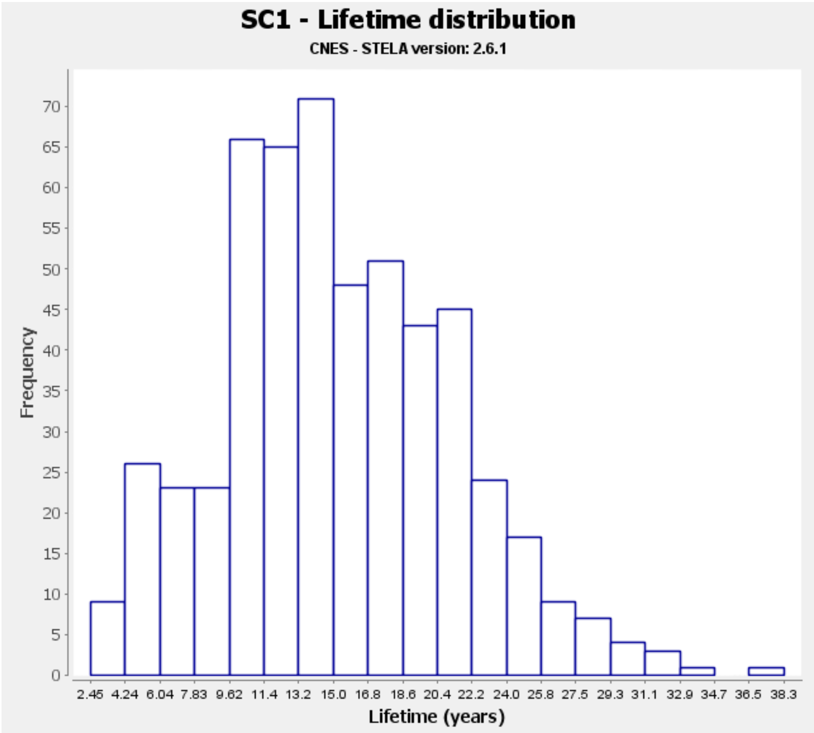

Figure 6-58 SSO780km orbit lifetime distribution for multi-parameter analysis

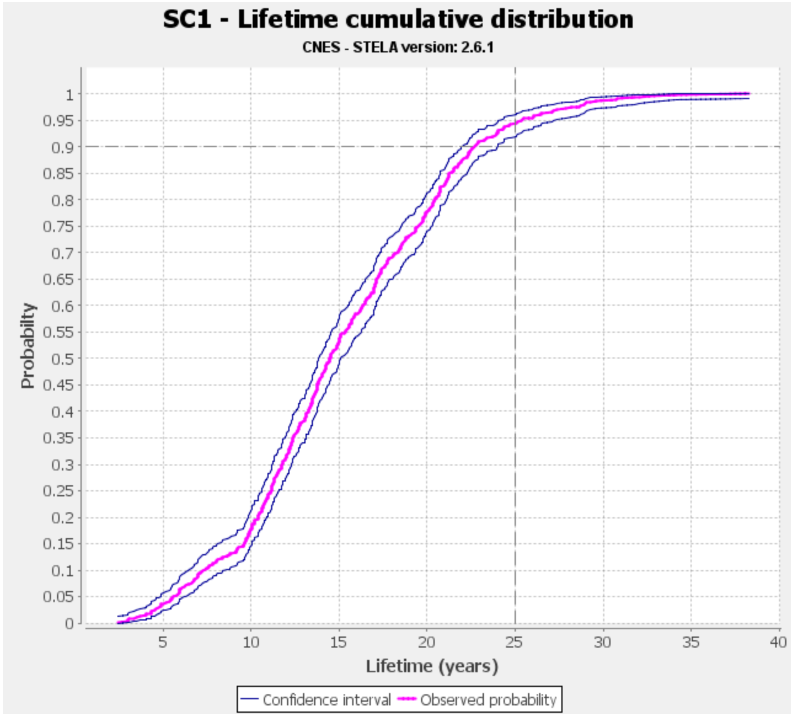

Figure 6-59 SSO780km orbit lifetime cumulative distribution for multi-parameter analysis

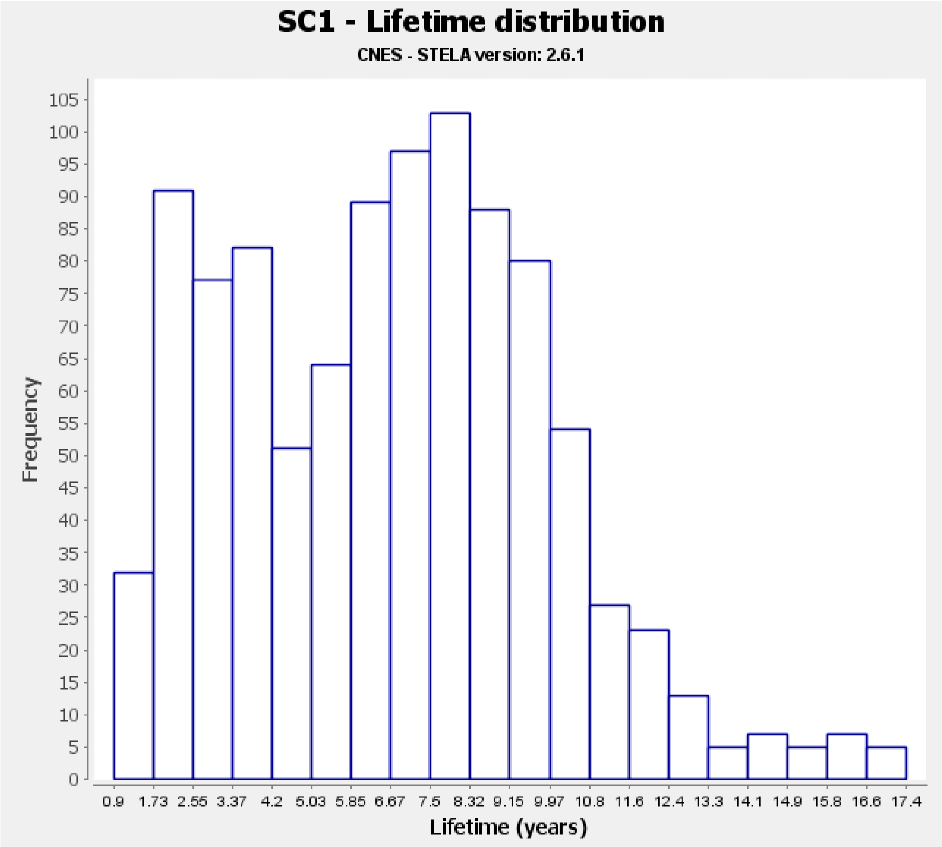

Figure 6-60 SSO700km orbit lifetime distribution for multi-parameter analysis

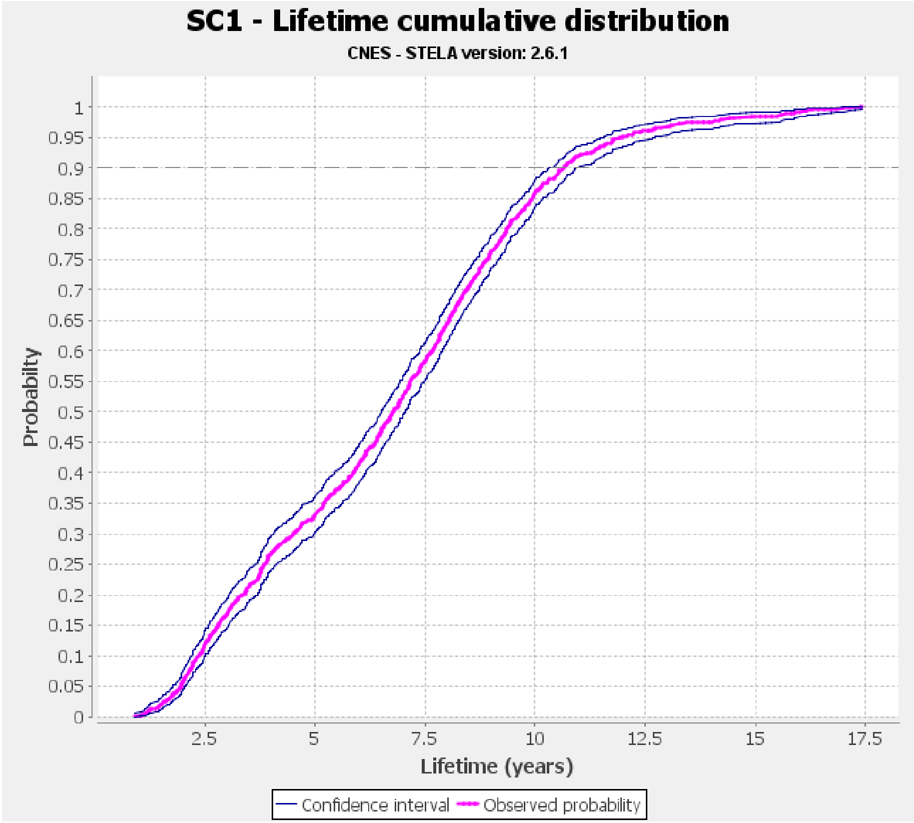

Figure 6-61 SSO700km orbit lifetime cumulative distribution for multi-parameter analysis

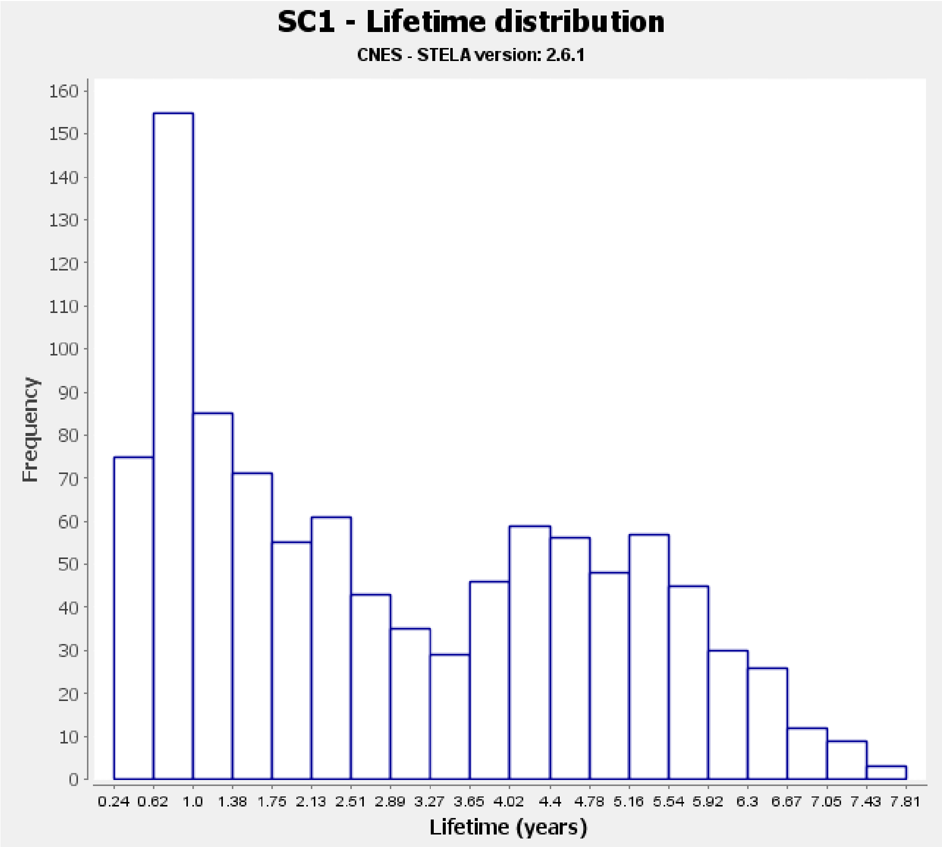

Figure 6-62 SSO600km orbit lifetime distribution for multi-parameter analysis

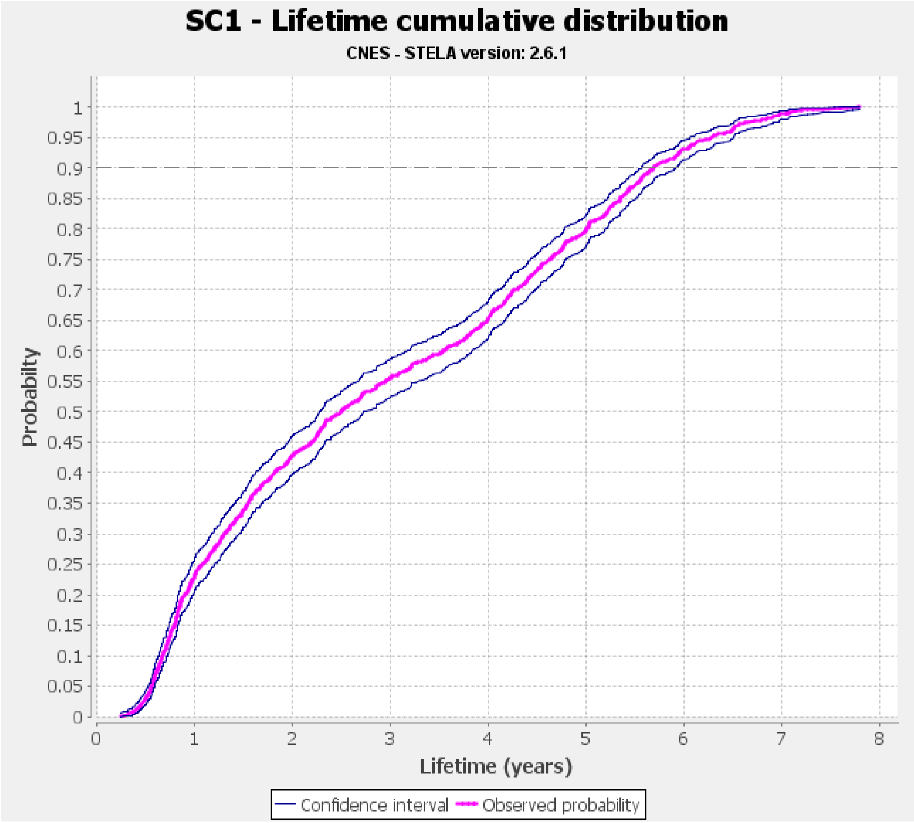

Figure 6-63 SSO600km orbit lifetime cumulative distribution for multi-parameter analysis

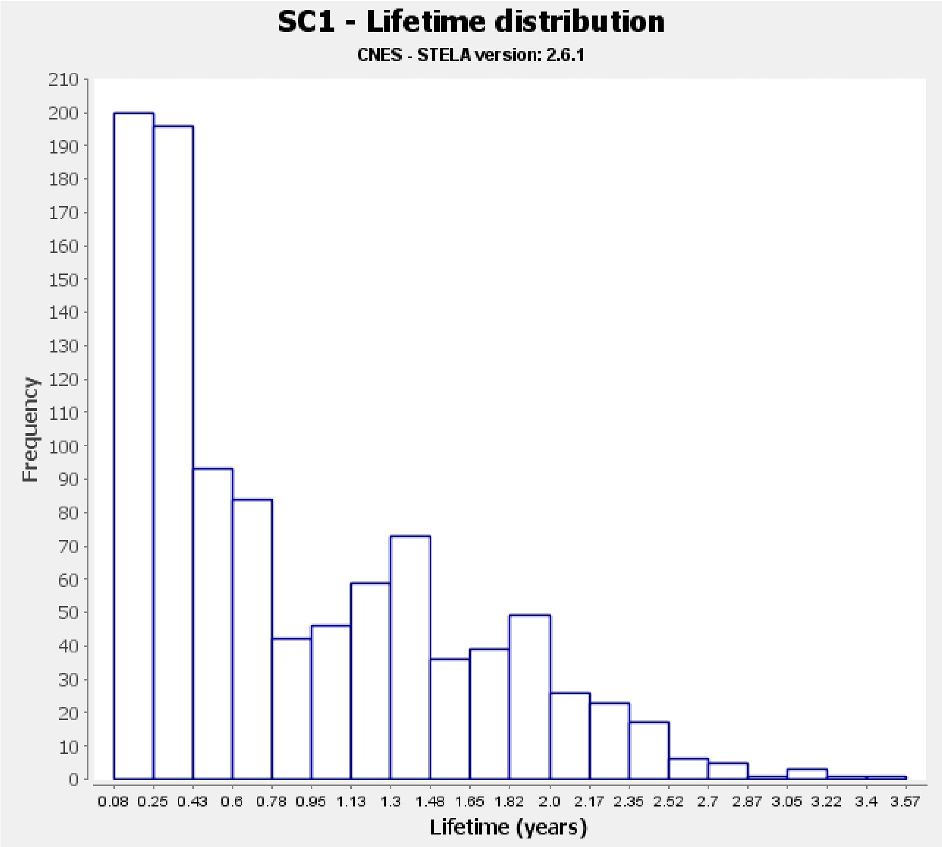

Figure 6-64 SSO500km orbit lifetime distribution for multi-parameter analysis

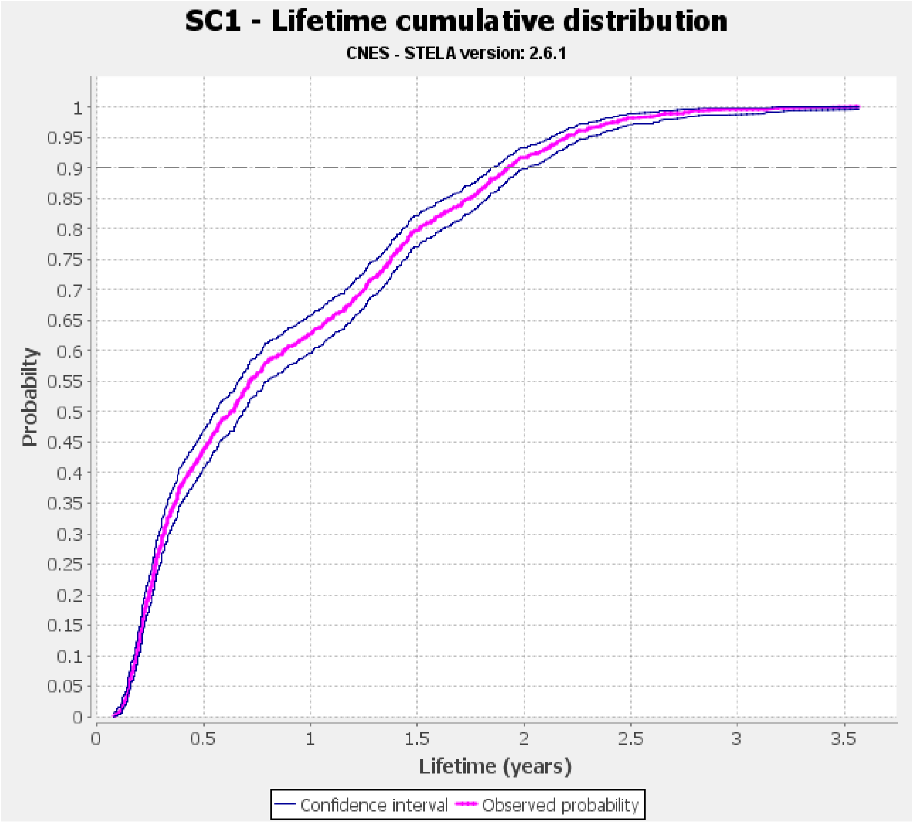

Figure 6-65 SSO500km orbit lifetime cumulative distribution for multi-parameter analysis

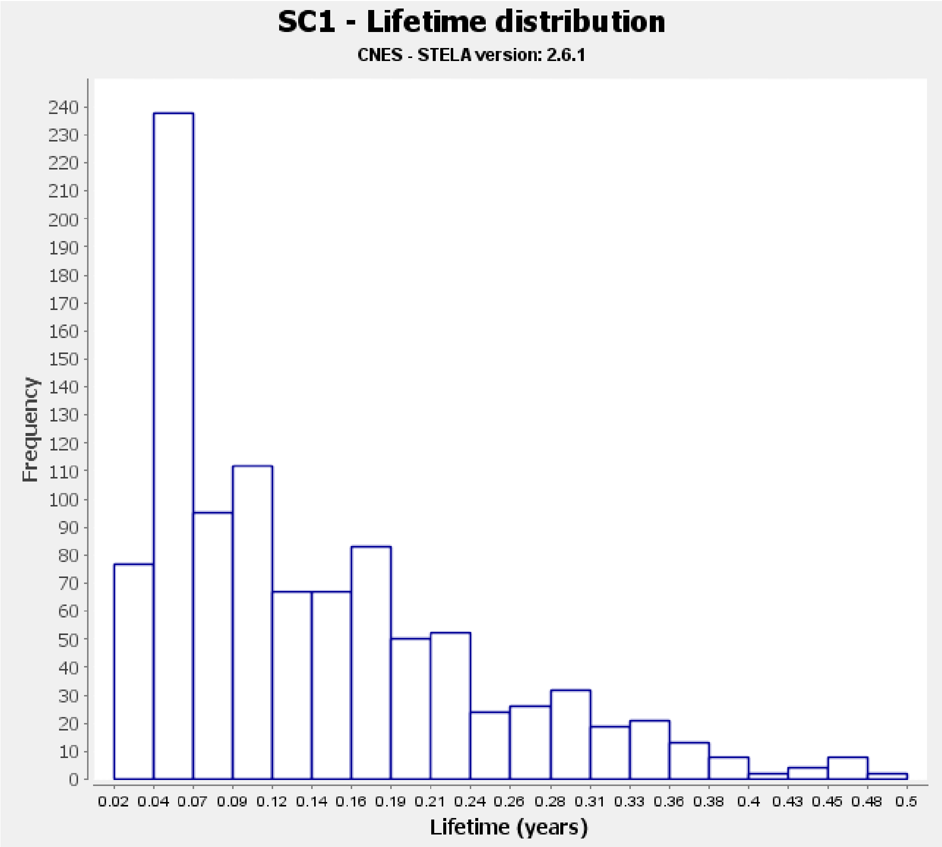

Figure 6-66 SSO400km orbit lifetime distribution for multi-parametermulti-parameter analysis

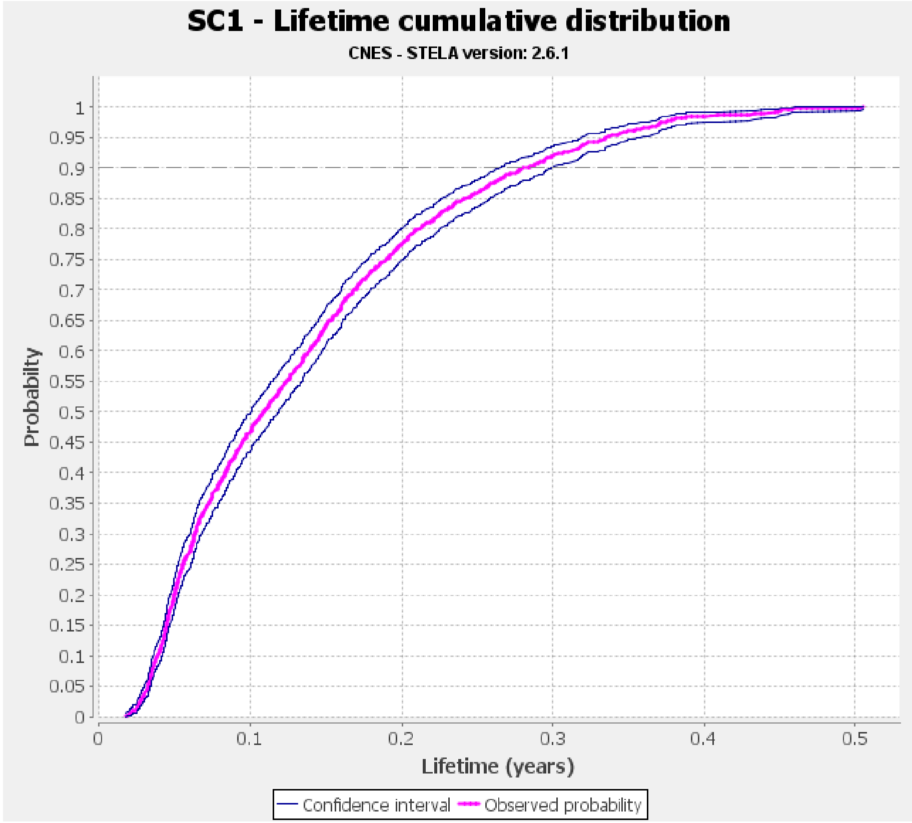

Figure 6-67 SSO400km orbit lifetime cumulative distribution for multi-parametermulti-parameter analysis

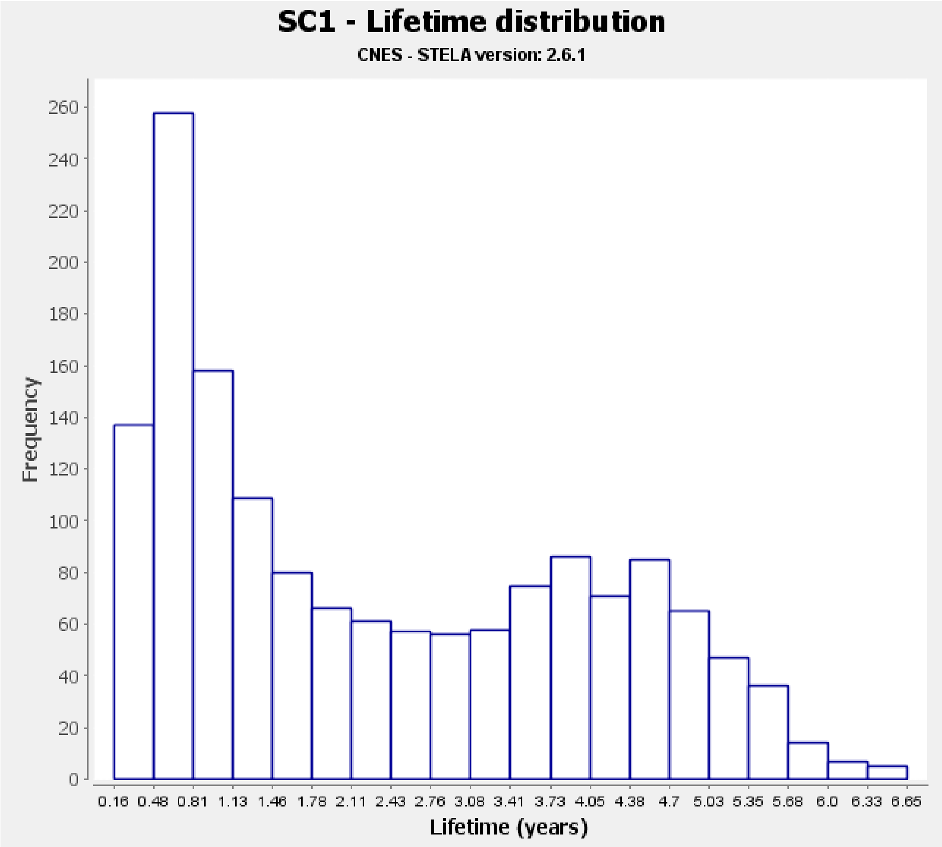

Figure 6-68 575km65deg orbit lifetime distribution for multi-parameter analysis

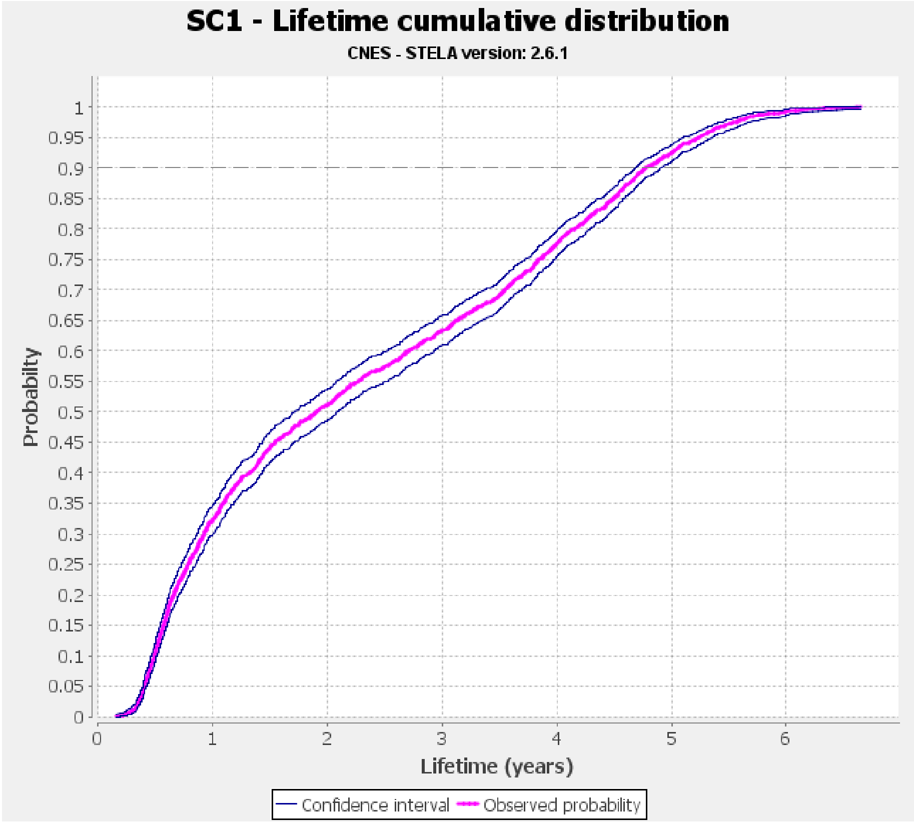

Figure 6-69 575km65deg orbit lifetime cumulative distribution for multi-parameter analysis

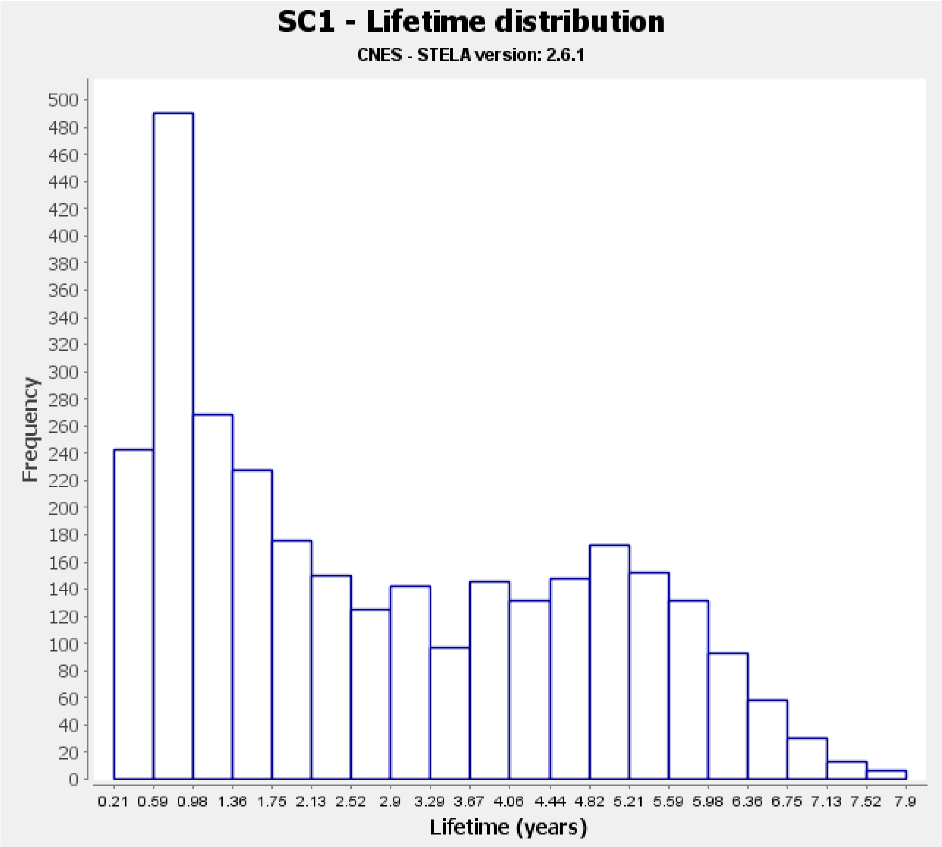

Figure 6-70 600km52deg orbit lifetime distribution for multi-parameter analysis

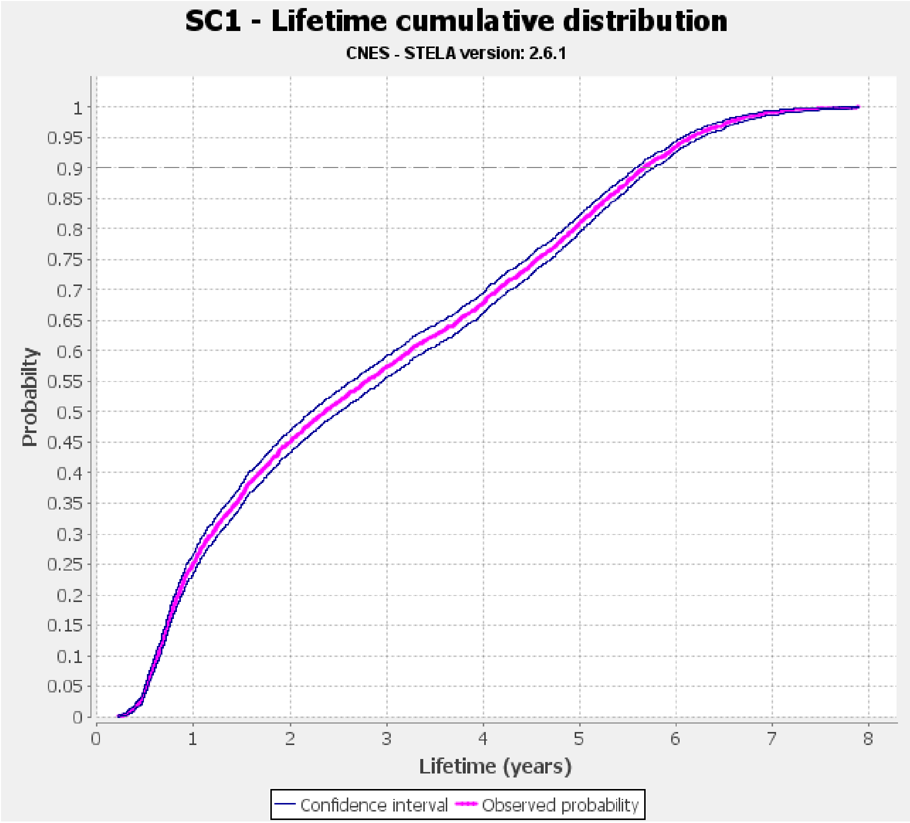

Figure 6-71 600km52deg orbit lifetime cumulative distribution for multi-parameter analysis

6.5.4.3 Summary of multi-Parameter variation analyses

Table 6-10 Summary of multiparameter analyses,nominal case

x [years]	Nominal case						
	Probability of lifetime shorter than x						
	SSO780 km	SSO700 km	SSO600 km	SSO500 km	SSO40 0km	600km 52deg	575km 65deg
< 1	25 %	44 %	81 %	100 %	100 %	80 %	94 %
< 2	44 %	62 %	100 %	100 %	100 %	100 %	100 %
< 3	57 %	75 %	100 %	100 %	100 %	100 %	100 %
< 4	68 %	93 %	100 %	100 %	100 %	100 %	100 %
< 6	91 %	100 %	100 %	100 %	100 %	100 %	100 %
< 10	100 %	100 %	100 %	100 %	100 %	100 %	100 %
< 15	100 %	100 %	100 %	100 %	100 %	100 %	100 %
< 25	100 %	100 %	100 %	100 %	100 %	100 %	100 %
min; max; max/min lifetime [years]							
max	7.56	5.29	2.18	0.48	0.07	2.08	1.50
min	0.20	0.09	0.04	0.01	0.00	0.03	0.03
max/min	37.36	56.82	61.88	50.56	27.17	61.69	55.53

Table 6-11 Summary of multiparameter analyses.worst case

x [years]	Worst case						
	Probability of lifetime shorter than x						
	SSO780 km	SSO700 km	SSO600 km	SSO500 km	SSO400 km	600km 52deg	575km 65deg
< 1	0 %	0 %	23 %	63 %	100 %	24 %	32 %
< 2	0 %	6 %	43 %	92 %	100 %	44 %	51 %
< 3	0 %	17 %	56 %	99 %	100 %	57 %	64 %
< 4	1 %	27 %	65 %	100 %	100 %	67 %	78 %
< 6	5 %	42 %	93 %	100 %	100 %	93 %	99 %
< 10	17 %	86 %	100 %	100 %	100 %	100 %	100 %
< 15	52 %	98 %	100 %	100 %	100 %	100 %	100 %
< 25	96 %	100 %	100 %	100 %	100 %	100 %	100 %
min; max; max/min lifetime [years]							
max	31.60	17.43	7.81	3.57	0.50	7.90	6.65
min	2.94	0.90	0.24	0.08	0.02	0.21	0.16
max/min	10.75	19.37	33.22	46.45	29.40	37.81	41.06

The lowest max to min ratio occurs for SSO780km orbit. It may be assumed that this orbit is the most stable with the analysis parameters variation and as such is the most suitable to perform the sail experiment. However, for final conclusion, more detailed analyses should be performed in phase C.

6.5.5 ITERATIVE ANALYSES

> STELA software is able to work in a "LEO Iterative mode". This computation mode allows the user to determine an initial orbit that will have an expected lifetime given by the user in the GUI. (STELA (v.2.6.1) *User's Guide* [RD. 2])

This mode was used to determine the height of the orbits for 2U CubeSat for which some sort of drag augmentation device (or other orbit lifetime decreasing device) would be needed to comply with the IADC recommendations - max. 25 years on LEO [RD. 9]. Two cases were considered according to the solar activity – worst case (small solar activity) and best case (high solar activity). Choice of solar activity parameters values is described in the following section 6.5.5.1. In these analyses "frozen orbit" mode was chosen in which the eccentricity is fixed and only SMA is being optimized to reach predefined orbit lifetime.

6.5.5.1 Solar Activity File

STELA default Solar Activity file consist of measured data of solar activity since 1957 to 2014 extended by the predictions up to 2318. Measured part of the data was analyzed to find mean values and standard deviation to determine the values for the best and worst scenario. As a best case (highest solar and geomagnetic activity) for both AP and F10.7 indices values equal to: $Mean\ value + 2 \times std.deviation$ were used. Values of solar activity are not normally distributed as shown on Figure 6-74 and Figure 6-75 so it was not possible to use the analogous criterion for worst case, as this would give negative (non-physical) values. For worst case scenario values of the 5^{th} percentile were chosen (5 % of samples were below this value). Data from STELA default Solar Activity File are shown on Figure 6-72.

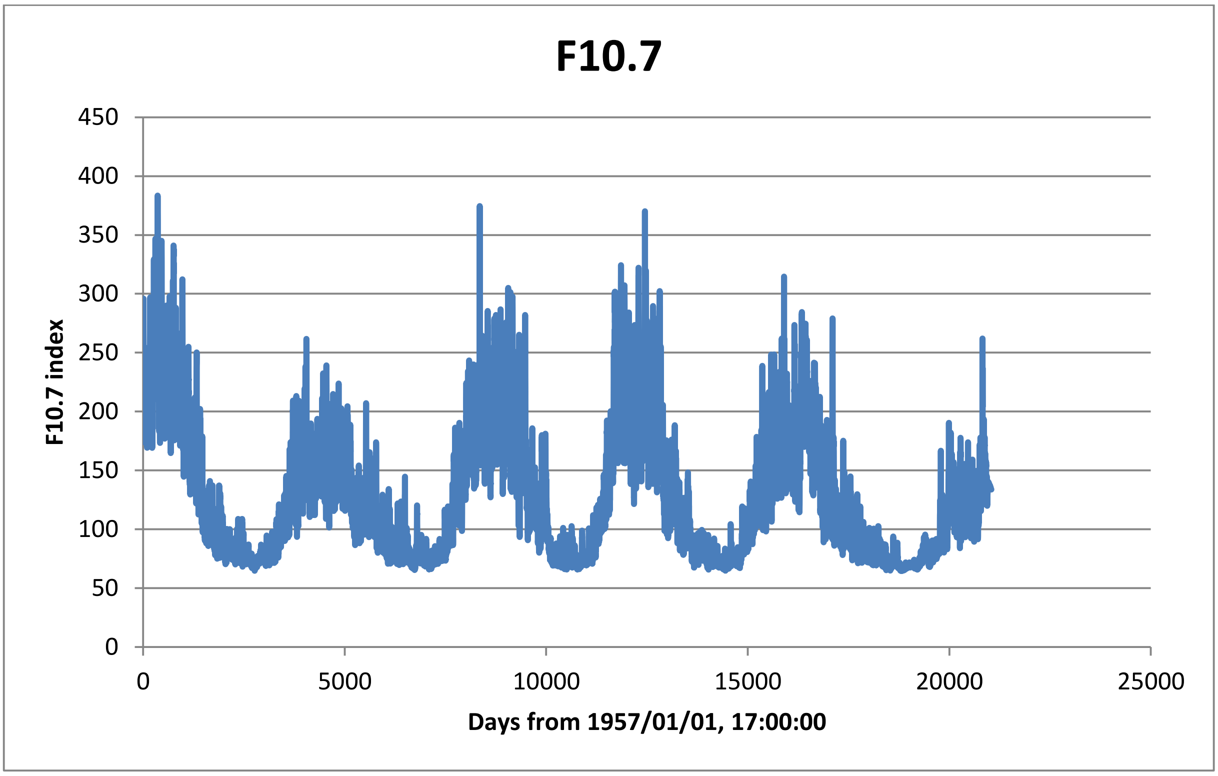

Figure 6-72 F10.7 index values between 1957/01/01 and 2014/09/24, STELA Solar Actvity File

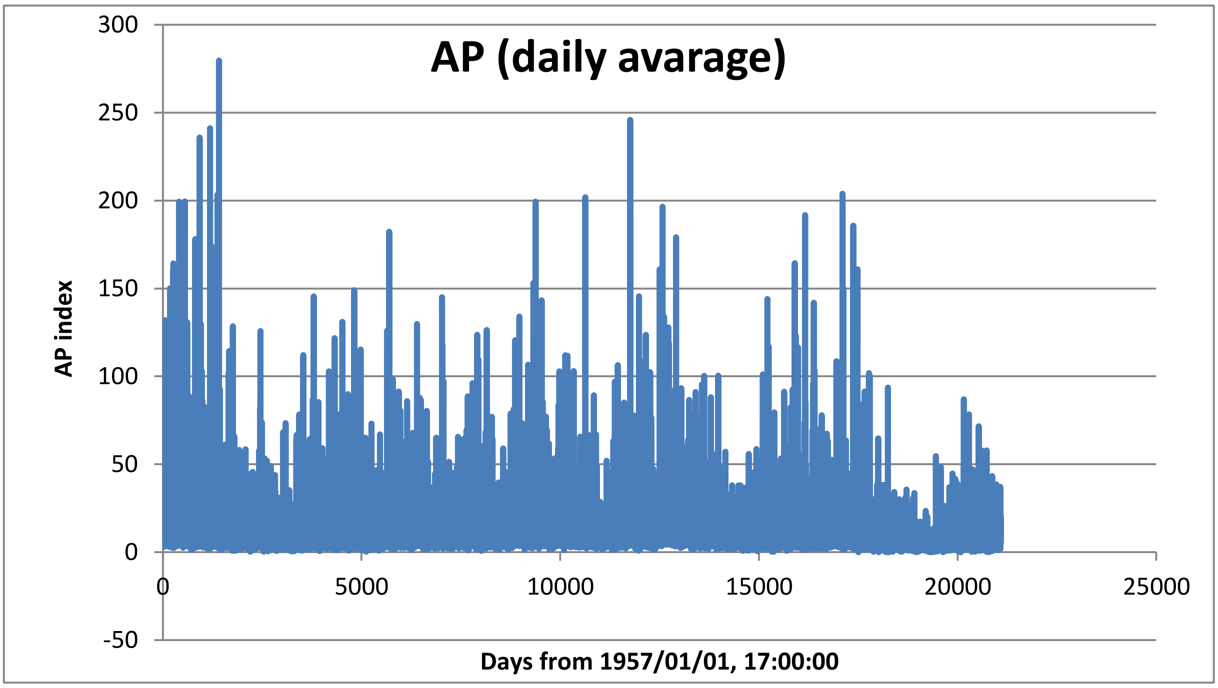

Figure 6-73 AP index values between 1957/01/01 and 2014/09/24, STELA Solar Actvity File

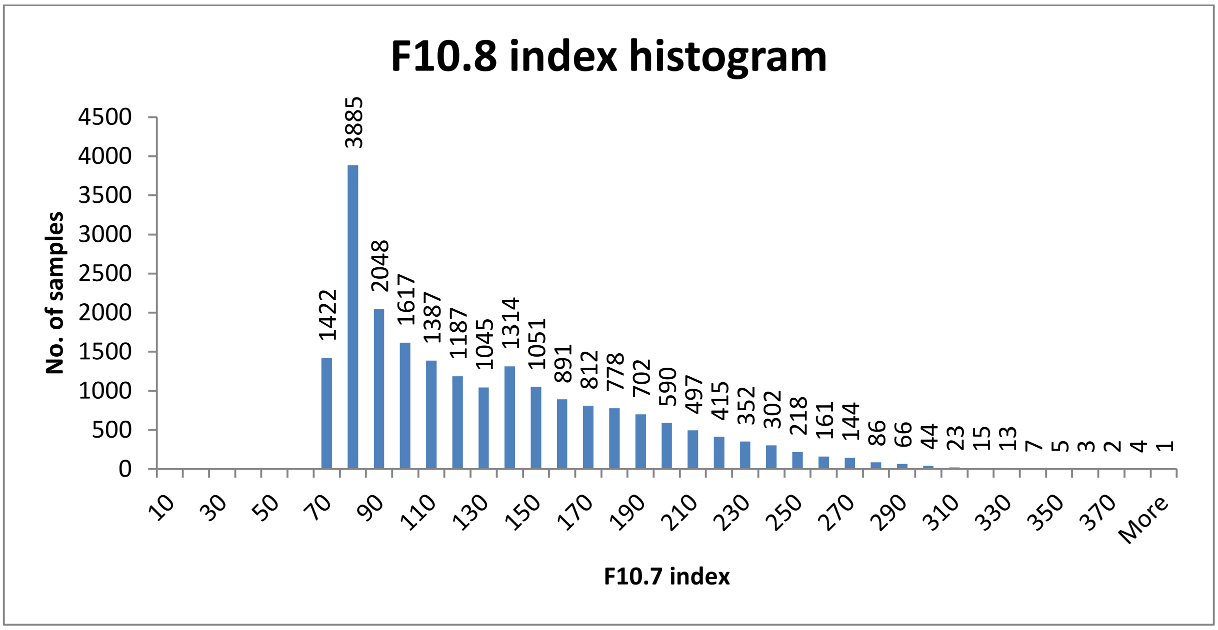

Figure 6-74 F10.8 index histogram, STELA SolarActivity File

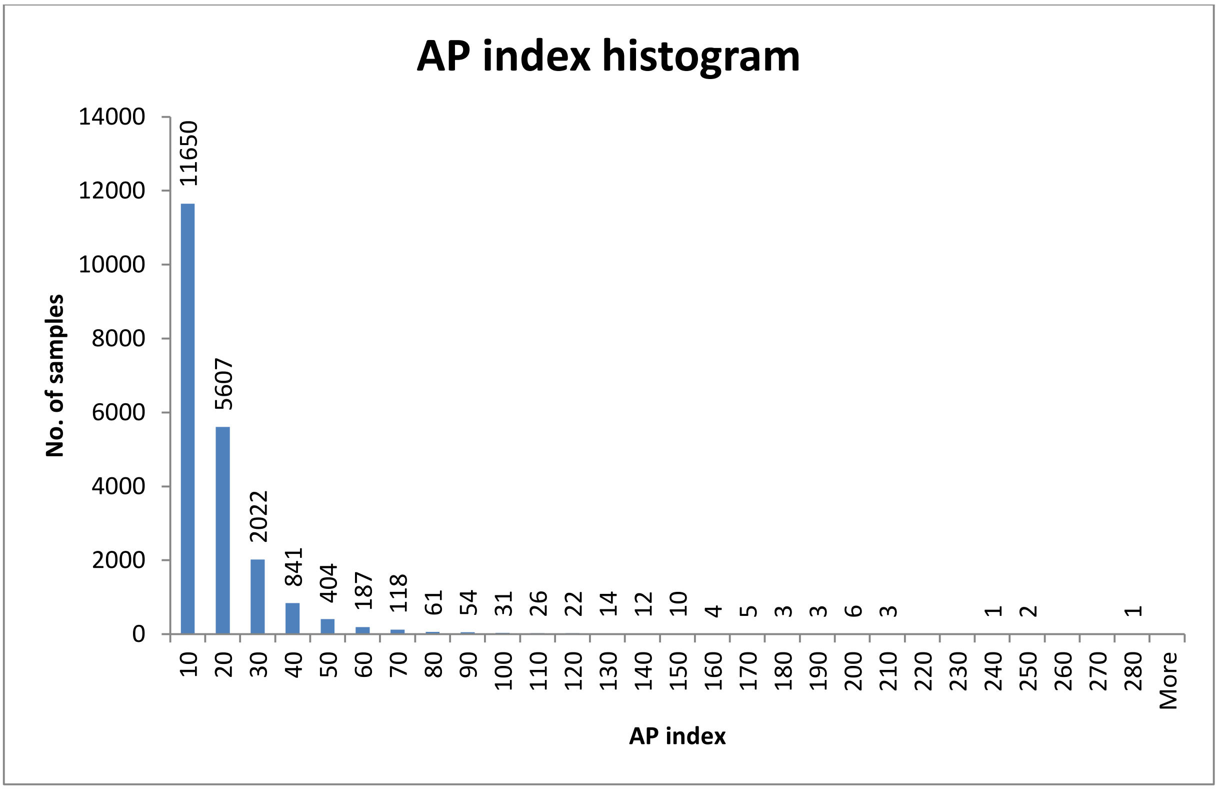

Figure 6-75 AP index histogram, STELA SolarActivity File

6.5.5.2 Maximum SMA optimization

Analyses initial parameters are shown in Table 6-12.

Table 6-12 Iterative analyses initial conditions

Parameter	Value	
Launch date	2016/13/02, 09:00:00UTC	
Initial Semi Major Axis (SMA)	7158.14 km (780 km altitude)	
Eccentricity (Ecc)	0.001225	
RAAN	111.738°	
Mean anomaly (M)	0	
Inclination (INC)	97.36351501°	
Mass	3.2 kg	
Coefficient of drag (Cd)	STELA Default file	
Reflectivity coefficient (Cr)	1.5	
Drag area	0.02667366 m^2	
Reflectivity Area	0.02667366 m^2	
Iterative analysis mode	Frozen eccentricity orbit (only SMA is optimized)	
Expected lifetime	24.9 years	
Solar activity mode	Constant (user defined values)	
	Best case	Worst case
Solar activity, F10.7 index	233.21	69.2
Geomagnetic activity, AP index	44.59	2.5

Results of the iterative analyses are shown on Figure 6-76 Figure 6-77.

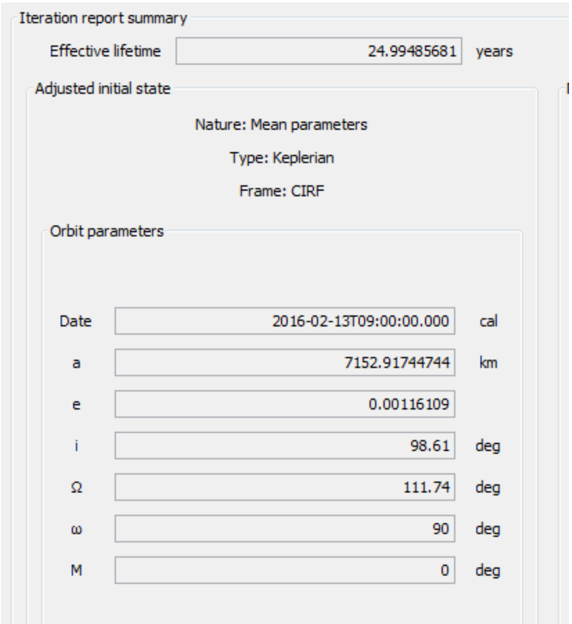

Figure 6-76 Iterative analysis best case (high solar activity)

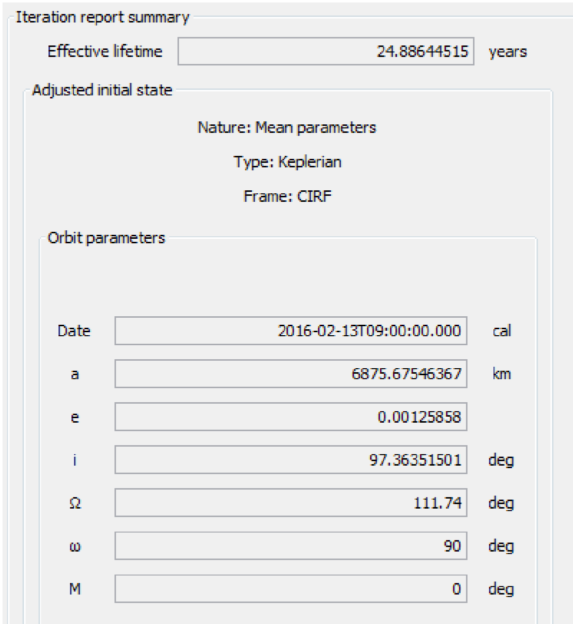

Figure 6-77 46 Iterative analysis best case (low solar activity)

Conclusion from these analyses is that for CubeSat 2U on circular SSO orbit, depending on the solar activity, critical SMA is in range between 7152 km and 6875 km which (altitudes between 775 and 497 km). Critical SMA is defined here as the SMA for which orbit lifetime is longer equal 25 years.

It should be noted that both for worst case and the best case scenario the F10.7 and AP indices values are very conservative. In real life these indices are never fixed on low or high level. For more conclusive analyses, values of whole cycles should be taken into account. Cycle with lowest mean activity could be chosen as a worst case and the cycle with the highest activity as the best case. It is recommended that this kind of analyses should be performed in phase C.

6.6 SUMMARY OF THE CONDUCTED ANALYSES

All considered orbits were LEO, between 400 km – 780 km, however obtained results were significantly different. Assuming that all of the seven selected orbits are equally probable as PW-Sat2 final orbit the worst case scenario that the satellite should withstand is summed up in a table below:

Table 6-13 Summary of conducted analyse worst cases

Parameter		Value (worst case)	Orbit
Total Access Time (Duration >60 s)	[-]	0.248 %	SSO 400km
Mean Access Time	[s]	141	SSO 400km
Accesses longer than 160 s	[-]	48.06 %	SSO 400km
Max Access Gap (Duration >60 s)	[s]	134446 (over 37 h)	SSO 400km
Mean Access Gap (Duration >60 s)	[s]	56660	SSO 400km
Total Eclipse Time fraction	[-]	37.60 %	SSO 400km
Max Eclipse	[s]	2134	575km65deg
Mean Eclipse	[s]	2089	SSO 400km
Max Exposure time	[s]	1047315 (over 12 days)	575km65deg
No. of Sun exposures > 1.1 Period	[-]	4	575km65deg

7 OPERATORS INTERNSHIPS IN BRITE-PL GROUND STATION

In the beginning of the 2015 year Polish BRITE Ground Station organized a short internship for PW-Sat2 COMM team. These were a few meetings of station operators (Kamil Sażyński – PW-Sat2 and Grzegorz Woźniak – BRITE-PL). The essence of the internship was to plan the construction of the ground station to communicate with the PW-Sat2. Another aspect was the communication sessions with BRITE satellites. Using the experience of BRITE team, PW-Sat2 team decided to use antennas with circular polarization – Tonna 20818 for VHF and Tonna 20938 for UHF. Antennas will be used with symmetrical splitters to eliminate a decrease in the radio signal associated with SC rotation. An important aspect of communication sessions was also software. Simple communication sessions take few minutes, so GS software should be easy to use and display conspicuously the most important parameters of PW-Sat2. Software for PW-Sat2 ground station will be prepared, according to team's guidelines by SoftwareMill, commercial company co-working with PW-Sat2 team.

8 ACTIVITIES PLANNED FOR PHASE C

8.1 ACTIVITIES DERIVED FROM TEAM OBJECTIVES

Team objectives are described in paragraph 3.1. Activities derived from these objectives and planned for phase C are described in a table below:

Table 8-1 Planned activities for phase C derived from Team Objectives

Task code	Task description	Activities planned for phase C w.r.t. task
PRR_MA_1	Finding a way to launch the satellite into orbit	In the beginning of phase C it is planned to issue a new request for offers to the launch providers taking into account updated project schedule.
PRR_MA_2	Mission and orbit analysis in Mission Analysis software	This is a general task divided into a smaller sub-tasks.
PRR_MA_2.1	Contact with software distributors	It is planned to maintain the contact with AGI and A.I. Solutions representatives to broaden the available software tools.
PRR_MA_2.2	Organization of training mission analysis software	In phase C more detailed analyses will have to be performed so the new team members will have to learn how to use available software tools.
PRR_MA_2.3	Mission modeling	This is a general task divided into a smaller sub-tasks. Analyses presented in this report will have to be enriched taking into account variations in the initial RAAN and Launch date. New analyses will be performed also in case of new orbits being potentially available for PW-Sat2.
PRR_MA_2.3.1	Modeling of solar panels' exposure to light	Analyses of the optimal opening angle of solar arrays are going to be performed in cooperation with EPS, ADCS, and DT teams.
PRR_MA_2.3.2	Modeling of communication session with ground station	This task's activities are presented in the chapter 6.3 of this document.
PRR_MA_2.3.2.1	Number of comm. Sessions for low orbits	Number of communication sessions before and after the sail deployment for lower orbits.
PRR_MA_2.3.3	Calculation of suitable time to test sun sensor	Further detailed analyses of communication sessions will be performed in close cooperation with COMM team.
PRR_MA_2.3.4	Orbital decay analysis	Further orbital decay analyses will be performed for in phase C.
PRR_MA_2.3.4.1	Nominal configuration analyses	Further orbital decay analyses will be performed for different RAAN and launch dates for nominal configurations for the orbits selected in chapter 6.5. and orbits selected from updated launch providers offers.
PRR_MA_2.3.4.2	Sail use for potential future missions	PW-Sat2 sail influence on possible future missions of micro and small satellites on LEO.
PRR_MA_2.3.4.3	Single-parameter analyses for other orbits	Single-parameter analyses for other (than SSO780km) selected in chapter 6.5. and orbits selected from updated launch providers offers.
PRR_MA_2.3.4.4	Multi-parameter analyses with no sun-activity distribution	Multi-parameter analyses which will all be performed for the same solar cycle to show minor parameters influence on the lifetime distribution.

PRR_MA_2.3.4.5	Iterative analyses for real solar cycles	Iterative analyses for two cases of the real solar cycles: high mean activity cycle (best case) and low mean activity (worst case).
PRR_MA_2.3.4.5	No-sail orbit decay for operations duration	Orbit decay analysis for PW-Sat2 without the sail deployed for first 1 month and 2 months after launch.
PRR_MA_2.3.4.6	Validation of STELA analyses	Variety of activities for STELA analyses validation: literature analysis, validation with different simulation packages, analysis of already-decayed satellites orbits.
PRR_MA_3	Implementation a of detailed mission plan	Separate group inside PW-Sat2 project is planned to be formed for preparation of the detailed mission plan with representatives of all interested teams: MA, EPS, OBC, ADCS, and payloads.
PRR_MA_4	Preparation of the satellite operators' team (OPER)	This task is scheduled for phase C.
PRR_MA_4.1	Radio amateur training organization	Radio amateur trainings are planned for the July-August 2015.
PRR_MA_4.2	Obtaining of radio amateur licenses	This task is scheduled for phase C. See task PRR_MA_4.1.
PRR_MA_4.3	Process mission plan to a set of telecommands	This task is scheduled for phase C when the mission plan will be available. This task is moved to be performed by OBC team.
PRR_MA_4.4	Develop contingency plans for emergency response of individual sub-systems	This task is scheduled for phase C when the mission plan and satellite software prototype will be available.
PRR_MA_4.5	Risk analysis for satellite mission	This task's activities were started in Phase A and are described in [PD.1]. Further activities and their schedule are still TBD due to lack of manpower and lower priority. However, ongoing risk management is performed by the project management in a non-formalized matter.

9 APPENDIX A: DIAGRAMS CLOSE-UPS

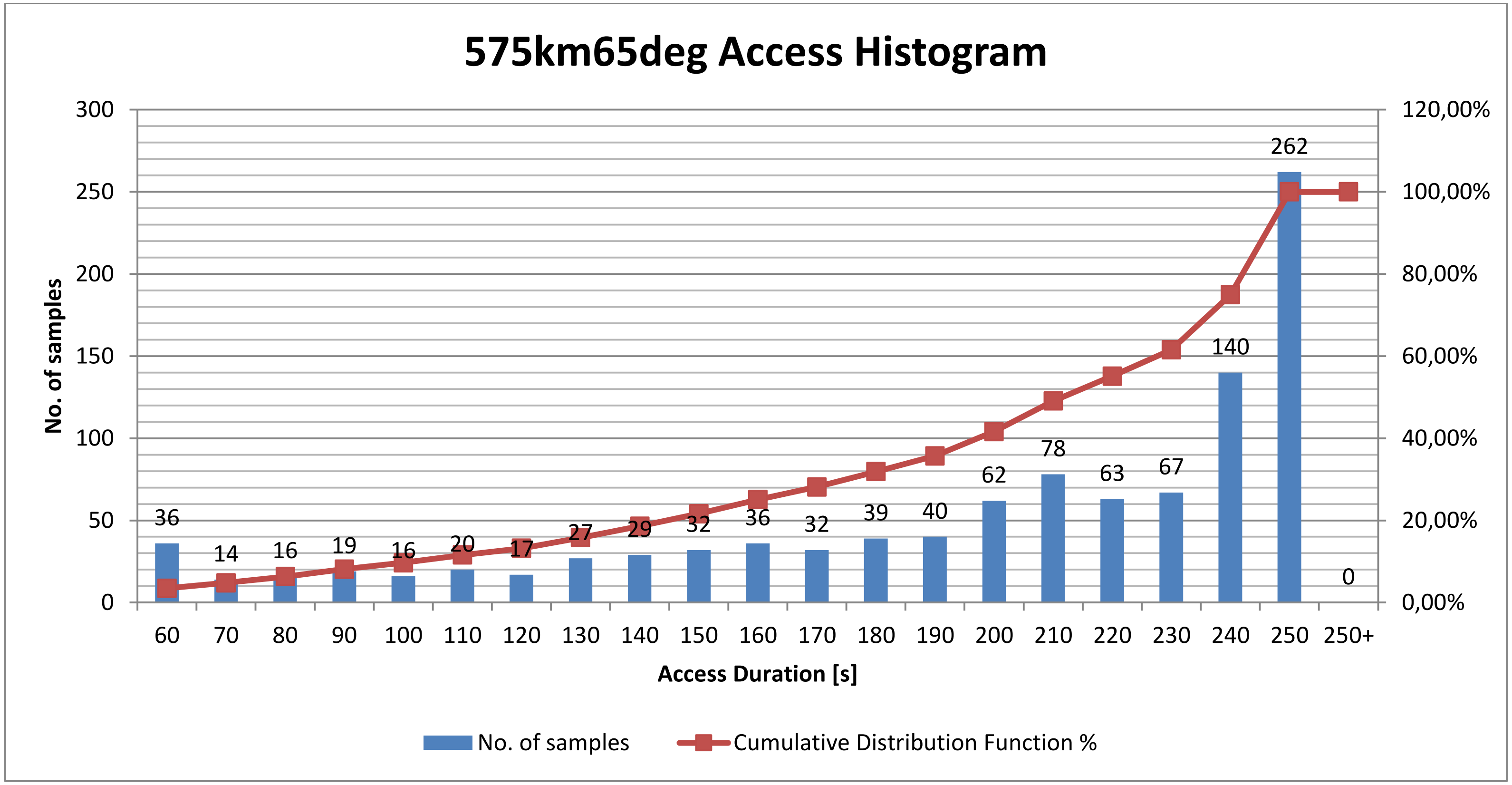

Figure 9-1 575km65deg Access Histogram

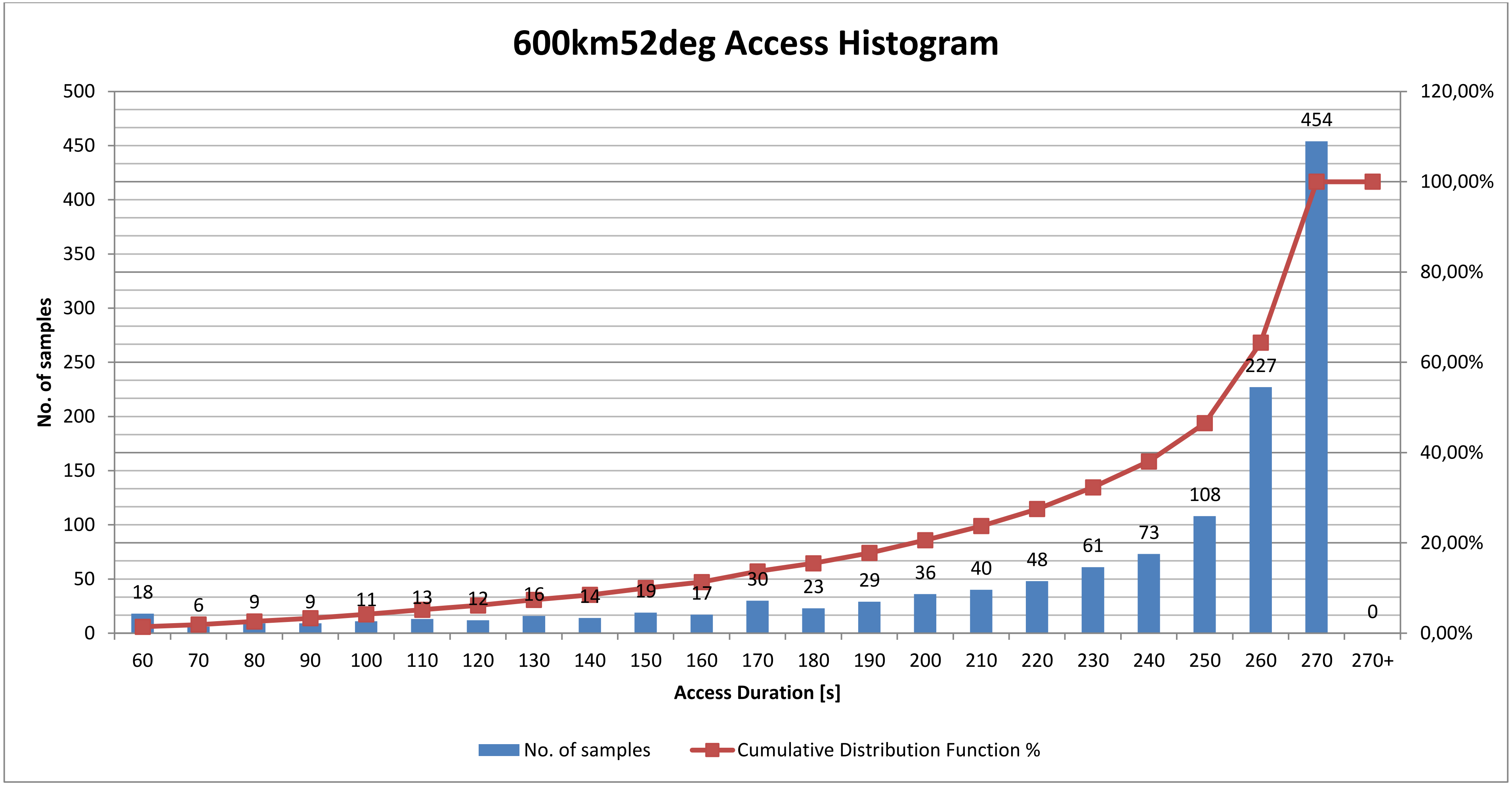

Figure 9-2 600km52deg Access Histogram

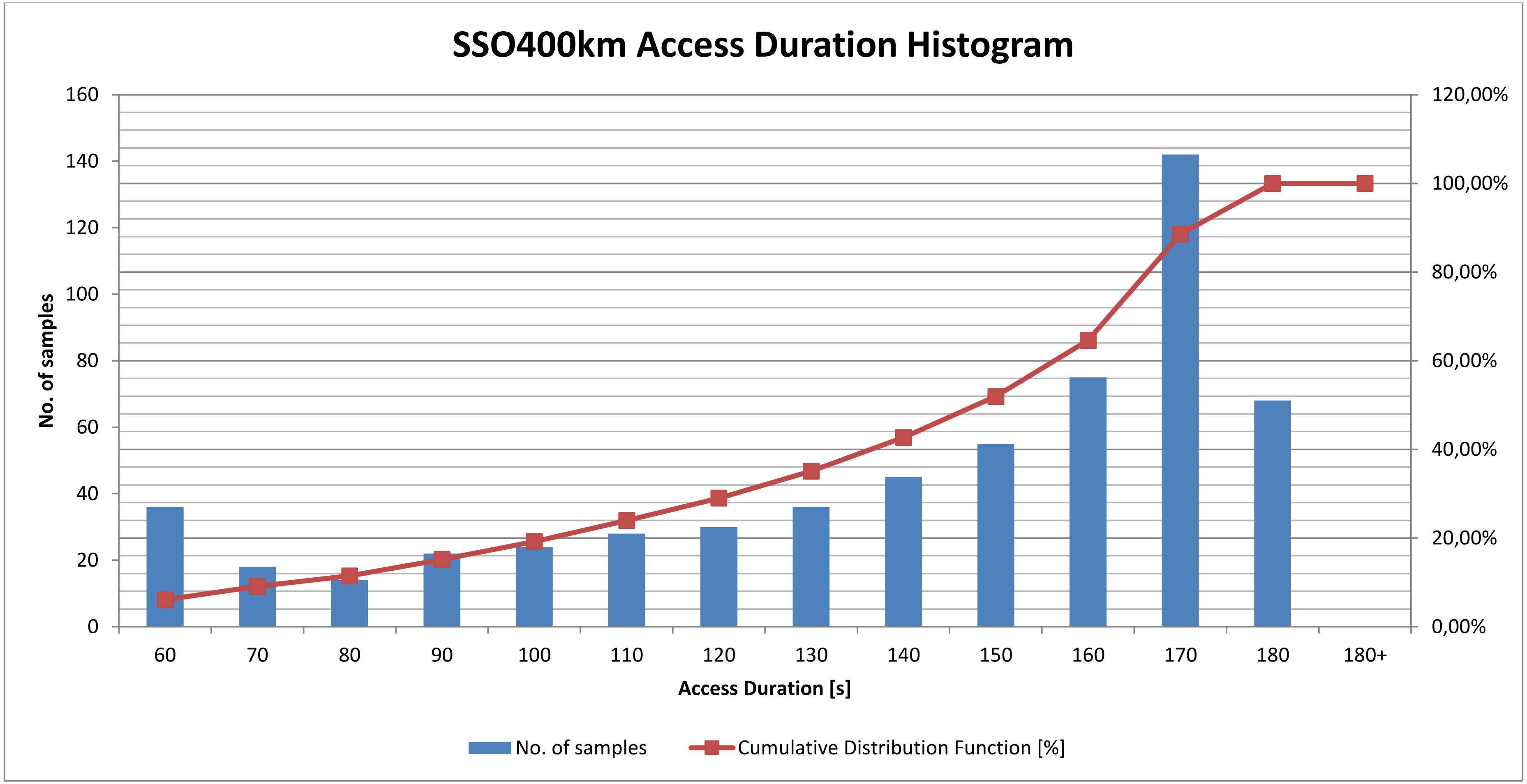

Figure 9-3 SSO400km Access Duration Histogram

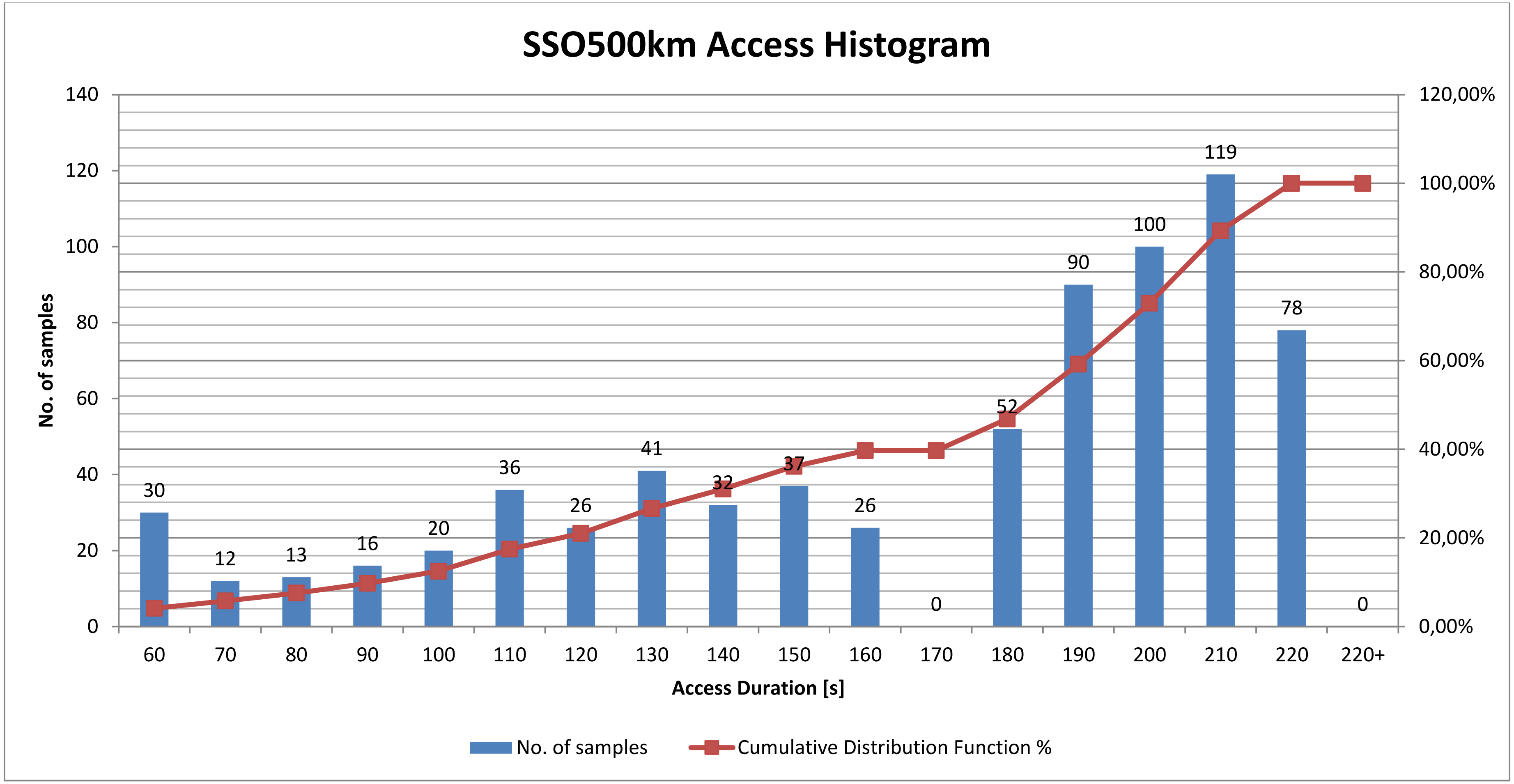

Figure 9-4 SSO500km Access Histogram

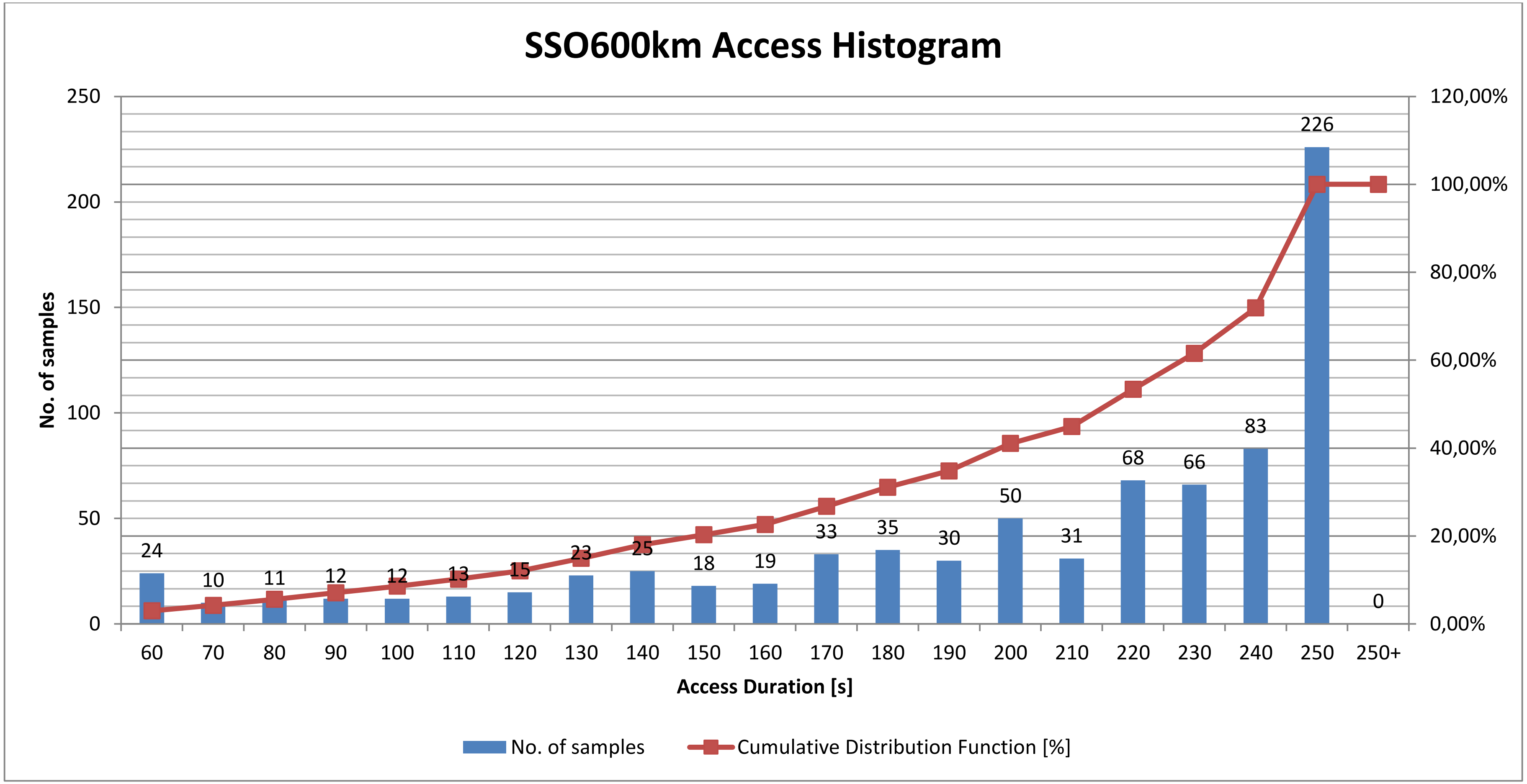

Figure 9-5 SSO600km Access Histogram

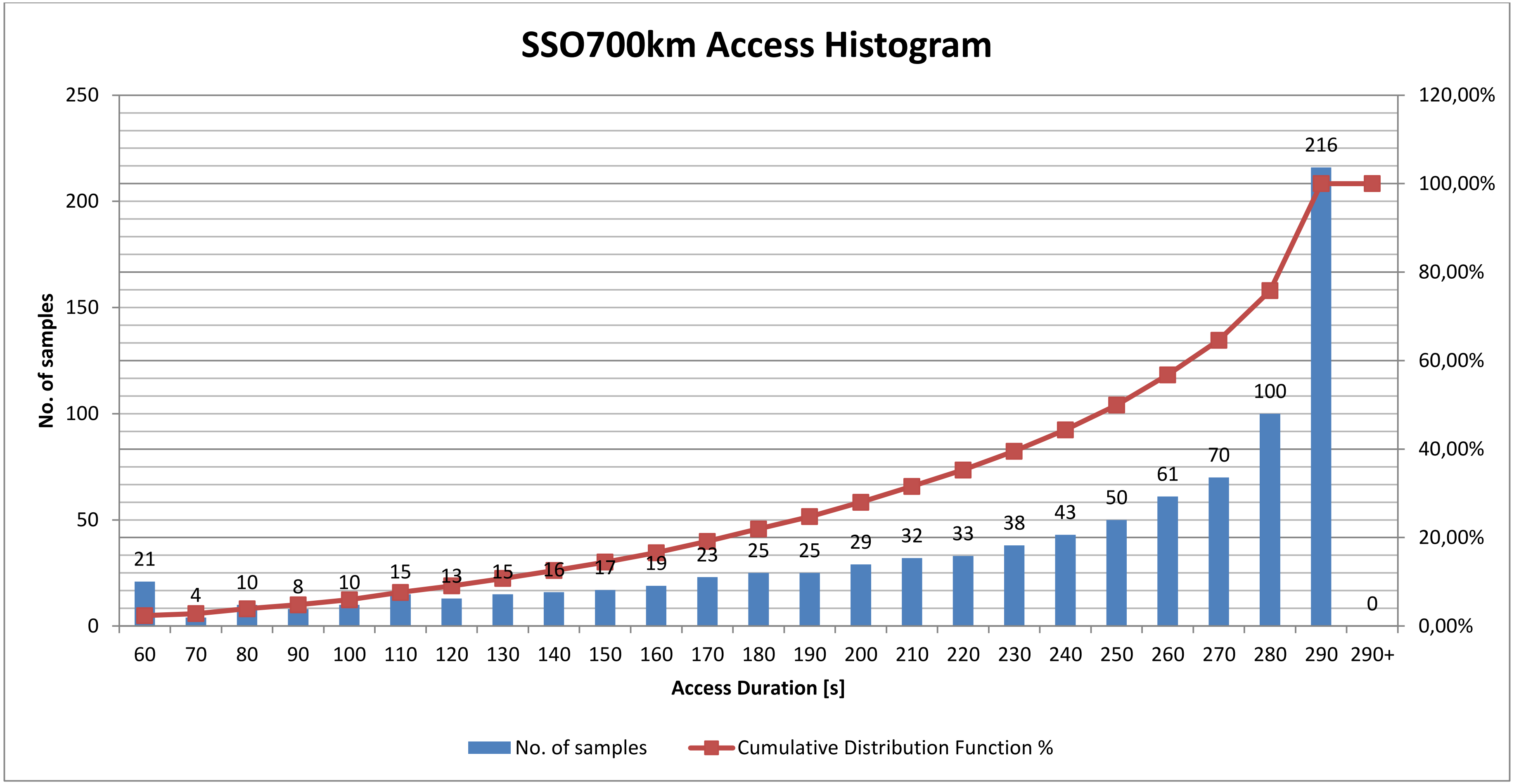

Figure 9-6 SSO700km Access Histogram

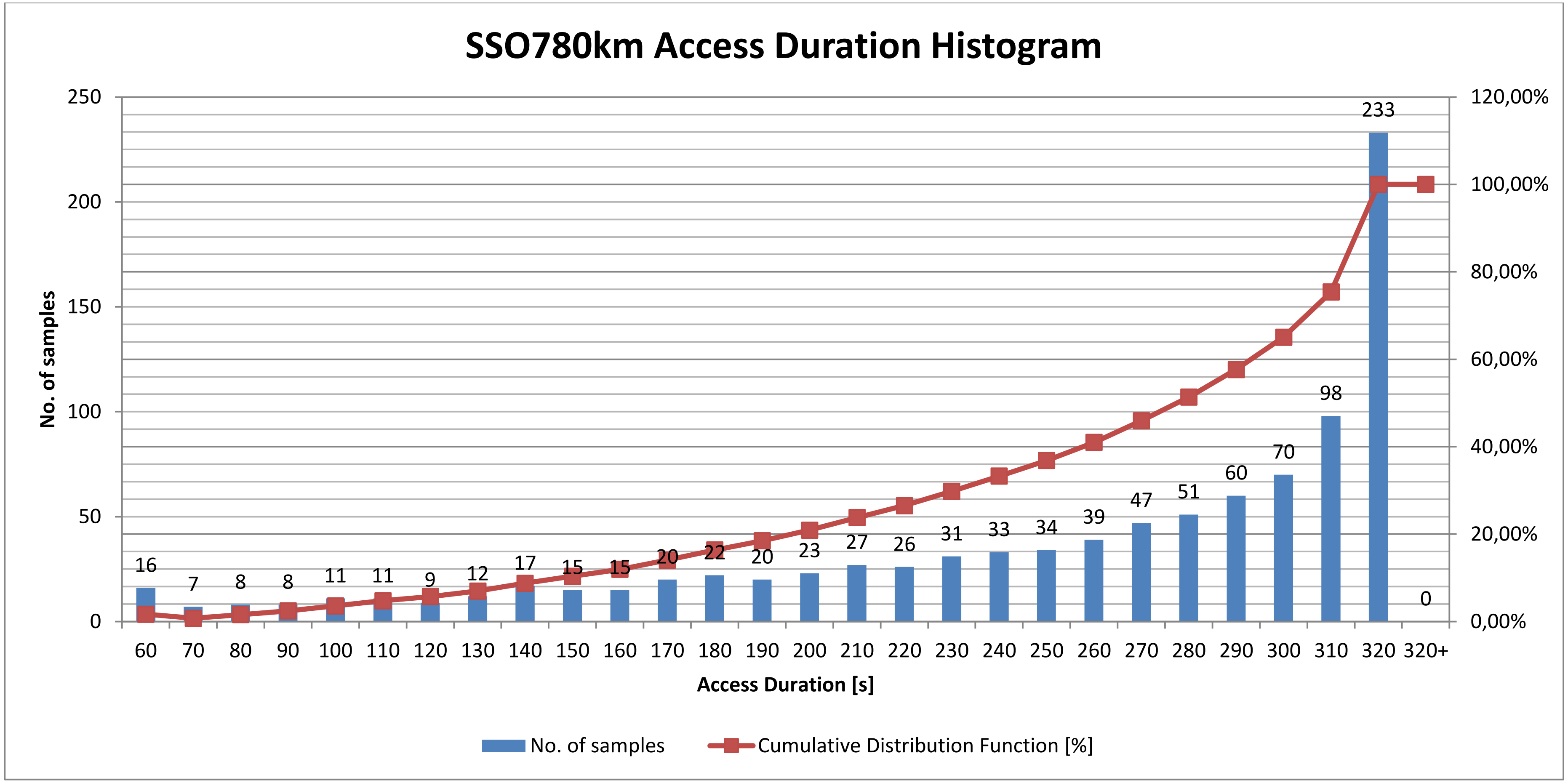

Figure 9-7 SSO780km Access Duration Histogram

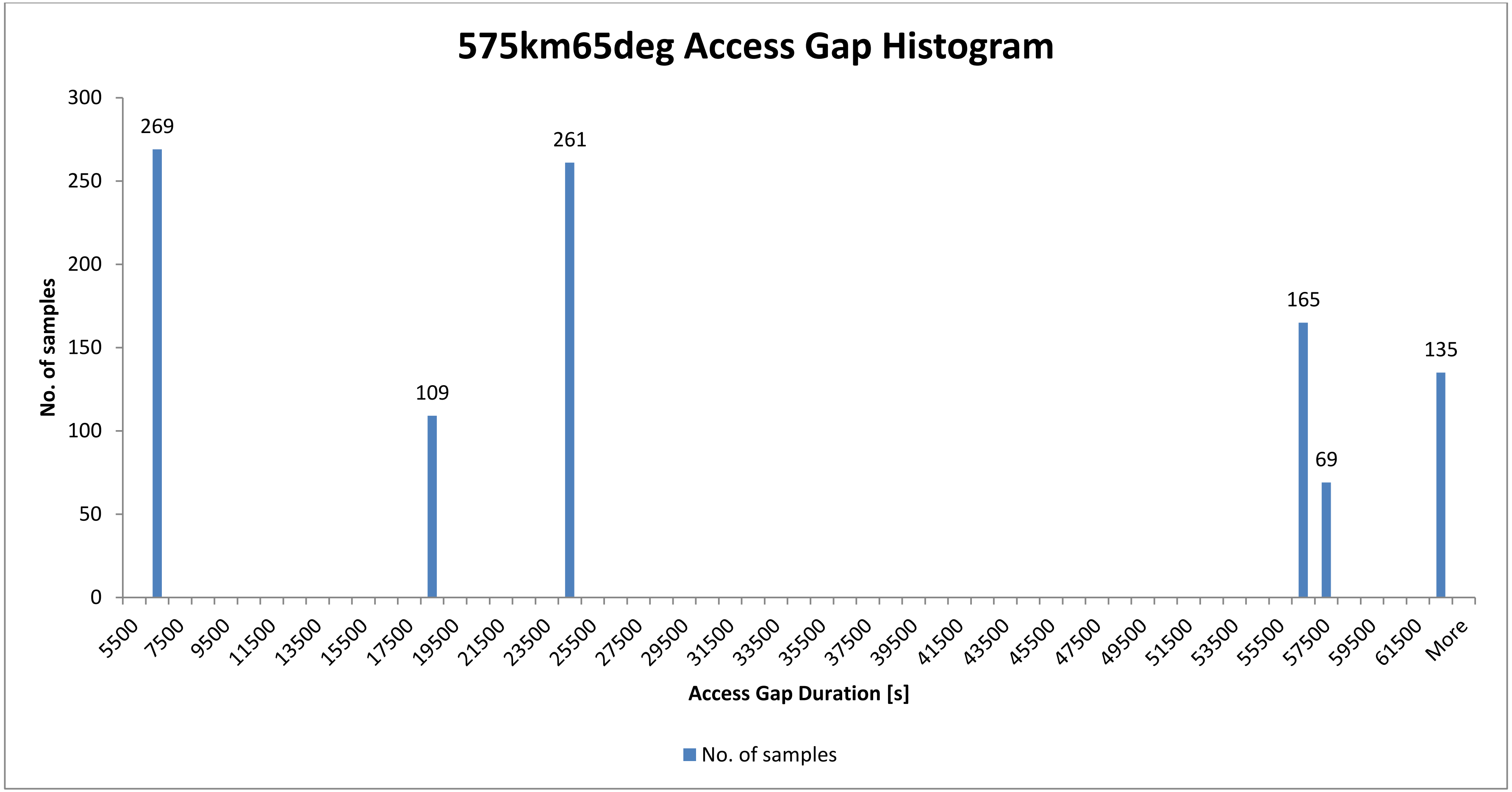

Figure 9-8 575km65deg Access Gap Histogram

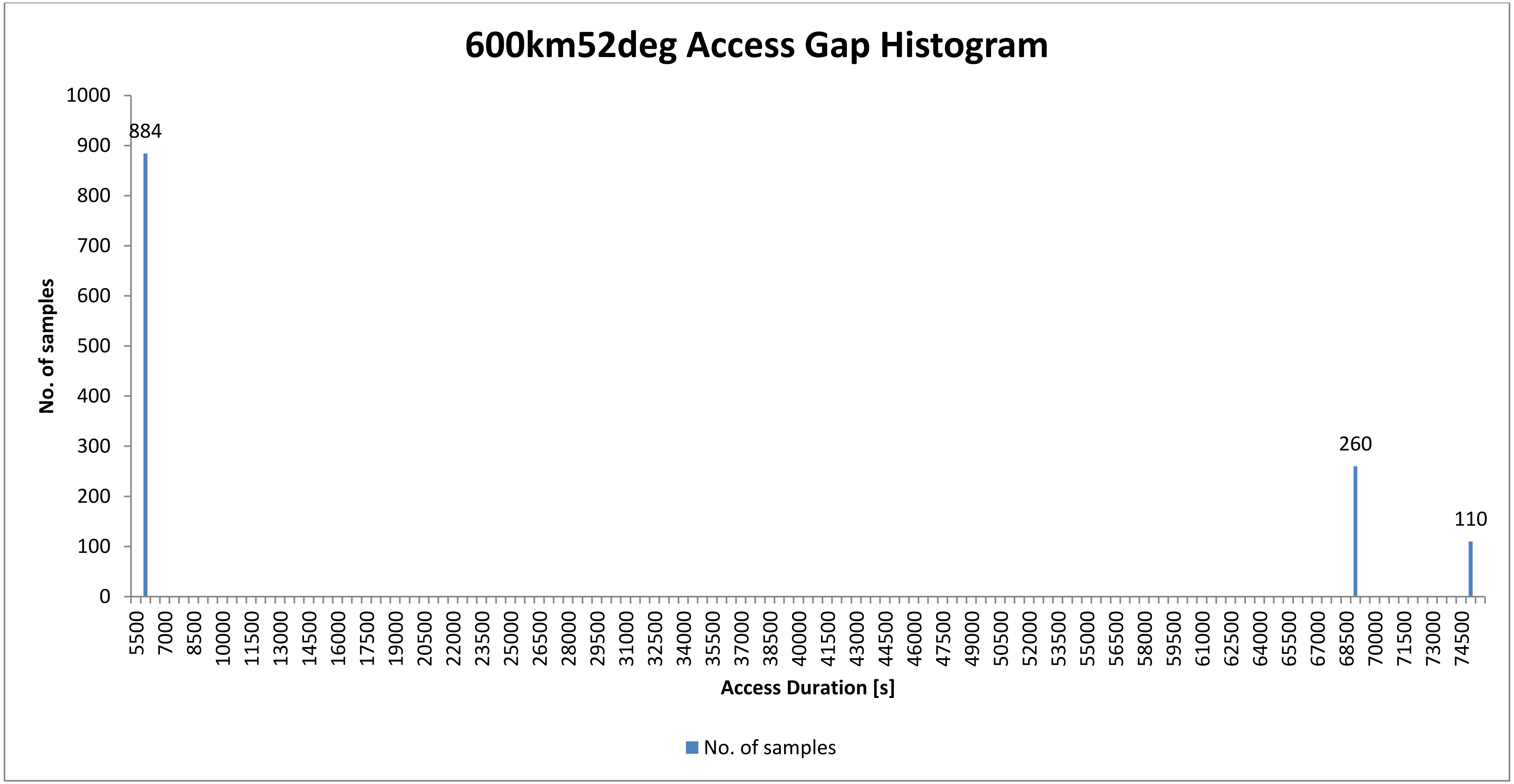

Figure 9-9 600km52deg Access Gap Histogram

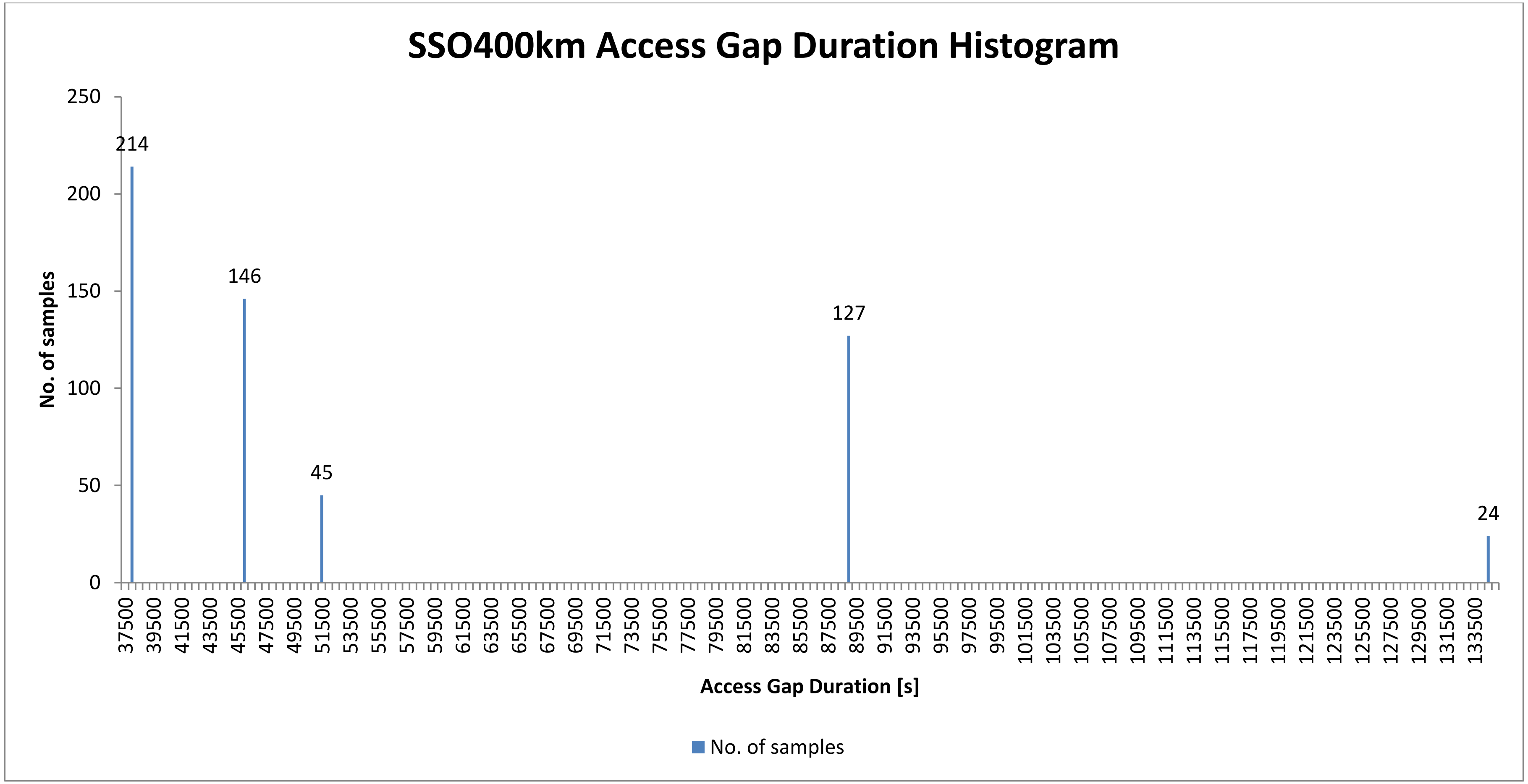

Figure 9-10 SSO400km Access Gap Duration Histogram

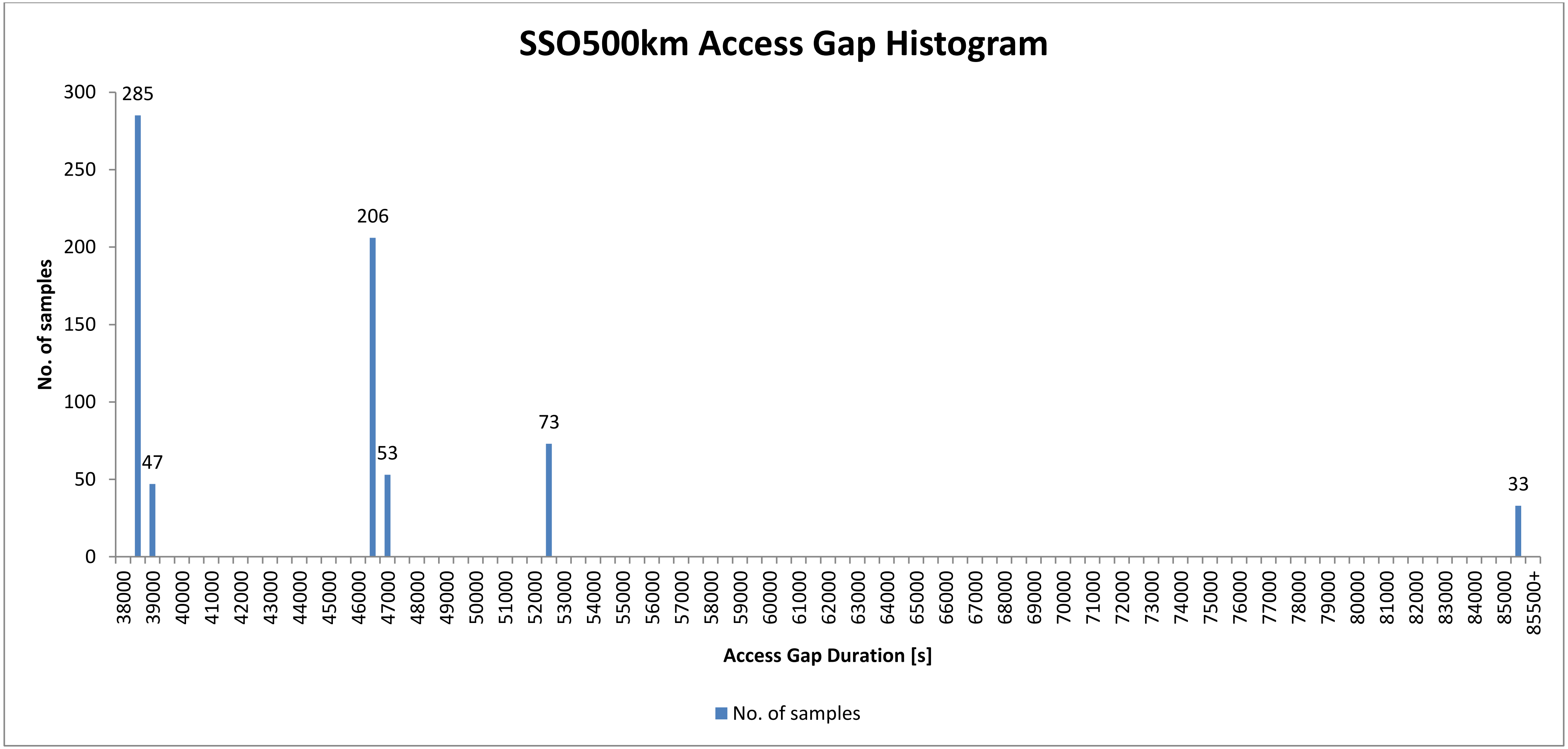

Figure 9-11 SSO500km Access Gap Histogram

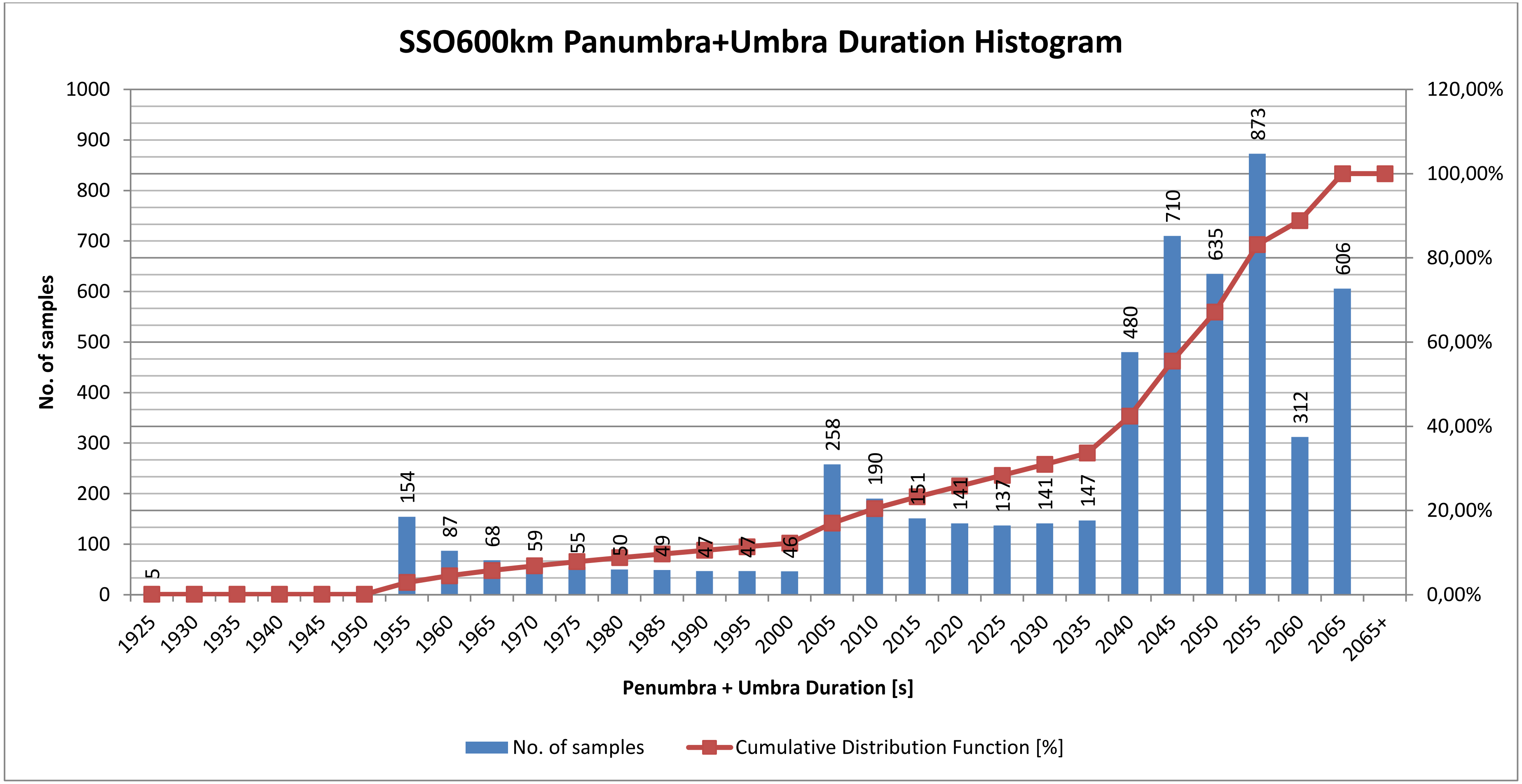

Figure 9-12 SSO600km Panumbra+Umbra Duration Histogram

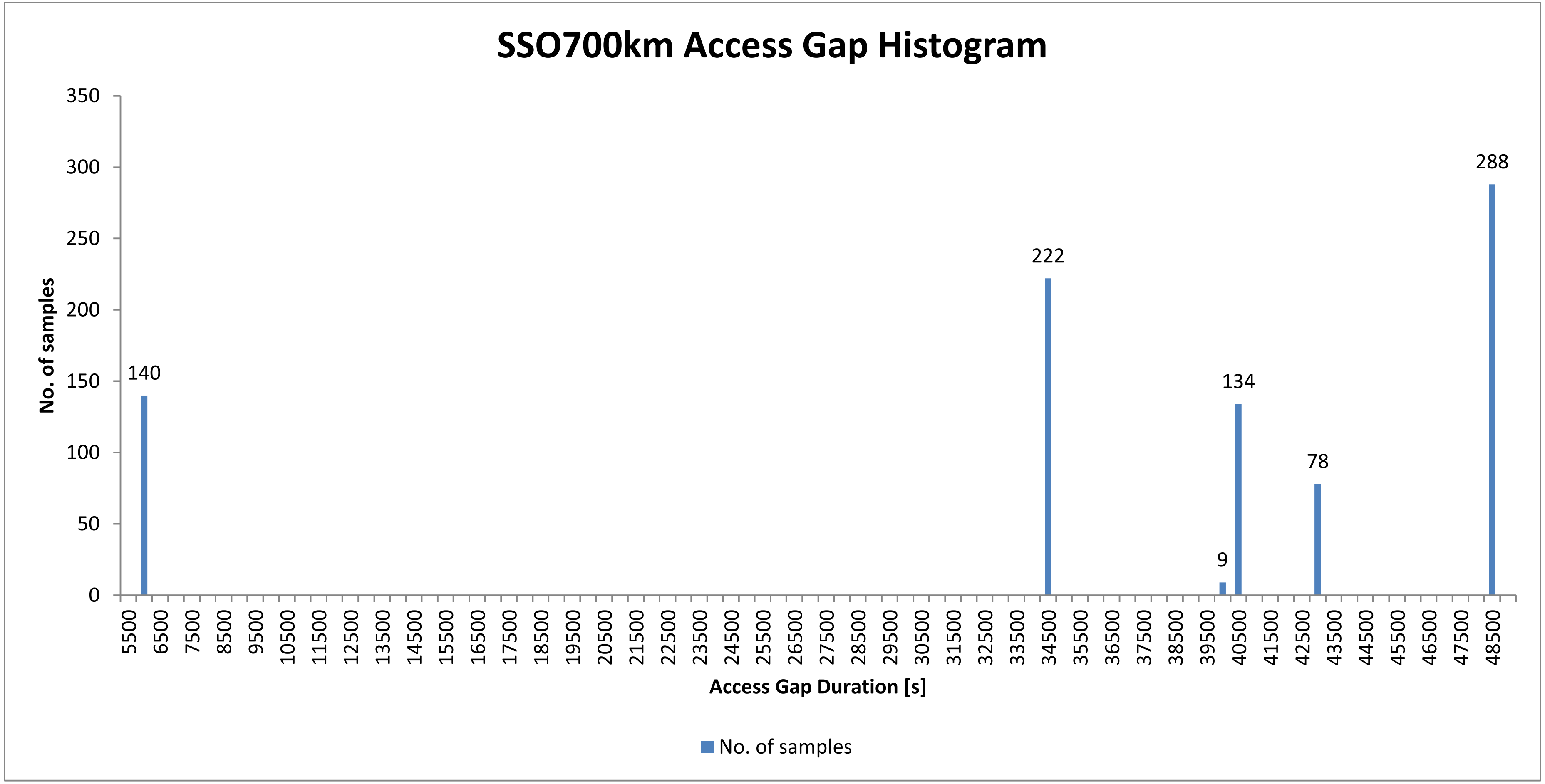

Figure 9-13 SSO700km Access Gap Histogram

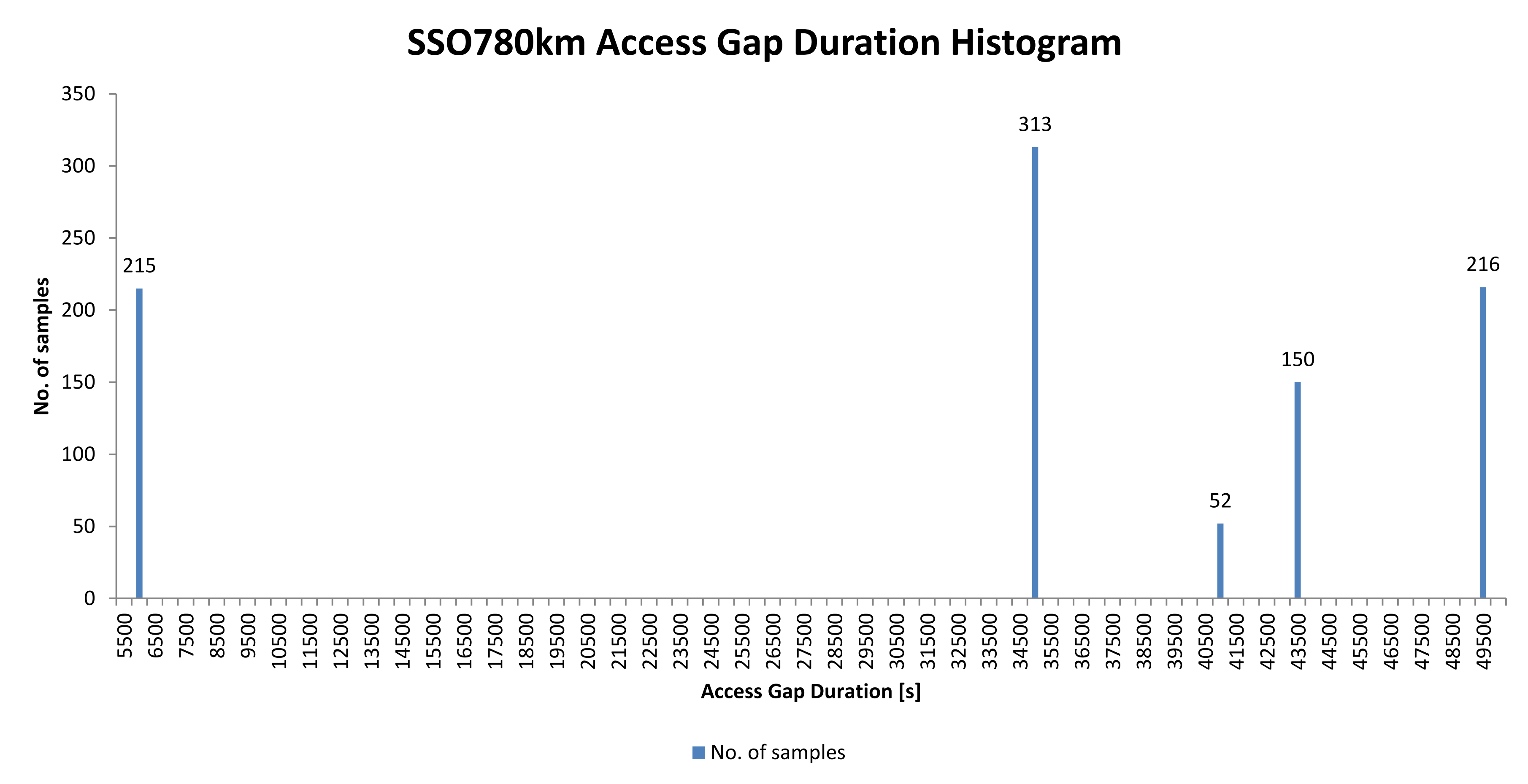

Figure 9-14 SSO780km Access Gap Duration Histogram

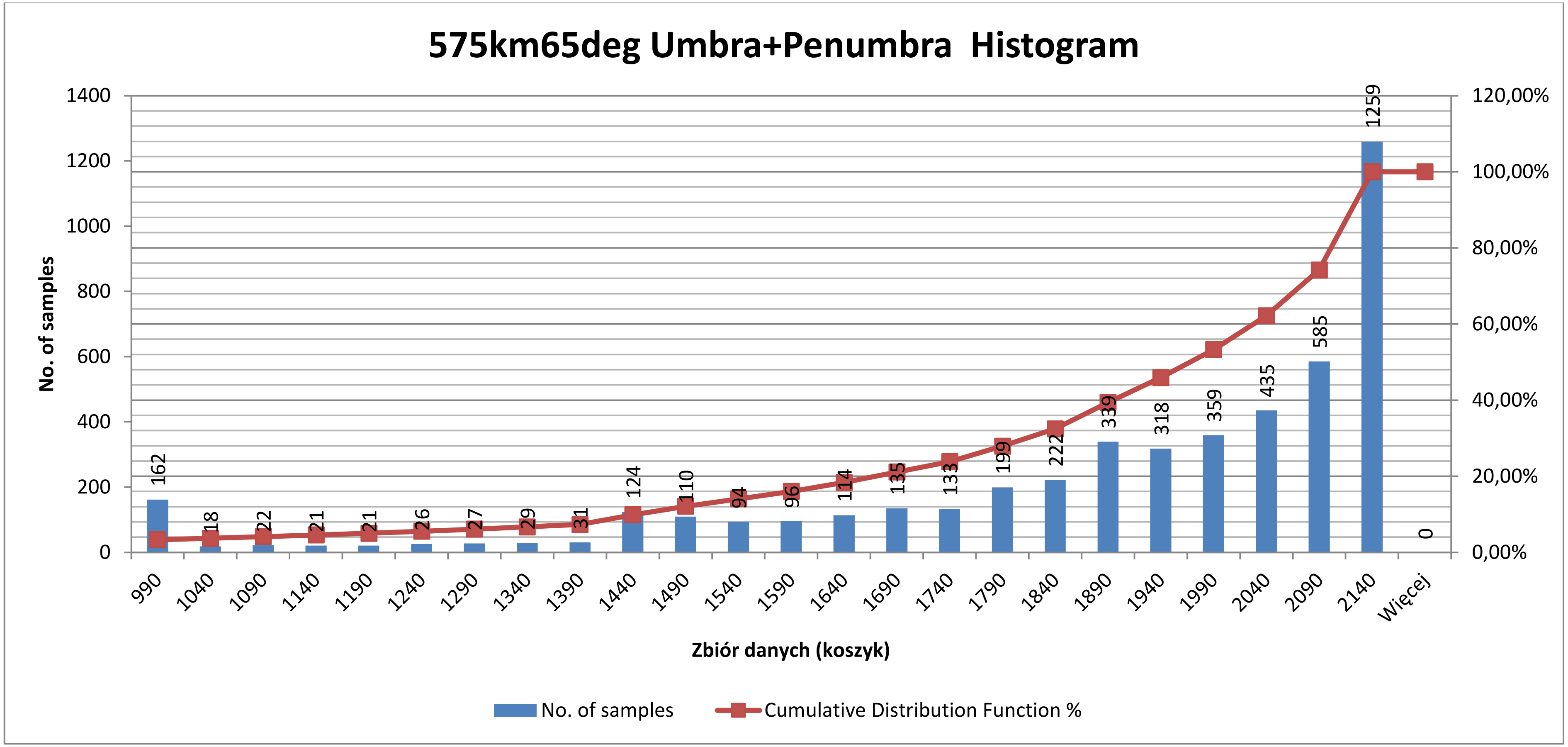

Figure 9-15 575km65deg Umbra+Penumbra histogram

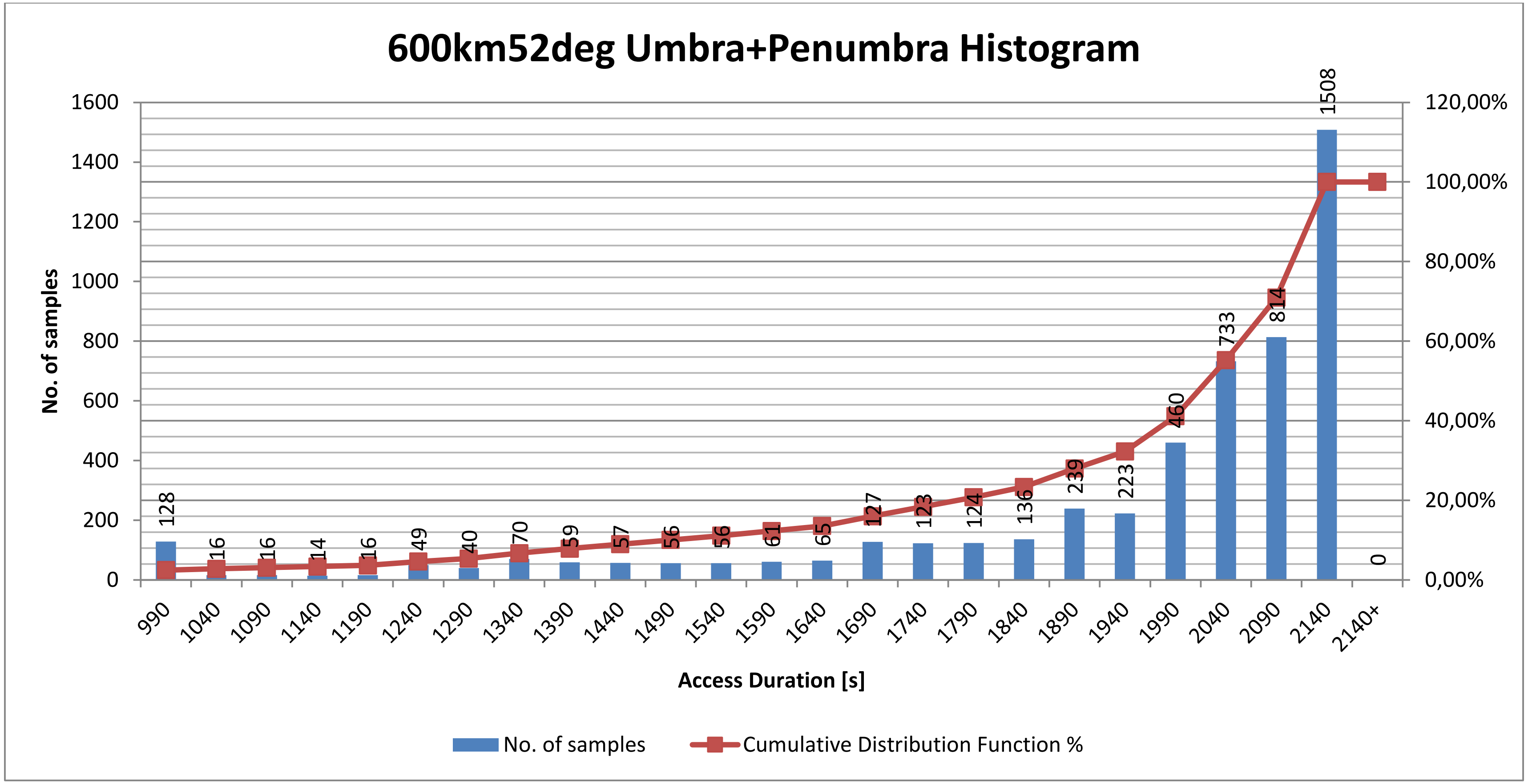

Figure 9-16 600km52deg Umbra+Penumbra Histogram

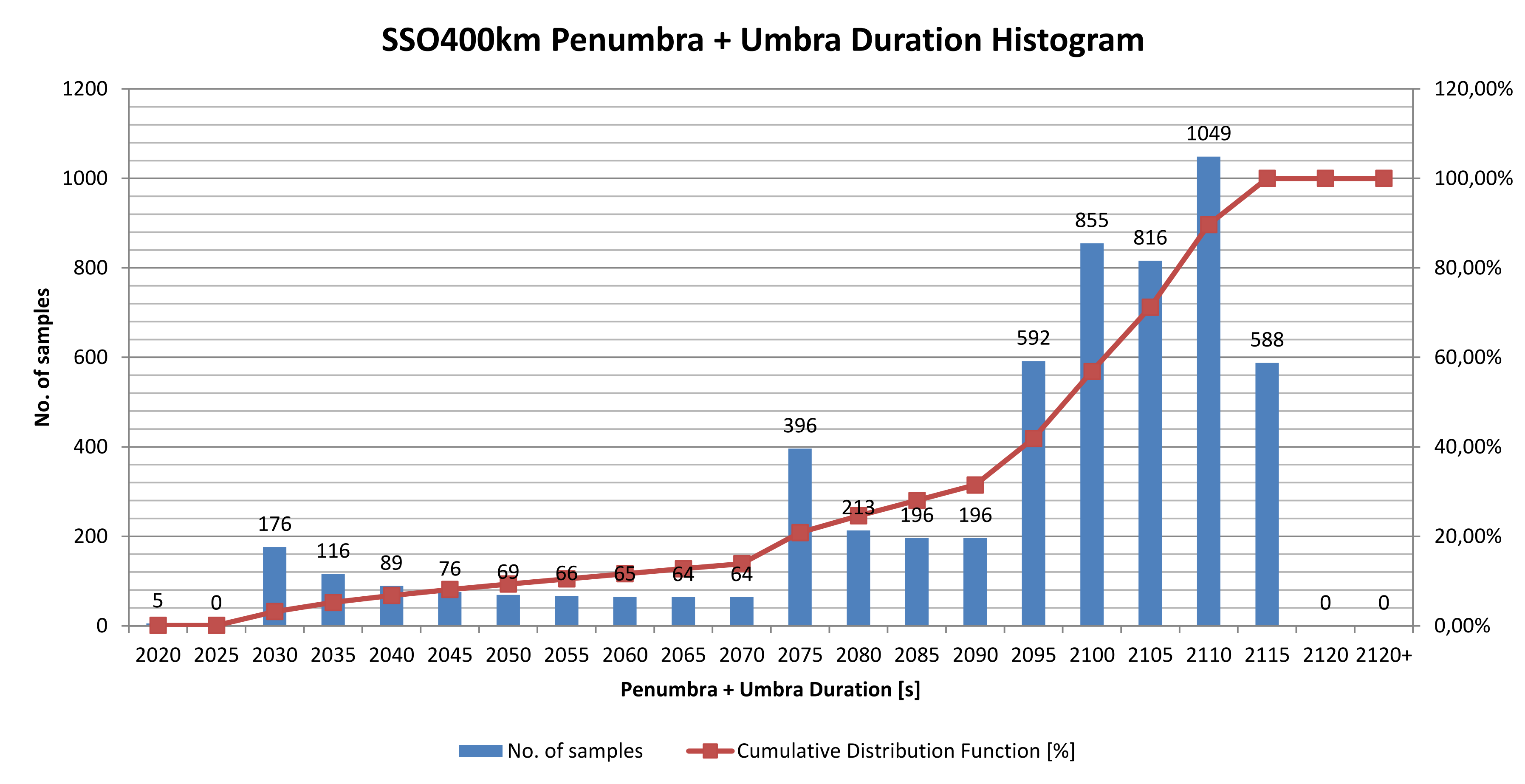

Figure 9-17 SSO400km Penumbra + Umbra Duration Histogram

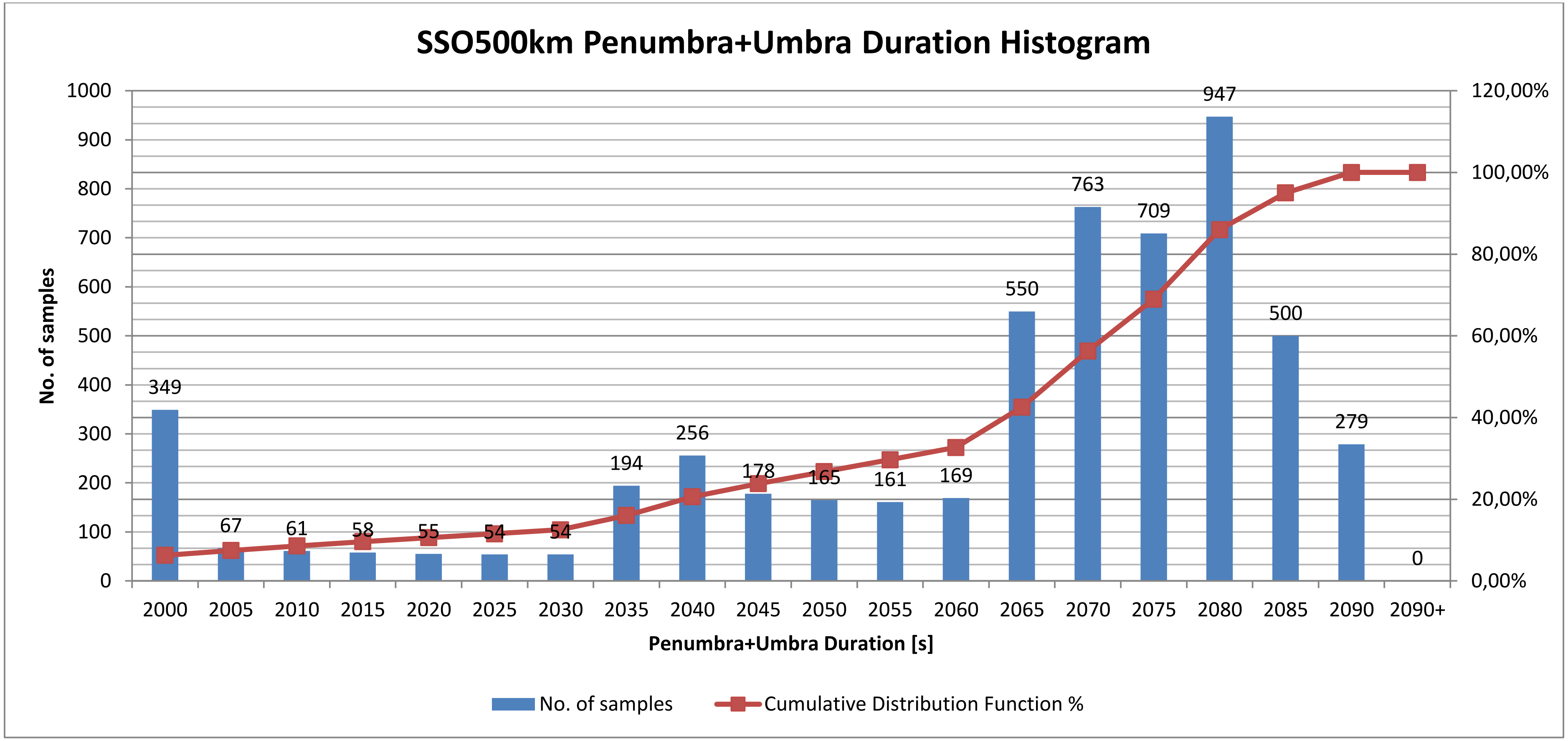

Figure 9-18 SSO500km Penumbra+Umbra Duration Histogram

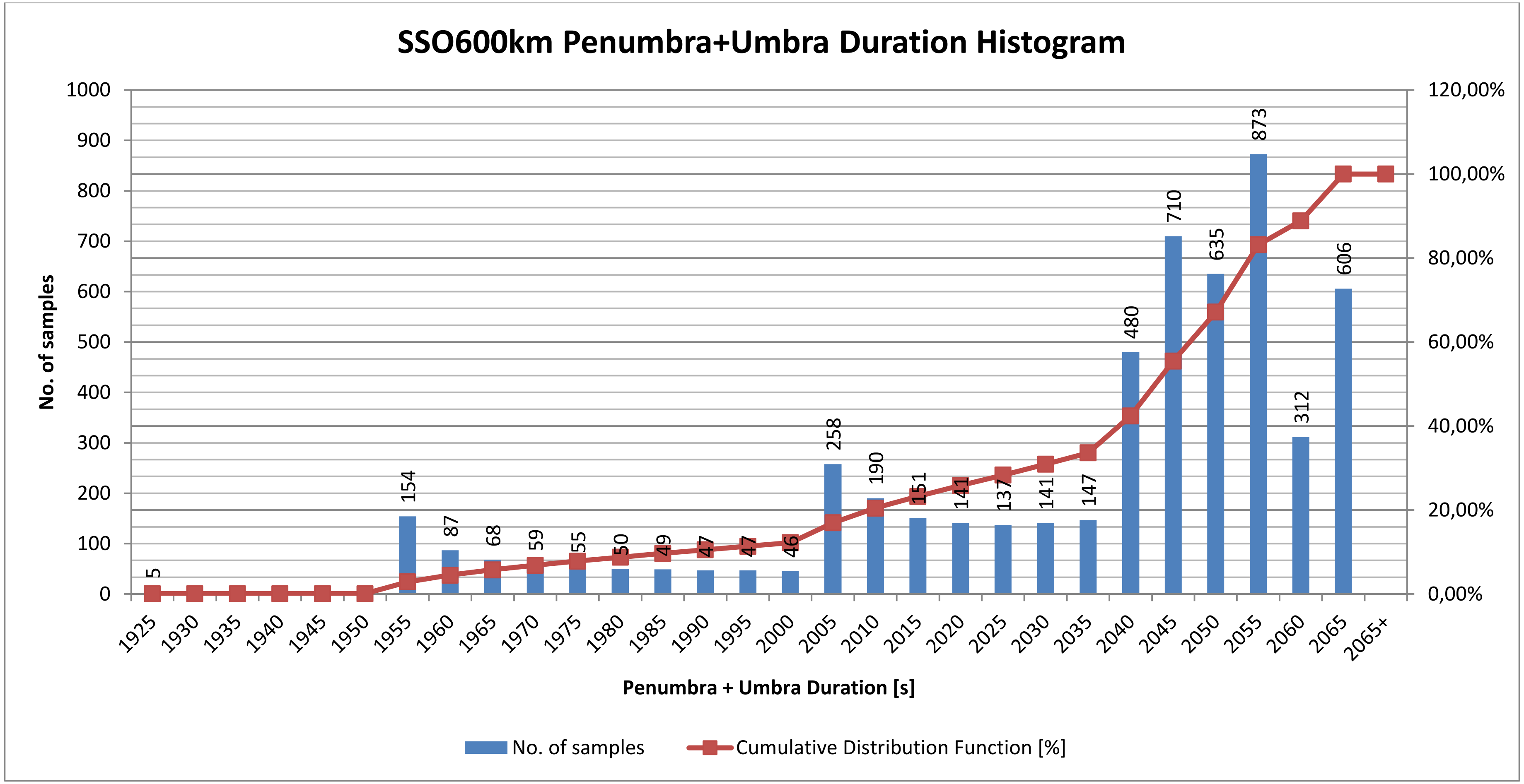

Figure 9-19 SSO600km Penumbra+Umbra Duration Histogram

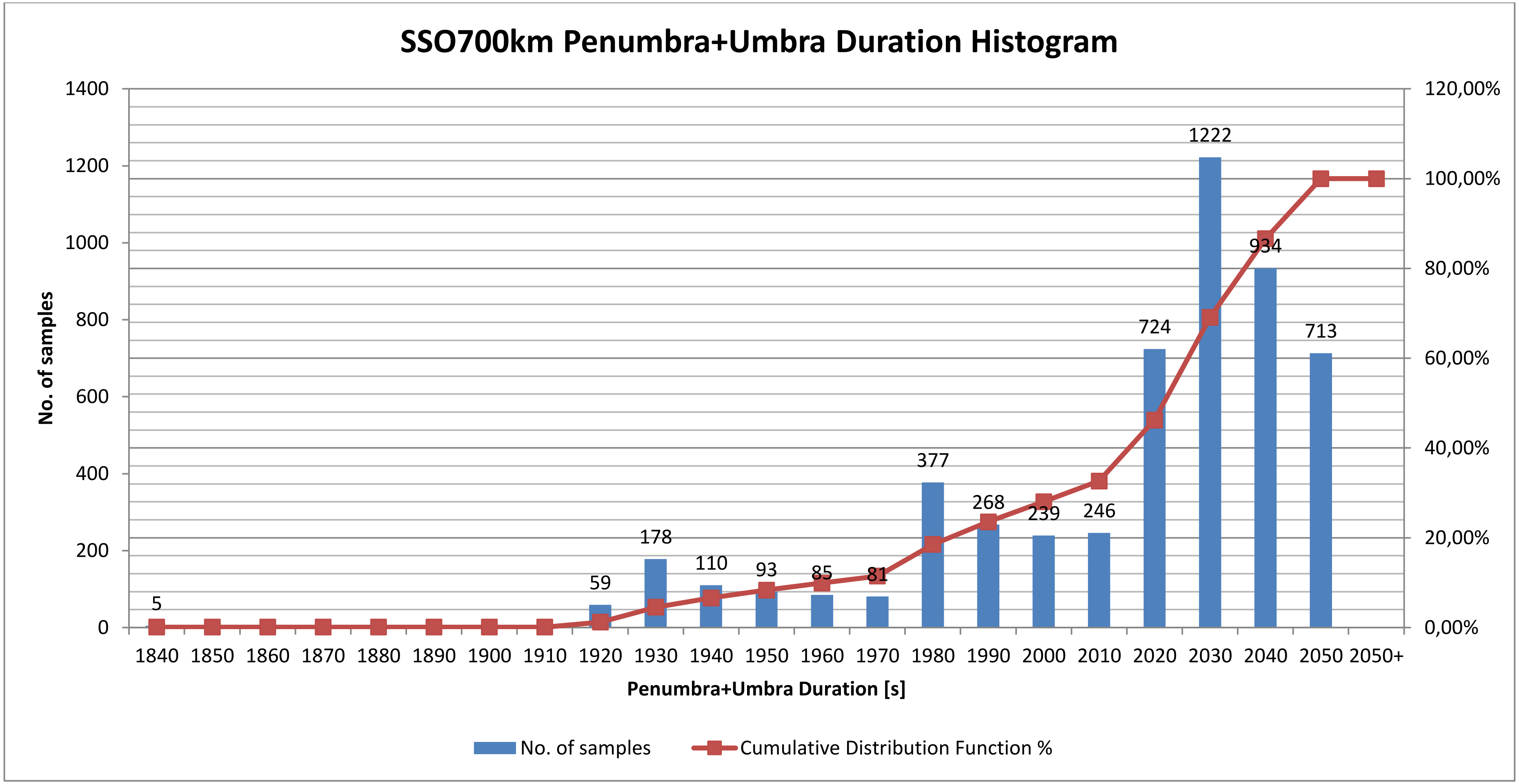

Figure 9-20 SSO700km Penumbra+Umbra Duration Histogram

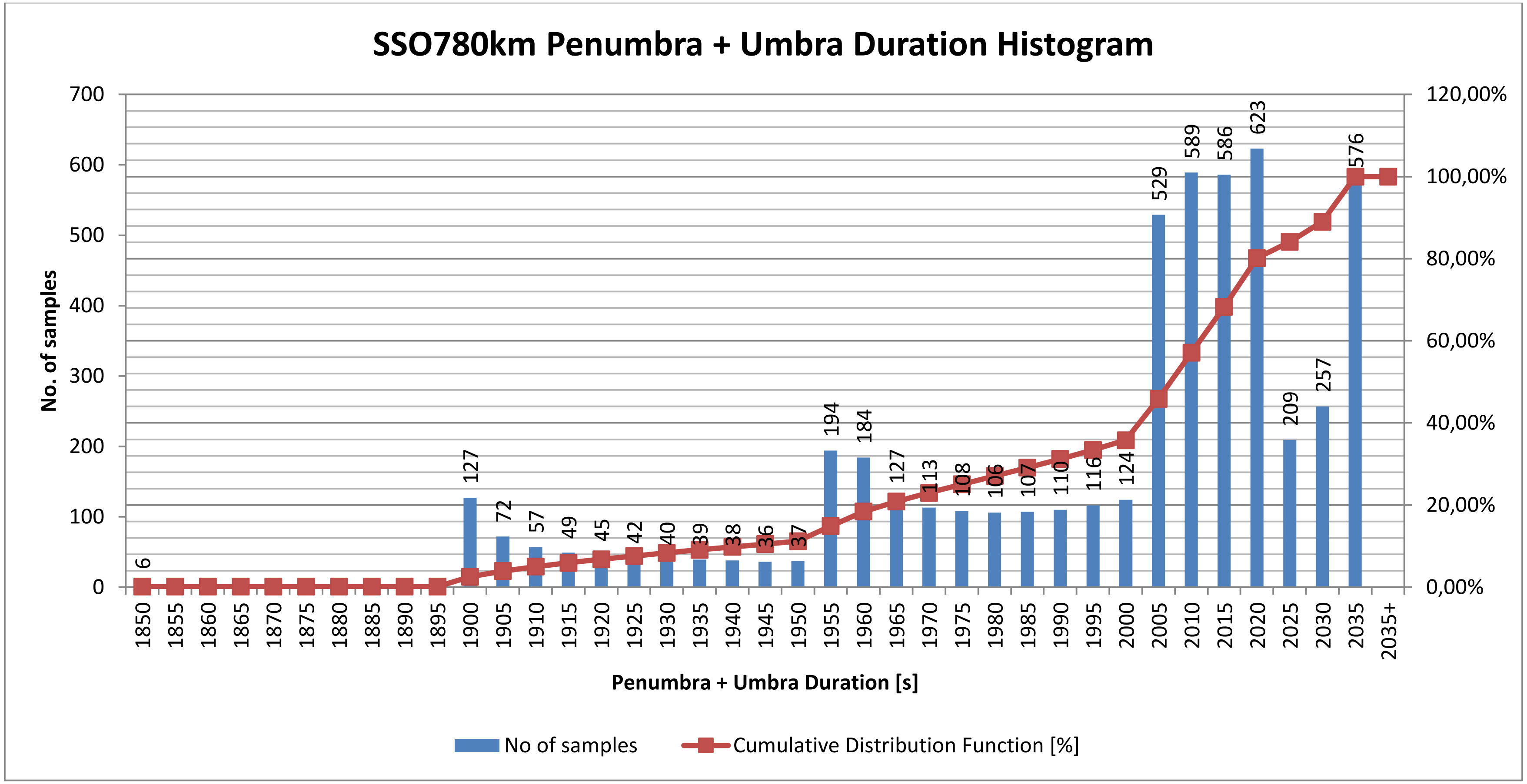

Figure 9-21 SSO780km Penumbra + Umbra Duration Histogram

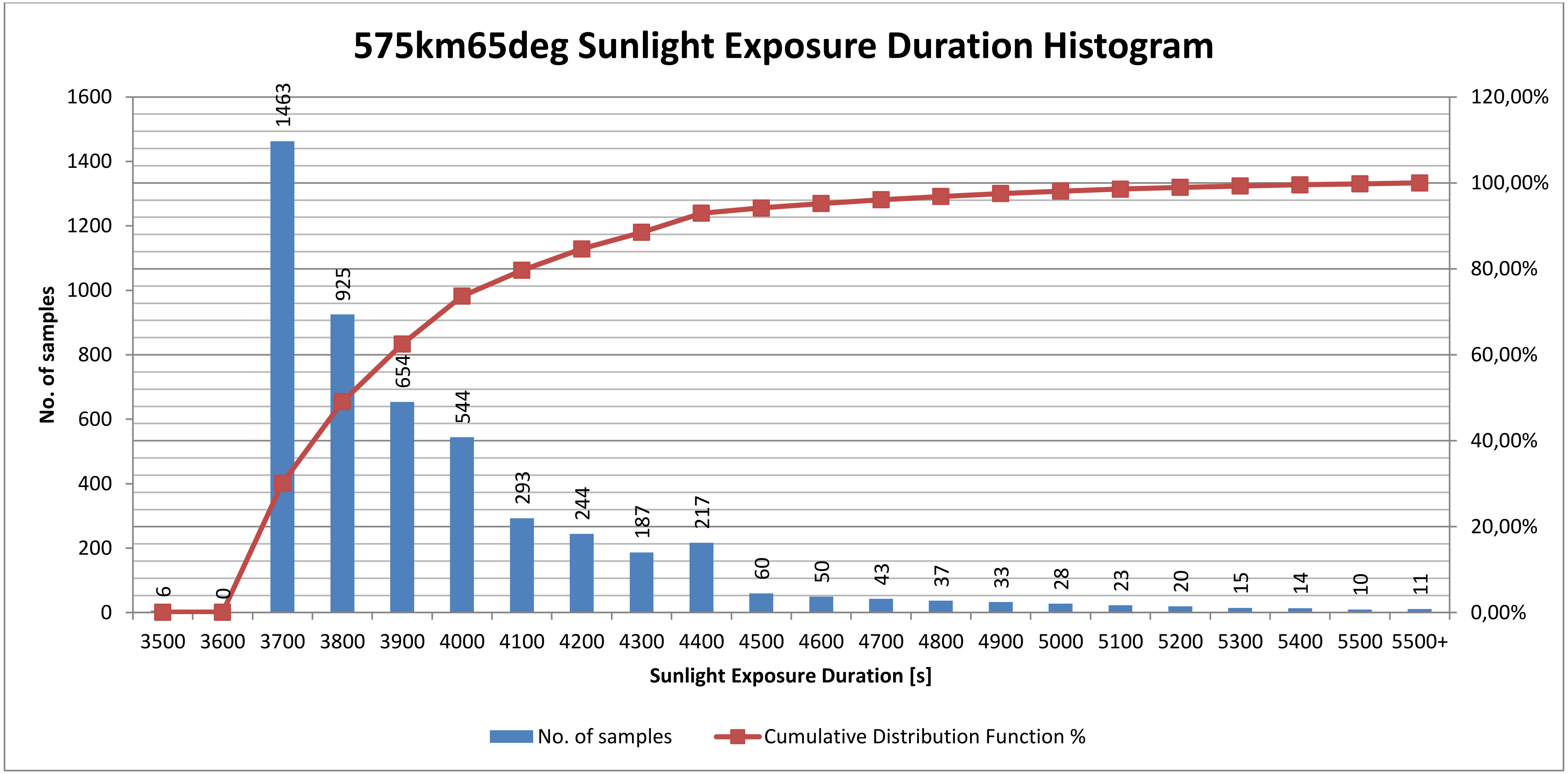

Figure 9-22 575km65deg Sunlight Exposure Duration Histogram

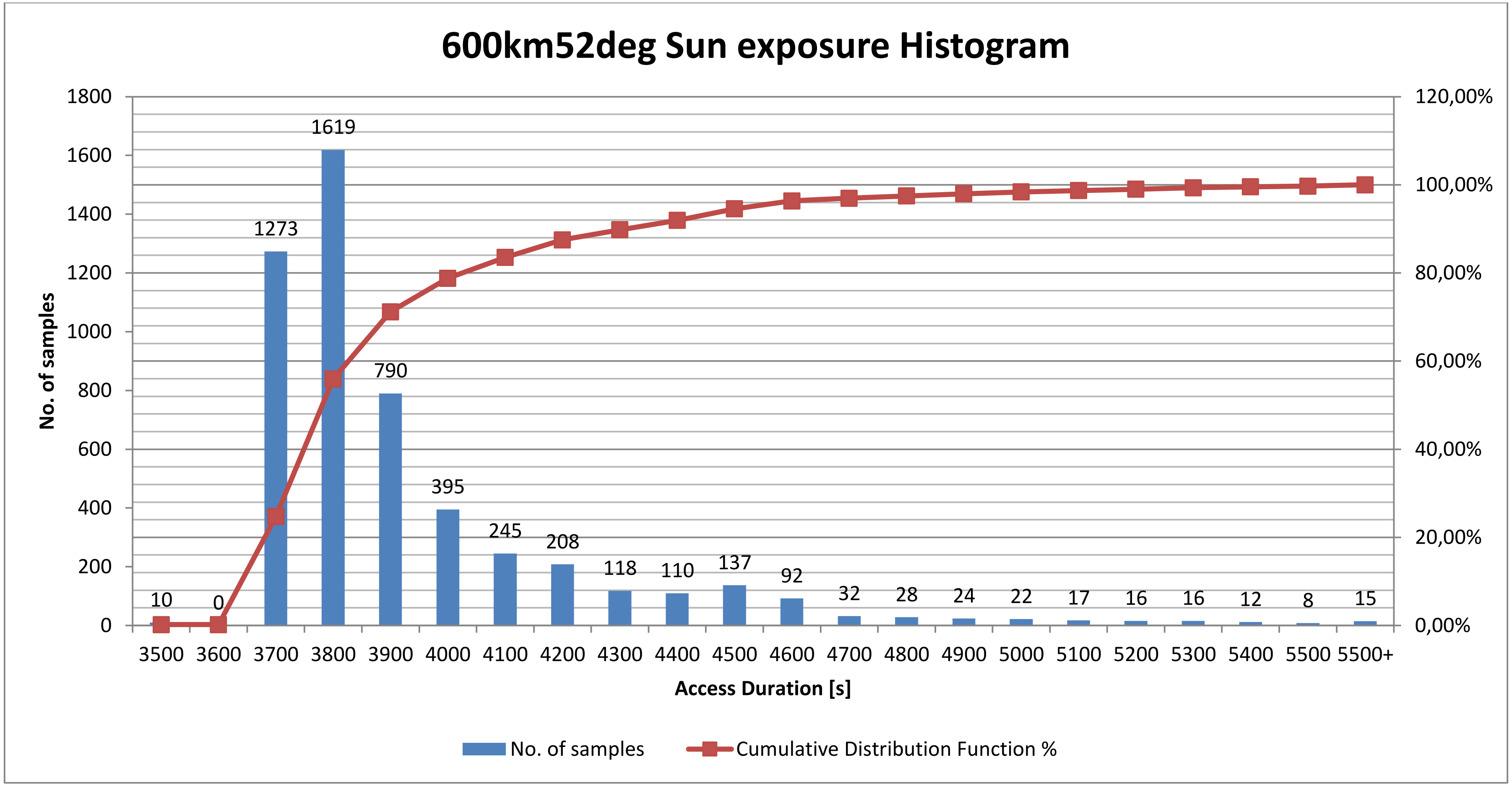

Figure 9-23 600km52deg Sun exposure Histogram

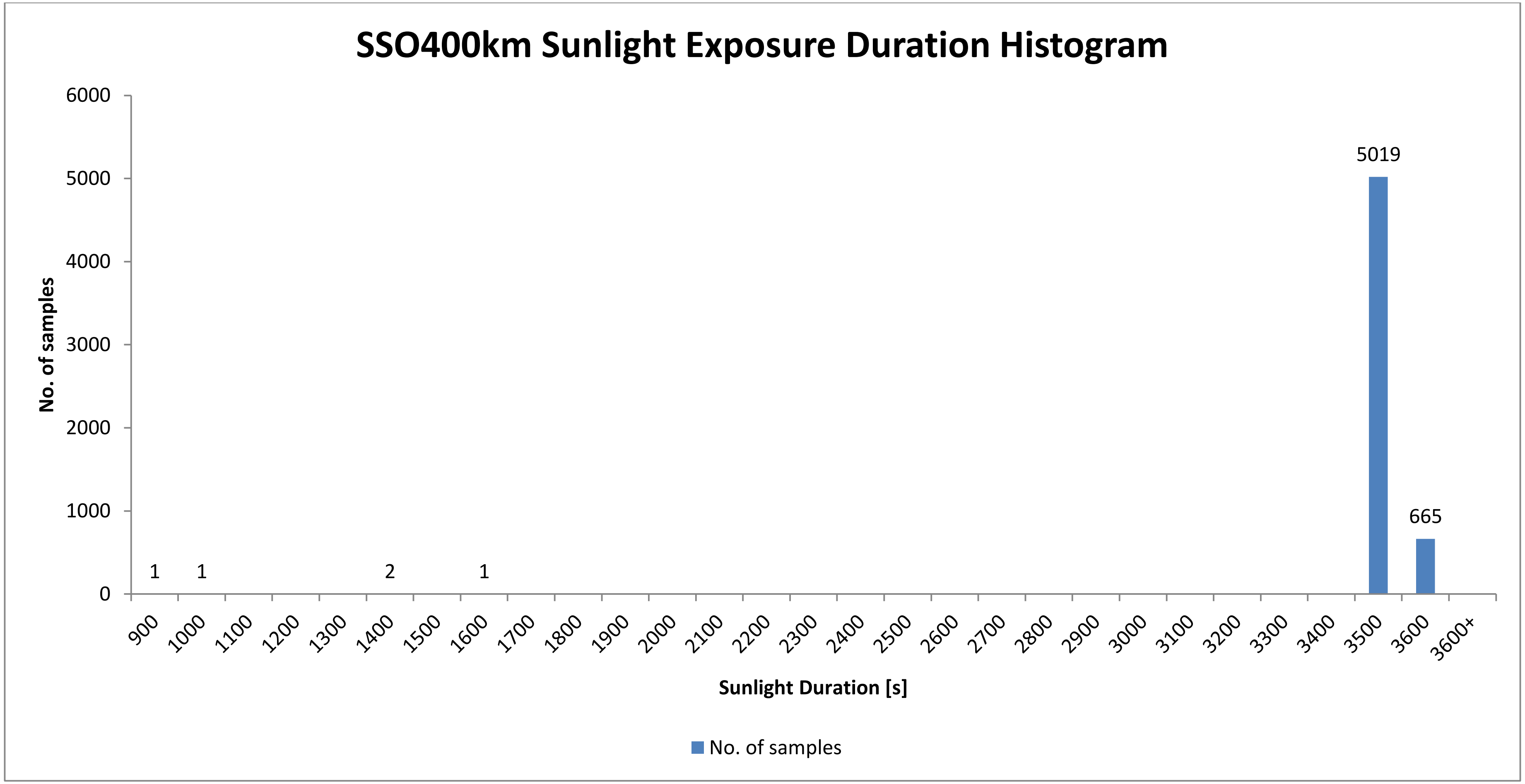

Figure 9-24 SSO400km Sunlight Exposure Duration Histogram

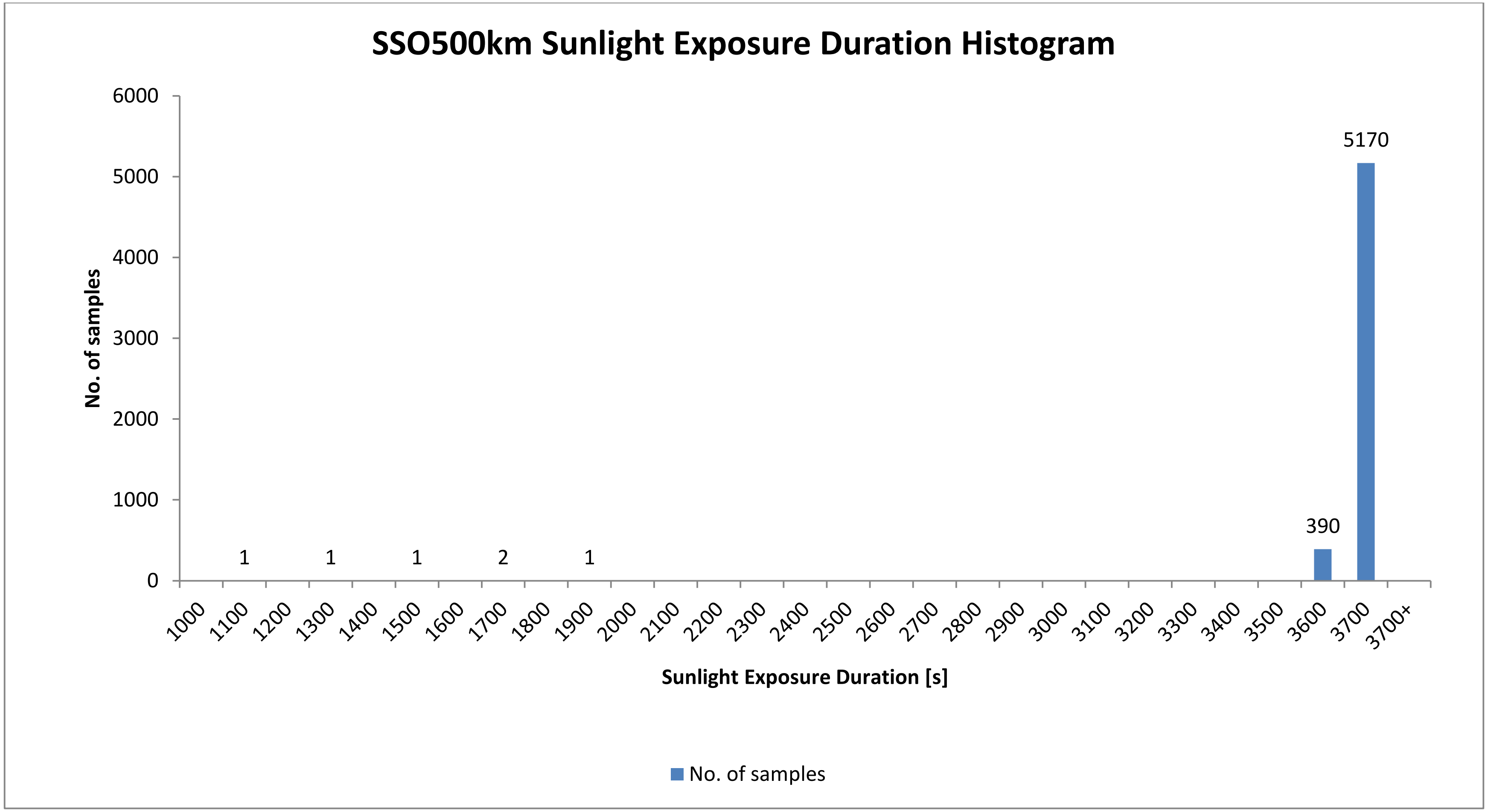

Figure 9-25 SSO500km Sunlight Exposure Duration Histogram

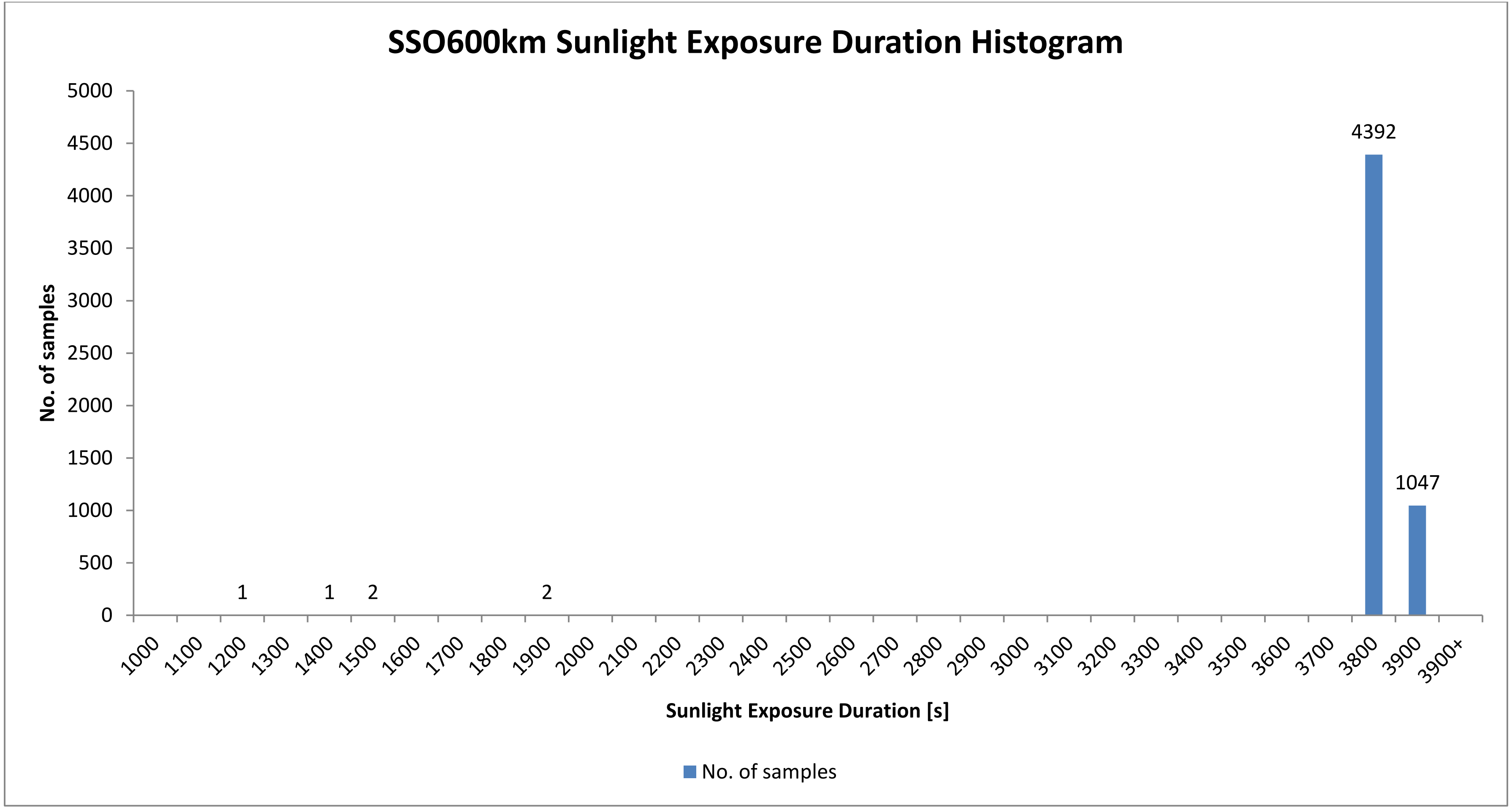

Figure 9-26 SSO600km Sunlight Exposure Duration Histogram

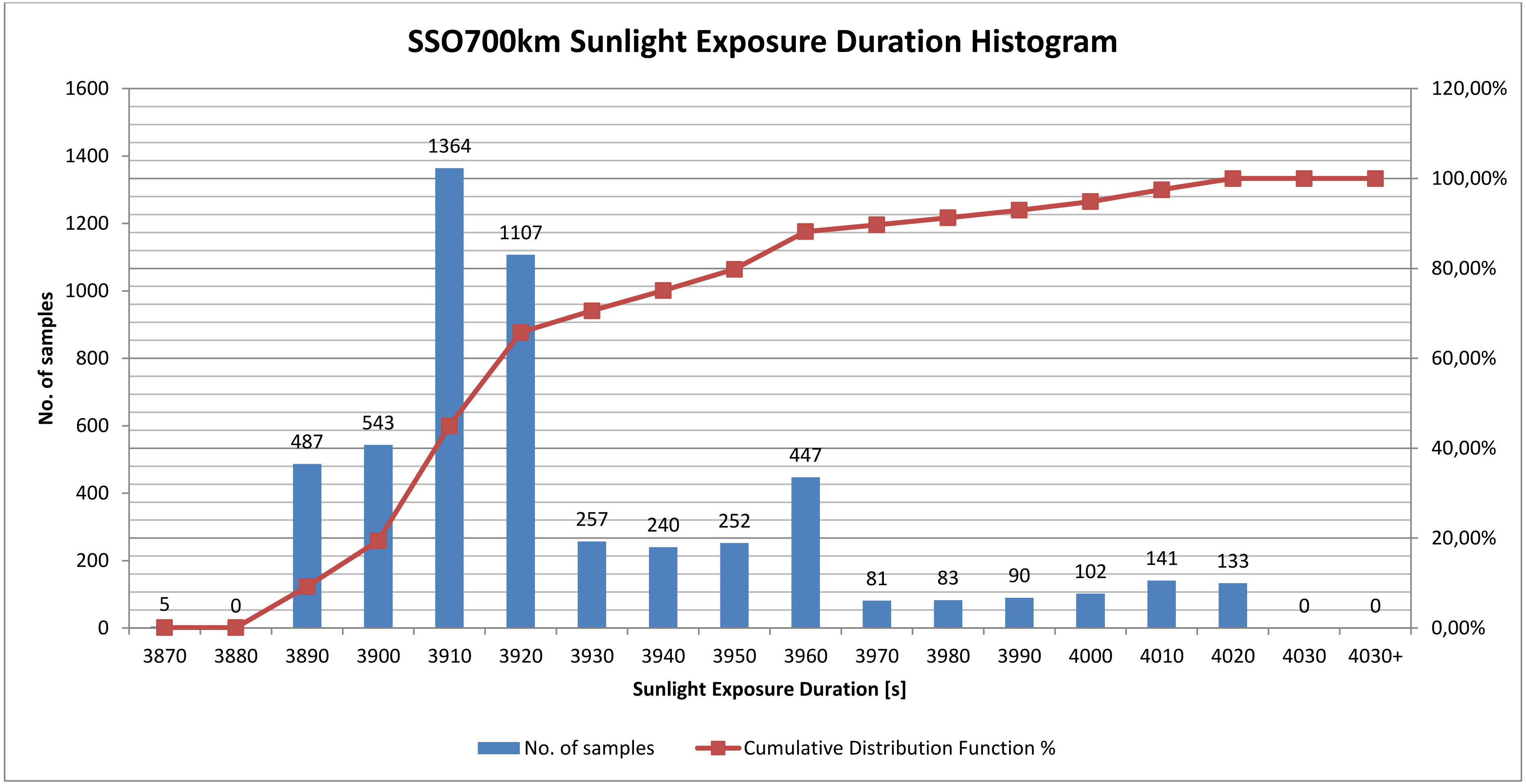

Figure 9-27 SSO700km Sunlight Exposure Duration Histogram

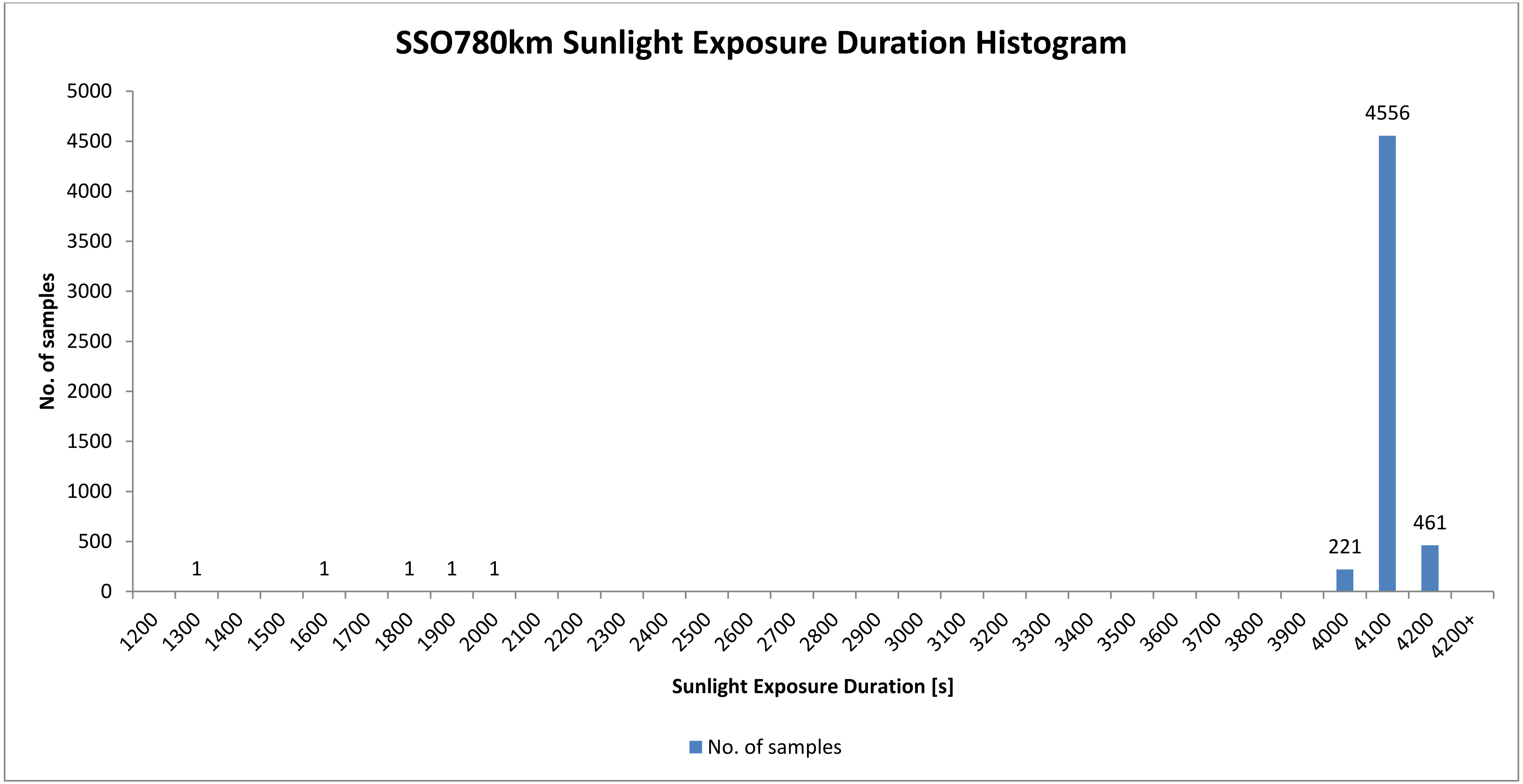

Figure 9-28 SSO780km Sunlight Exposure Duration Histogram