ASPA Nexus Rotating Space Station: The Attitude and Orbital Determination

By Emmanuel Ehimeme Airiofolo
Student ID: 220057235

EMS690U - Integrated Design project

Individual Detailed Design Report

April 2025

Supervisor: Dr. Angadh Nanjangud

Emmanuel E Airiofolo
Date: 25/04/2025
Aerospace Engineering

Abstract

This feasibility design study attempts to provide a useful reference for the Attitude and Orbit Determination System (AODS) for a rotating space habitat design that advance the ability of humans to live in space for long periods of time. The Nexus design concept is developed with the principal aim of addressing the problems in long term space exploration: artificial gravity, radiation and shielding protection, sustainable food, structural design and commercial values.

This paper covers station operating conditions for maximising crew comfort, where a station spin rate of 2 Revolutions per minute (rpm) resulted in a station radius of 223 m. The gravity gradient and coriolis forces are optimised under these conditions in maximising the crew comfort during their missions. The design of principal categories of the orbital and attitude conditions, station keeping and electric propulsion approaches are presented with a focus on establishing useful sources in the literature, as well as useful calculations and simulation of data. The overarching theme of the paper is to show the feasibility of the Nexus station design to combat a fundamental problem of space exploration.

Contents

Acronyms

AODS: Attitude and Orbit Determination System. ii, 1, 4, 5, 21, 22
AoP: Argument of Perigee. 13, 15
ASPA: Ad Astra Per Aspera. 1, 14, 22

C&TS: Communication and Tracking System. 1
C/ES: Colloid/Electrospray. 20–22
CAD: Computer Aided Design. 3
CODH: Command and Data Handling. 1

DRAMA™: Debris Risk Assessment and Mitigation Analysis. 22

ECEF: Earth-Centered Earth-Fixed. 4
ECI: Earth-Centered Inertial. 4
EPS: Electrical and Power System. 1

GEO: Geostationary Orbit. 13, 14
GIE: Gridded Ion Engine. 20–22
GMAT™: General Mission Analysis Tool. 15, 16, 22

ISS: International Space Station. 1, 13, 14, 17, 21
ITU™: International Telecommunication Union. 13, 14

LEO: Low Earth Orbit. 13, 14
LSS: Life Support System. 1

NASA™: National Aeronautics and Space Administration. 1, 15, 20

R&DS: Rendezvous and Docking System. 1
RAAN: Right Ascension of Ascending Node. 12, 14, 15
rpm: Revolutions per minute. ii, 7, 8, 17, 18, 21

SA: Space Station Attitude. 4
SAO: Sun-Asynchronous Orbit. 13, 14, 21, 22
SDS: Strucural Design System. 1, 3
SMA: Semi-Major Axis. 12, 15
SPS: Shielding and Protection System. 1, 22

Nomenclature

$1G$	Nexus station Earth-like gravity. Value: 9.78 Unit: m/s^2
$\bar{r}$	Position vector for Nexus station in orbit.
$\hat{h}$	Specific angular momentum unit vector.
Ω	Angular velocity of the station. Unit: rad/s
Ω_o	Right ascension of the ascending node (RAAN). Unit: $^\circ$
ω_o	Argument of periapsis. Unit: $^\circ$
ϕ	Angle between the ECI to the ECEF frame on the xy plane. Unit: $^\circ$
θ	True anomaly. Unit: $^\circ$
a	Orbit semi-major axis. Unit: m or km
a_c	Acceleration due to coriolis effect. Unit: m/s^2
a_g	Acceleration due to station gravity. Unit: m/s^2
a_T	Station edge tangential acceleration. Unit: m/s^2
e	Orbit eccentricity.
f	Frequency. Unit: $1/s$
F_c	Force due to coriolis effect. Unit: N
G_E	Acceleration due to gravity on Earth. Value: 9.807 Unit: m/s^2
i	Orbit inclination. Unit: $^\circ$
I_r	Moment of inertia about station radial axis. Unit: m^4
I_s	Moment of inertia about station symmetrical axis. Unit: m^4
R	Radius of the station. Unit: m
t_s	Station spin-up or spin-down duration. Unit: $hours$
$t_{s(E)}$	Station emergency spin-up or spin-down duration. Unit: $hours$
U_T	Station initial tangential velocity. Unit: m/s
V_T	Station final tangential velocity. Unit: m/s
$V_{relative}$	Rotational frame relative speed. Unit: m/s

Emmanuel E Airiofolo
Date: 25/04/2025
Aerospace Engineering

Acknowledgements

All glory to **God** for this blessed day, I would like to thank God for the journey taken to get this far into this dissertation, my degree, my education and my life. *Oluwamodupe*! (Matthew Chapter 6).

I would like to especially thank **Dr Angadh Nanjangud**, for his guidance, support, ability to instill passion and his continued encouragement to do better each day. For your assistance in making my choice in this project the most enjoyable and memorable during my time at the university, i am forever grateful. May God continue to bless and keep you sir

I am grateful to my design project colleagues and friends, **Ilanthiraiyan Sivagnanamoorthy, Wania Farooq, Abaas Nunow, and Yam**. I am grateful for the opportunity i had to be with you all since day one. May God continue to bless and keep you all.

I would like to thank the Project group A2 teams, **ASPA, WALL-S, Deep Space and 3D BPO**. Your fearlessness and passion in tackling you individual design projects have been a continued source of inspiration and respect. Thank you all!

I would like extend my gratitude to **Denisha Priya Anasamy, Hardit Ravinder Saini, Mitansh Choksi, Mrs Wardat Khamdun, Michaela Lastovikova, Om Dutta, Anuhya Kotakadi, Noah Leigh, Emma Nicoli, Joshua Amar, Jarifa Shah, Arrin Fernandes, Daniel Igwe, Onye Devis, Kydavia McCarthy, Joost Hubbard, Hamda Elmi, Finlay Smith, Sam Crisp, Paul McGowan, Mtr Roxanne and big mama** for all their endless support and love.

I am grateful for the organisational support i have received during my studies by Queen Mary, University of London.

This dissertation would not have been possible without the endless support of **my family**, and most especially my Mother; **Theresa Taiwo Opadeyi**, who has been patient with my staying up late while conducting research.

Chapter 1

Introduction: Why Artificial Gravity?

SPACE is considered the final frontier in the development of the human civilisation, and this is only the beginning of the story. The space race[1] (and National Aeronautics and Space Administration (NASA™)) began in 1957-1958 and since then, new avenues for understanding our space environment have been developed and have improved the quality of life on Earth. From satellite networks, to modern day Computed Axial Topography (CAT) scanners and wireless headsets.[2]

Long-term space station programmes such as Skylab[3] and the International Space Station (ISS)[45] have encountered and documented how the adverse effects of microgravity on the human body have been dealt with. These effects such as bone demineralisation and cardiovascular de-conditioning requires exercise to counteract,[4] which reduces the time available for research and quality of life for the crew. Recovery times for returning crew can take up to months, and result in reduced life expectancy in the long run. This needs to change for the future of space exploration - gravity needs to be redefined!

The Ad Astra Per Aspera (ASPA) group[6] are conducted research into designing a space station that will improve the quality of life for any crew in space, not to facilitate competition, but a united collaboration of private and government agencies. We have designed a rotating space station called the ASPA Nexus, that generates artificial gravity.

A feasibility design study was completed to assess the starting parameters that would lay the foundation for the station design. The main parameter was the gravity of the space station, and it is equivalent to the gravity on Earth (1G = 9.81 m/s^2). This would enable smooth transitions for the crew, and minimum time spent training for their missions.

Research revealed essential systems[7] needed to realise the ASPA Nexus station, and these include the: Attitude and Orbit Determination System (AODS); Strucural Design System (SDS); Shielding and Protection System (SPS); Life Support System (LSS); Propulsion System; Rendezvous and Docking System (R&DS); Command and Data Handling (CODH); Robotics System; Electrical and Power System (EPS); Communication and Tracking System (C&TS) and so on.[7]

Out of which research into four streams have been conducted. This paper addresses the AODS, the SDS is addressed by Wania Farooq;[8] the SPS by is addressed Abaas Nunow;[9] a major focus on the LSS and a minor focus the R&DS are addressed by Ilanthiraiyan Sivagnanamoorthy.[10] The other research streams were referenced in each research stream in providing a concrete foundation of each system design. Further in-depth analysis will need to be conducted on the other station systems in future works.

The rest of this paper covers; the station design in chapter 2; analysis of the AODS results in chapter 3; the station keeping and electric propulsion in chapter 4. Finally, conclusions and future work considerations are presented in chapter 5 and chapter 6 respectively.

Chapter 2

ASPA Nexus Station Design

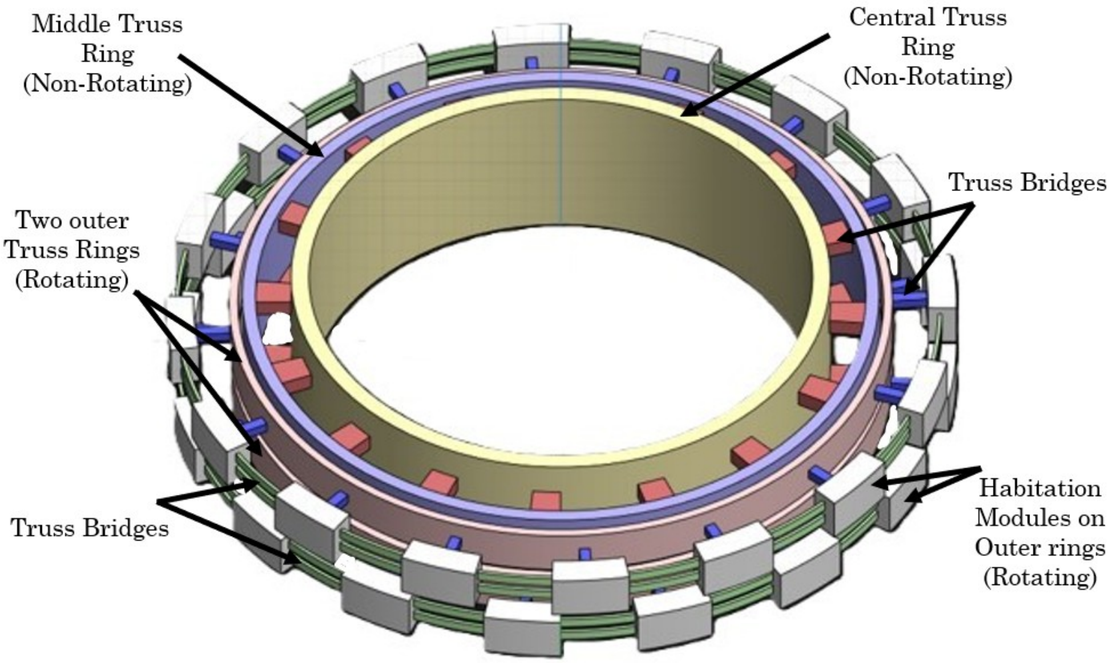

FIGURE 2.1. Rotating space station CAD Design by Wania Farooq[8]

The station is designed to have four truss rings (Figure 2.1). The central truss ring is 75 meters in radius, and 100 meters in length to reduce the probability of wobble along the principal axis of rotation. This is the axis that passes through the center of gravity of the station rings, and is also known as the symmetry axis[11] as shown in Figure 2.2. In this study, station will be modelled as a symmetrical rigid body. This simplifies the moment of inertia (I) calculations performed for the axis of rotation about the symmetric axis (I_s) (2.1) and about the radial axis (I_r) (2.2).

$$I_s = Mass \times (Radius)^2 \tag{2.1}$$

$$I_r = \frac{1}{2} \times Mass \times (Radius)^2 \tag{2.2}$$

Based on the equations above, $I_s > I_r$. A high I_s can help the station maintain a stable spin rate and resist small torques or disturbances. Overall the probability of station wobble occurring is greatly reduced when the station is stationary. When the station is in motion, there will be variation in the mass of the ring structure. this results in 3 principal axis of rotation and will follow the Dzhanibekov effect.[12]

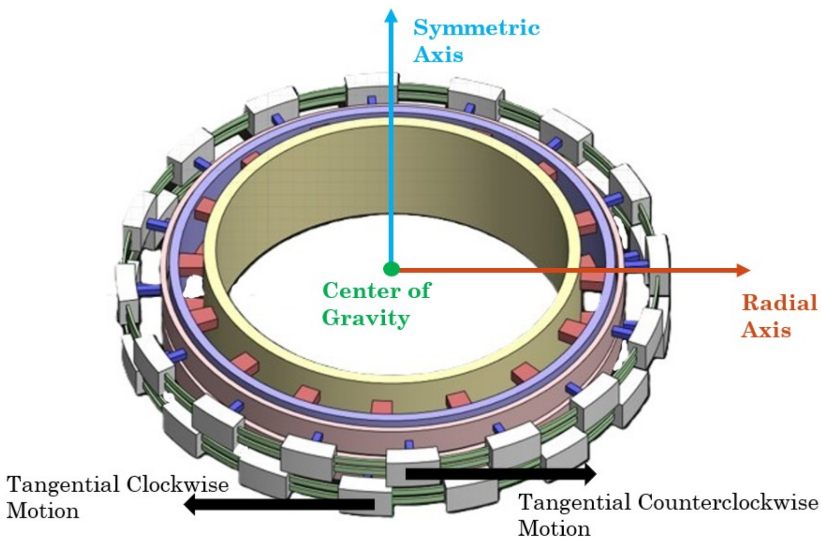

FIGURE 2.2. Rotating space station Computer Aided Design (CAD)[8] and the reference frames[13]

The middle truss ring is connected to the central ring via trusses and houses elevator transport vehicles that move between rings, operating under microgravity and the gravity gradient (covered in chapter 3). The central and middle truss rings remain fixed allowing for microgravity conditions. Hence missions currently conducted on the ISS[14] and Tiangong space station[15] will continue. The middle and outer rings are connected via wheels designed by the head of the SDS, enable the outer rings to rotate with little friction.[8] The 2 outer rings rotate in opposing tangential directions as shown in Figure 2.2. This is to improve the stability of the station by creating a gyroscopic effect on the overall body and the central rings remain stationary without a lot of external thrust corrections. The outer rings are connected via trusses to the habitation modules.

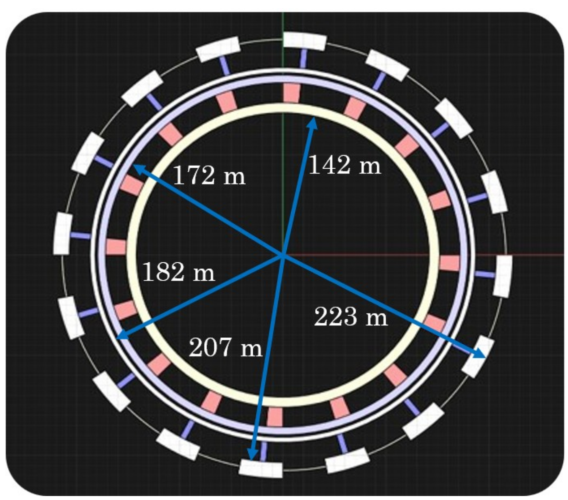

FIGURE 2.3. Radius distribution[13] of each station truss ring[8]

2.1 Fundamentals of the AODS

The AODS defines the motion, propulsion and orientation necessary for the station to rotate during operation. As the station spins the desired position, orbit and station gravitational force need to be maintained.

Figure 2.4 breaks down the basic reference frames used by the station, about the Earth Equatorial plane.[16] These are the:

(1) The Earth-Centered Inertial (ECI) reference frame. It is centered at Earth's center and does not rotate with the earth. Where $\hat{z}_i$ is the Earth's axis of rotation. $\hat{x}_i$ points in towards the vernal equinox, with $\hat{x}_i\hat{y}_i$ defining the equatorial plane.

(2) The Earth-Centered Earth-Fixed (ECEF) reference frame. It is centered at Earth's center and rotates with Earth's surface, hence ground stations are fixed. Where $\hat{z}$ is the axis of rotation, $\hat{x}$ is related to $\hat{x}_i$ via ϕ. $\hat{x}\hat{y}$ also defines the orbital plane of the station.

(3) The Space Station Attitude (SA) reference frame (or the Station Orbit frame). It is centered at the center of mass/gravity of the space station. The motion of this frame of reference is only based on the orbit of the spacecraft, hence it is a non-inertial frame. Linking back to Figure 2.2, $\hat{y}_s$ is the axis of rotation/symmetrical axis, $\hat{x}_s$ and $\hat{z}_s$ act as the radial axes, hence $\hat{x}_s\hat{z}_s$ defines the rotational plane of the station.

The combination of attitude adjustments with with respect to each frame, provides the necessary gravitational, micro-gravitational and station transportation conditions.

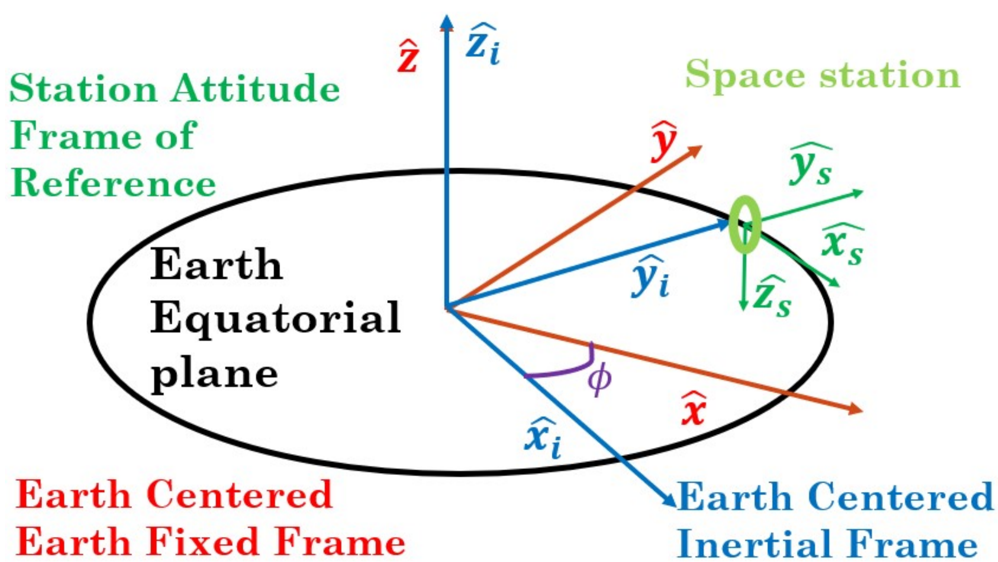

FIGURE 2.4. Reference frames for the ECI, ECEF and Station Attitude[13]

The gravitational condition on the outermost rings occurs by centripetal acceleration. it is experienced by an object moving in a circular path, and is directed towards the center of the path.[17] It is observed in an inertial frame. The centrifugal acceleration is a virtual acceleration only observed in the non-inertial frame of the moving station.

Coriolis force is another important parameter to consider when dealing with circular motion.[18] This deflective force curves the path of an object with an initial tangential velocity within the rotating body and the curved path is perceived from the rotating frame.[19] It is considered a fictitious force due to being perceived in the rotating frame, similar to centrifugal acceleration.[20] To summarise, a straight line within a rotating environment, becomes a curved path in the direction of rotation as shown in Figure 2.5.

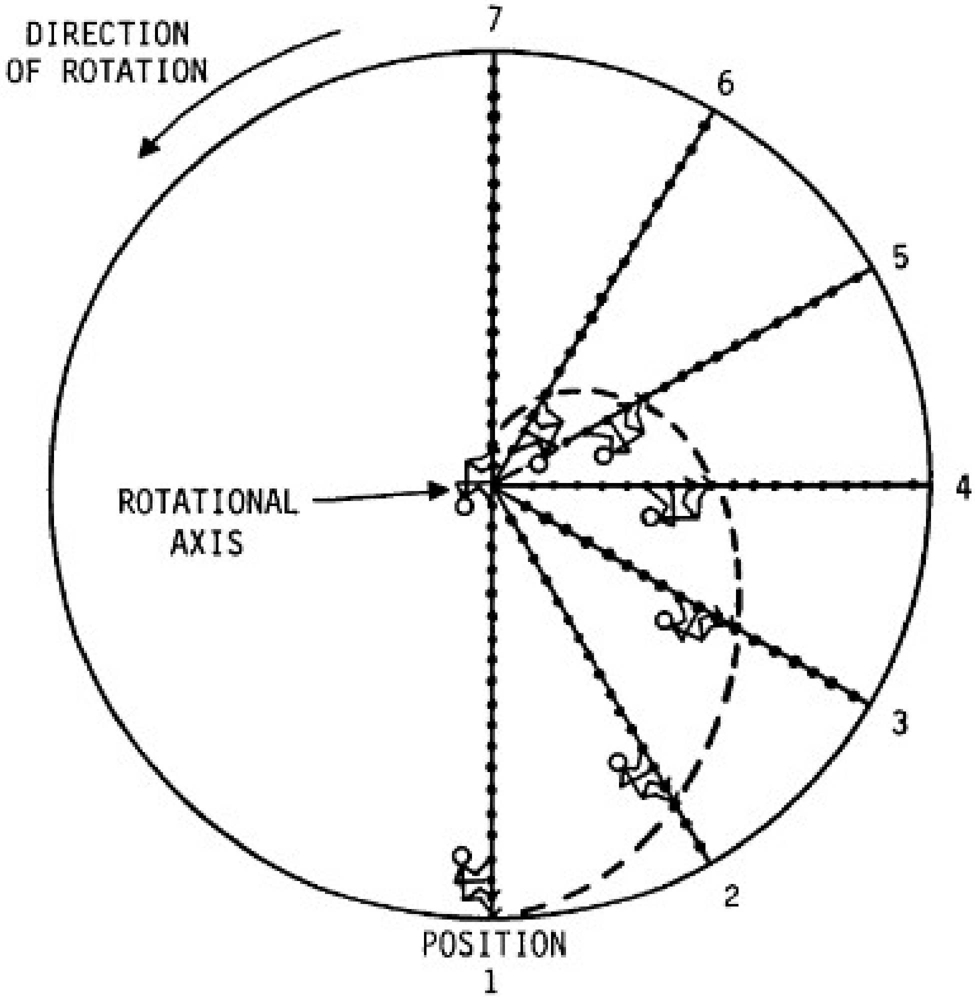

FIGURE 2.5. Straight line motion of a crew member in a rotating frame[21]

The AODS is also responsible for station keeping. Station keeping is maintaining the desired course and heading of a station in orbit. A spacecraft in Earth orbit encounters drag from the atmosphere, solar pressure,[22] Earth's oblateness (J_2 perturbations/external torques) and debris collisions.[23] Internal torques can also be generated when the mass and inertia in the system varies over time. Control systems are developed and used to automate the AODS, by taking in sensor input in detecting and measuring the effects of these drag on the space station. Then station corrections to be made (station keeping).

Chapter 3

AODS Results and Analysis

This chapter covers specific station parameters that form the foundation for dynamic and crew operation. Humans born on Earth have been exposed to the Earth's rotation their whole lives. The effects of the spin are generally unnoticeable due to how large the average radius of the Earth is. The boundaries of the effects of spin on the human body is covered in this chapter.

The station is designed to allow access to most of the population without much training towards spin adjustments. To achieve this, there are guidelines that define the comfort zone of the station.[24]

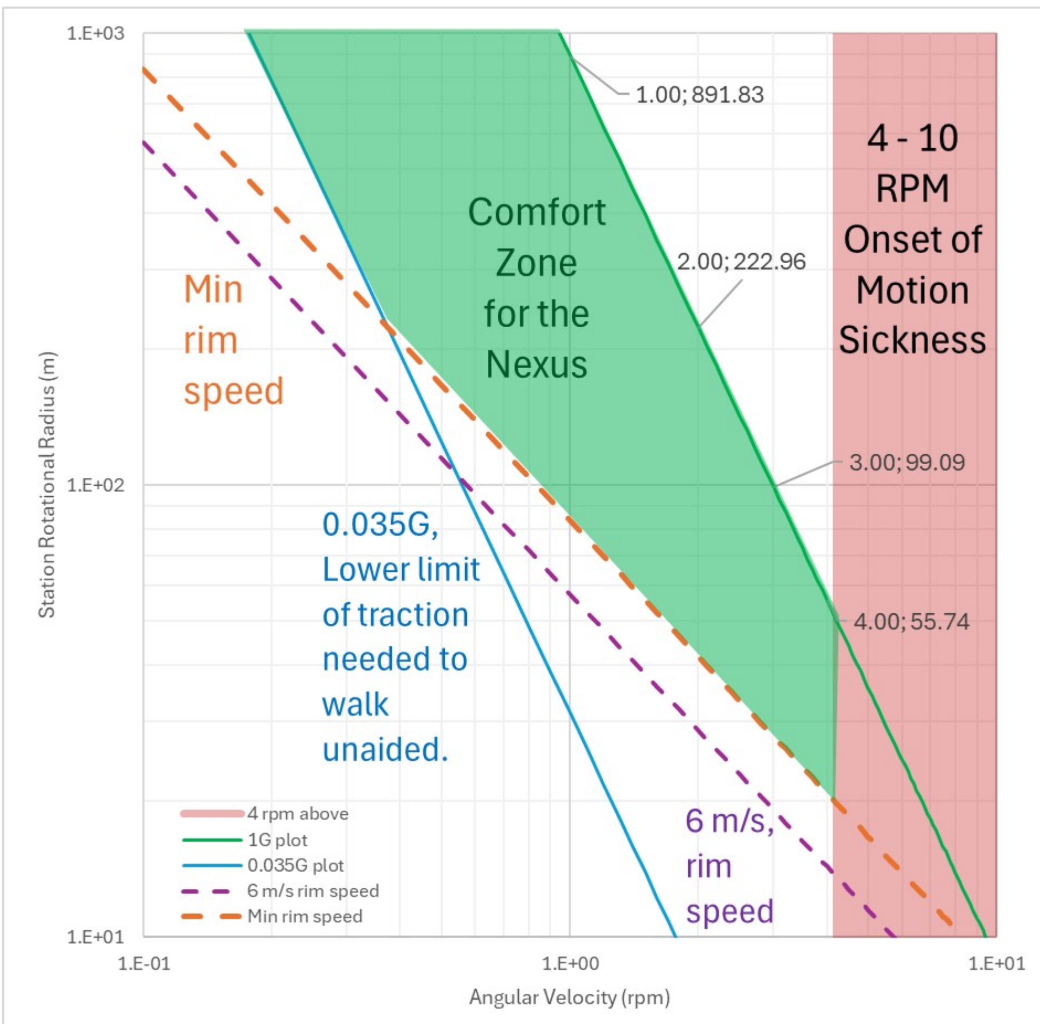

FIGURE 3.1. Rotating space station radius (m) against Angular velocity (rpm).[132425]

The first is to provide traction without external aid, allowing for crew and residents to walk on the station. This requires a minimum centripetal acceleration of 0.035 of Earth's gravity.[24] The second guideline is to avoid motion sickness during spin, which typically arises above 2 rpm. The tolerance for spin can be increased through training[25] beyond up to 6 rpm. To avoid stressing the body, the last guideline for comfort requires the gravity gradient between head and feet be kept below 6 %[24].[25] $1G$ of the station gravity is the Earth-like gravity that is experienced by the crew long term. This is set at $9.7819\,m/s^2$.

Based on these guidelines, the comfort zone design for the Nexus station is presented on Figure 3.1 in green. This shows the relationship between the rotational radius (m) of the station and the angular velocity (rpm). The properties of the graphs will be discussed in the following sections of the chapter. The data used in plotting the graphs are tabulated in Appendix A.

3.1 Nexus station spin (2 rpm)

Artificial gravity on a rotating space station typically depend on four independent variables:

- Station spin radius
- Revolutions per minute (rpm)
- Target gravity (centripetal acceleration)
- Tangential velocity

Supplementary variables include mapping the **gravity gradient** and how **coriolis force** affects the station structure and crew. The station spin radius, rpm and target gravity are linked together through Equation 3.1, where a_g is the acceleration of gravity in m/s. Ω is the angular velocity and R is the radius of the station.

$$a_g = R \times \Omega^2 \tag{3.1}$$

Using Equation 3.1, at a constant a_g of $9.7819\,m/s^2$, the required R and rpm are calculated and shown in Table 3.1.

TABLE 3.1. 1G plot required diameter and angular velocity[13](Figure 3.1)

a_g (m/s^2)	**rpm**	**Radius** (m)	**Diameter** (m)	**Angular velocity** (rad/s)
9.7819	0.5000	3568.0100	7136.0200	0.0524
9.7819	1.0000	891.8300	1783.6600	0.1047
9.7819	2.0000	222.9600	445.9200	0.2094
9.7819	3.0000	99.0900	198.1800	0.3142
9.7819	4.0000	55.7400	111.4800	0.4189

From the literature,[21] the discussed maximum tolerance of station rpm on a crew or resident who has not undergone training to adapt is 2 rpm.[26] However, another study[25] discusses for an rpm up to 6. As rpm increases, more training is necessary for full adjustments. The higher the required rpm, the smaller the radius of the station, as shown in Table 3.1. A reduced radius is more feasible and cost effective, however there is less chance for permanent habitation, defeating the purpose of the Nexus station.

To better accommodate the crew, scientists residents and visitors of the station, 2 rpm is chosen. Reducing the required training to the minimum makes the Nexus station accessible to a large population of humans whom are already used to small scale rotations. The Angular Velocity shown in Table 3.1, for 2 rpm is calculated below:

$$\Omega = 2\pi f = 2\pi \frac{2}{60} = 0.2094\, rad/s \tag{3.2}$$

An rpm of 2 is equivalent to a frequency of, $f = \frac{2}{60} s^{-1}$. Substituting a_g for 9.7819 ms^{-2} and f for $\frac{2}{60} s^{-1}$:

$$9.7819 = (2\pi \frac{1}{30})^2 R \Rightarrow R = 223\, m \pm 1\, m \tag{3.3}$$

With a radius of $223\, m \pm 1\, m$, the station has an overall diameter of $446\, m \pm 2\, m$. The uncertainty in the radius and diameter of the station accounts for the external truss and propulsion structures outside the modules of the station.

3.1.1 The gravity gradient ($< 6\%$)

As mentioned in the guidelines, the gravity gradient between head an feet of any crew should be less than 6%. The gravity gradient remains uniform across the station radius as shown in Figure 3.2. The value for the gravity gradient is calculated below:

$$\frac{9.7819}{223} = \mathbf{0.0439}\, s^{-2} \tag{3.4}$$

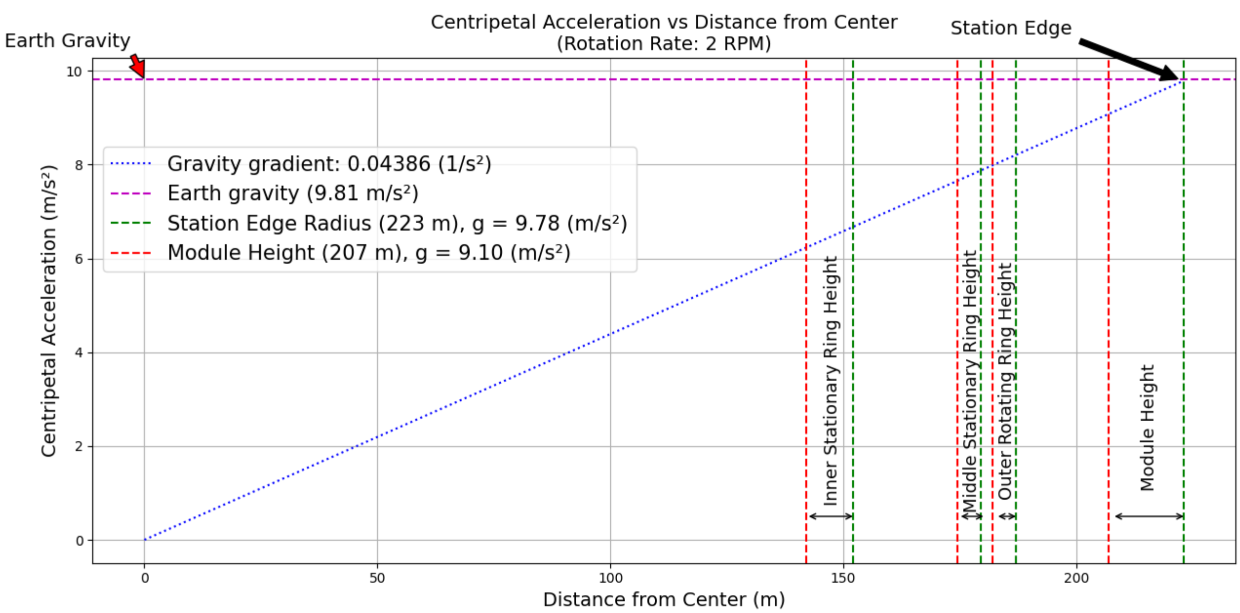

FIGURE 3.2. Graph of centripetal acceleration against radius of the station[13]

This gives a % difference of **4.39%** for the gravity gradient. This is the same between head and feet, hence 4.39% < 6% and fulfills the last guideline[24].[25] Figure 3.2 is designed using the Python™code found in section A.1.

As shown in Graph 3.2, the expected gravity at the station edge is 9.78 ms^{-2}, and 9.10 ms^{-2} at the roof of the habitation modules shown earlier in Figure 2.1. Irrespective of module height, or crew height, the gravity gradient set on the station is ideal as stated in the literature.

3.1.2 The coriolis force ($< 8.17\,\%$ of $1G$)

When a body moves in a linear direction within a rotating frame (Figure 2.5), an extra force due to the acceleration is felt by the object. This is know as the coriolis force[21,27] and it is a fictitious force since it can only be observed in the non-inertial frame of reference. It is two times the cross product of the angular velocity of the station ($\bar{\Omega}$) and the linear velocity ($\bar{V}$) vector of the object within the rotating frame. This means that at a specific angular velocity of the station, the magnitude of the coriolis force of the object will be proportional to its velocity in the rotating frame.

The coriolis force and acceleration can be calculated using Equations 3.6 and 3.5 respectively. Where V is the relative change in tangential velocity within the rotating body.[19]

$$\bar{a_c} = 2(\bar{\Omega} \times \bar{V}) \tag{3.5}$$

$$\bar{F_c} = -2m(\bar{\Omega} \times \bar{V}) \tag{3.6}$$

Note that $\bar{F_c}$ is negative and $\bar{a_c}$ is positive, but they both act in the direction of $\bar{a_c}$. The negative sign means that the the coriolis force in the non-inertial frame is opposite from the real inertial frame effect.

Study and testing has shown that the safe upper limit for coriolis acceleration on the human body[21] is $0.8\,m/s^2$. This also gives an upper limit % acceleration of $\frac{0.8}{9.7819} \times 100 =$ **8.17 %**.

The right hand rule can be used to simplify the vector direction relationship between all 3 parameters, $\bar{F_c}$, $\bar{\Omega}$ and $\bar{V}$. This applies to Figure 3.3, which was generated from the study.[21] Using the right hand rule;

(1) $\bar{\Omega}$ is positive in the anticlockwise direction, and pointing out of the page. It is defined using the right thumb.
(2) $\bar{V}$ is positive in the tangential direction of the spin (pro-spin) and positive in the increasing radial direction. It is defined using the middle finger.
(3) $\bar{F_c}$ is positive in the direction of the station gravity ($1G\,or\,\bar{F_g}$ in Figure 3.3), and negative in the direction of spin. It is defined using the index finger.

Different crew motion scenarios within a rotating body is modelled in Figure 3.3. Where the rotation of the station occurs in the anticlockwise direction (positive), hence the angular velocity vector ($\bar{\omega}\,or\,\bar{\Omega}$) is pointing out of the page in scenarios (a, b, c and d).

Scenarios (a) and (b) depict a crew member walking in the direction of the station spin (pro-spin) and (anti-spin) respectively. (c) and (d) depict a crew member climbing up and down a ladder respectively, while (e) depicts movement in the axial direction, parallel to the axis of rotation.

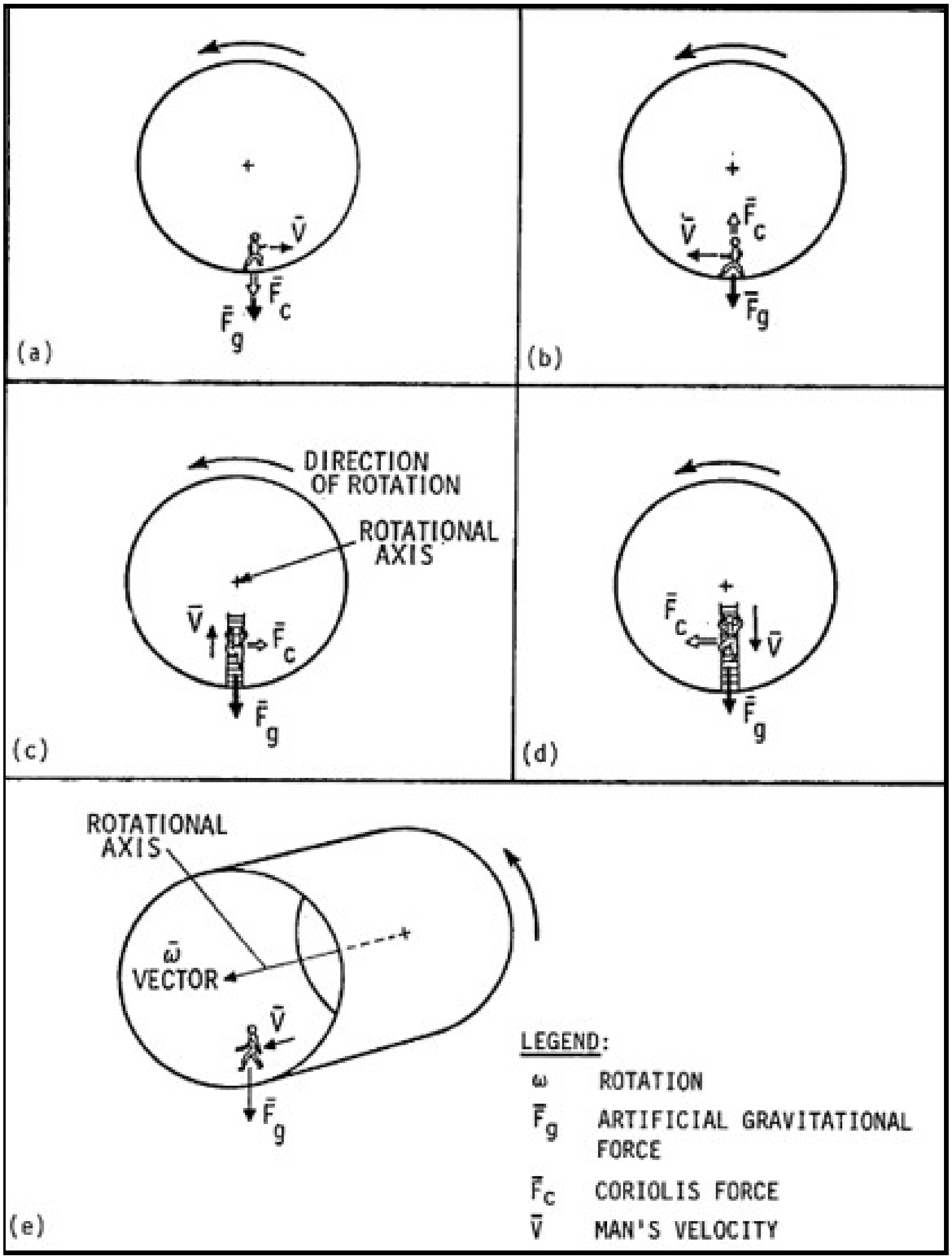

FIGURE 3.3. The coriolis force F_c experienced when moving in a rotating body.[21]

For average crew mass of 82 kg,[28] an example of the coriolis force for a crew climbing a ladder from the floor to the top roof of the habitation module floors (scenario (c) in Figure 3.3) can be calculated. The upper limit of the coriolis acceleration to be tolerated by any crew moving within the station, is dictated by the velocity of the crew in motion within the rotating frame.

For scenarios (a) and (b) in Figure 3.3, which model pro-spin and anti-spin motion, the coriolis equation (Equation 3.5) can be rearranged to find the maximum relative tangential velocity $V_{relative}$ that can be tolerated by the crew. with the upper limit for a_c being $0.8\,m/s^2$:

$$V_{relative} = \frac{a_c}{2\Omega} = \frac{0.8}{2 \times 0.2094} = 1.91\,m/s \tag{3.7}$$

A speed of **1.9** m/s (Equation 3.7) within the habitation module is the maximum walking speed on the floor or the station. This is above the average human walking speed of 1.5 m/s, hence the design is appropriate for nominal research and crew operations that do not require running. The average running speeds can be up to 3.0 m/s, which will introduce negative coriolis effects on the crew. To increase the maximum walking/running speed threshold, the angular velocity of the station needs to be reduced. This means a station with a larger radius. The tradeoff with the Nexus at 223 m in diameter is its ability to be built when compared to larger radial stations.

For scenarios (c) and (d) in Figure 3.3, which model ascent and descent motion, the maximum radial velocity $V_{relative}$ that can be tolerated by the crew is the same as in Scenarios (a) and (b). However, when the velocity of the crew member is parallel to the axis of rotation, the cross product becomes zero, and there is no coriolis effect.

Overall, the station design limits the maximum velocity any crew can take without side effects at **1.9** m/s. Speeds within the station that are higher than this are achieved in the elevator lifts connecting the station rings together. Given that the coriolis forces only apply to the rotating rings of the station, the lifts connecting the rotating rings will be fitted with restraints and hand railings if $V_{elevator} > 1.9\,m/s$.

3.2 Orbit Perturbation and Modelling

An orbit is the curved path taken by an object around another object due to the gravitational effects between them.[29] Describing the motion of a satellite in Earth orbit begins with Newton's two body dynamics equations. This describes the motion between two masses through the position vectors within their reference frames. A satellite in orbit is perpetually falling towards to Earth's surface, however due to its tangential velocity, the satellite's path remains curved around the planet. The curve path can result in 4 types of orbital trajectories; a circular orbit, an elliptical orbit, a parabolic orbit and a hyperbolic orbit. The eccentricity parameter (e) dictates what trajectory a satellite/station or orbit is in and they can be useful for different mission plans.

3.2.1 Orbital elements

The magnitude of the Nexus station's position vector $\bar{r}$ shown in Figure 3.5 is given by Kepler's first law for an elliptical orbit:[29]

$$|\bar{r}| = \frac{p}{1 + e\cos\theta} = \frac{a(1 - e^2)}{1 + e\cos\theta} \tag{3.8}$$

The magnitude of the position vector in Equation 3.8 is defined using a few of the six orbital elements/quantities. These constants fully describe the position of any object in a two-body orbit around the Earth, and they are as follows:

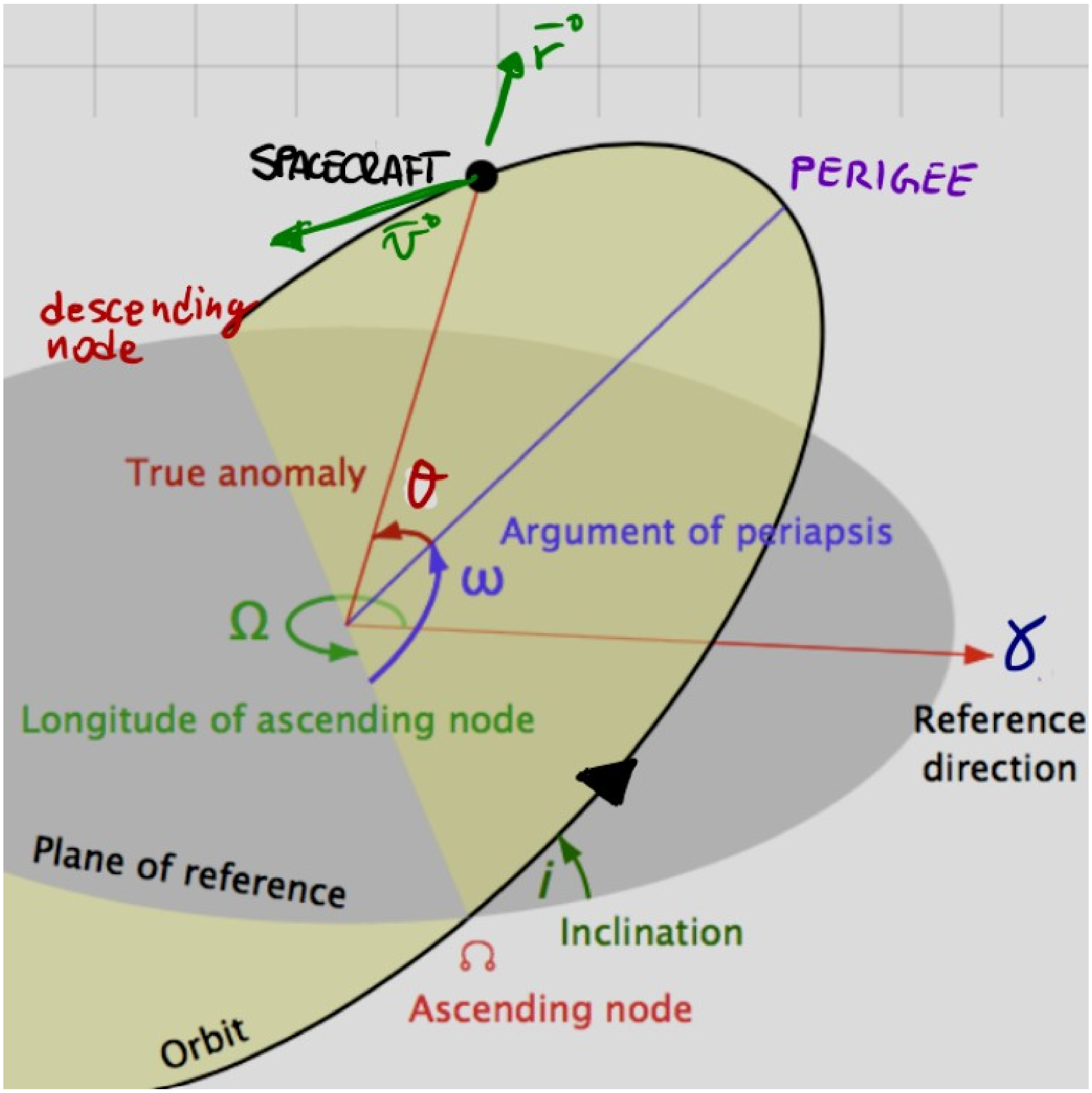

FIGURE 3.4. Classical orbital parameters in 3D[29]

(1) The Semi-Major Axis (SMA) (a): This half the sum of the apogee and perigee distances. It describes the size of the orbit. For a circular orbit, the SMA $= r$.
(2) The eccentricity parameter (e): This is a dimensionless number that describes the shape of the orbit/trajectory. For a circular orbit, $e = 0$; for an elliptical, $0 < e < 1$; for a parabolic orbit, $e = 1$; and for a hyperbolic orbit, $e > 1$.
(3) The orbit inclination (i): This describes the angle between Earth's equator and the space station. This is done by comparing the specific angular momentum unit vectors ($\hat{h}$) of both orbital plane.
(4) The Right Ascension of Ascending Node (RAAN) (Ω_o): This is the angle between the Earth ascending node direction (a reference direction) and the line where the Earth equatorial plane and the orbital plane meet.

(5) The Argument of Perigee (AoP) (ω_o): This is the angle between the station ascending node line and the perigee of the station orbit.
(6) The true Anomaly (θ): This is the orbital position of the satellite at a given time. The perigee time passage (t_p) can also be determined from the true anomaly.

Figure 3.5 and Figure 3.4 both provide a visual representation for these orbital elements. Note that in Figure 3.5, r_a and r_p are the apogee and perigee distances respectively.

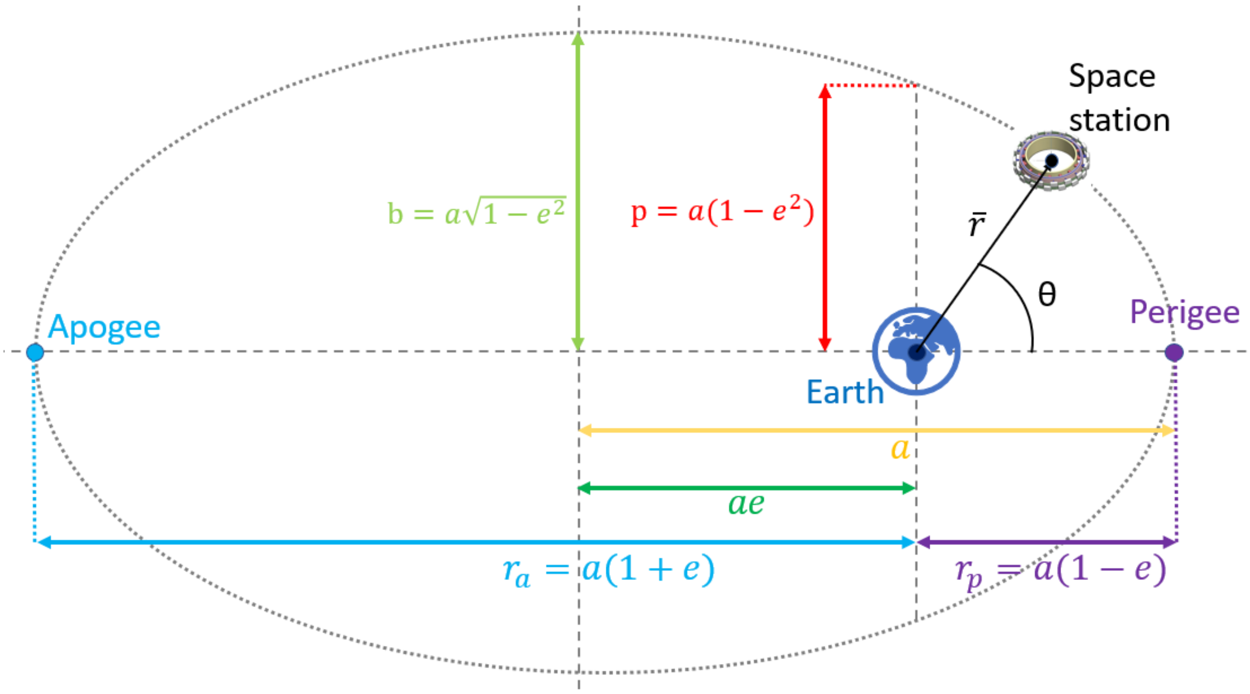

FIGURE 3.5. Orbit parameters of space station in Earth orbit[13,29]

3.2.2 Types of Orbits

The aim is to determine the most suitable operational orbit for the Nexus station. Important considerations Include:

- How often the station faces the sun to collect solar energy for power (and support station thermal regulations)
- The average radiation exposure
- The probability of debris contact with the station
- The cost effectiveness to rendezvous with the station from Earth
- Emergency scenarios and station end of life

The ISS[75] for example orbits at an altitude between 370 and 460 km, with an inclination of 51.6°.[30] Paired with the other orbital parameter values, the ISS is in an inclined Sun-Asynchronous Orbit (SAO). The properties of the potential orbits considered are presented in Table 3.2. The table shows comparisons of SAO for the ISS, Low Earth Orbit (LEO) and Geostationary Orbit (GEO) with governing bodies such as the International Telecommunication Union (ITU™).[31]

TABLE 3.2. Literature comparison of the ISS SSO, LEO and GEO[32]

	Sun-asynchronous (ISS)	**LEO**	**GEO**
Main Orbit Properties	LEO with rate of RAAN approximately 1° a day due to J_2 perturbation	Between altitudes of 400km to 2000km	Altitude of 35,786km. Limited spaces[31]
Inclination (i)	Between[33] 51° and 52°	0° to 90°	0° (equatorial)
Period (T)	90 to 93 minutes	90 to 128 minutes	1436 minutes
Pros	Allows ease of orbital rendezvous for resupply and crewed missions. The trajectory is the most protected from solar and cosmic radiation due to the Earth's magnetic field	Highly protected orbit from solar and cosmic radiation due to the Earth's magnetic field	Lower debris probability, Low atmospheric drag. Covers one area of the Earth's surface
Cons	There is a probability of debris contact at this orbit. The effects of J_2 perturbation on the orbit is at a maximum due to the orbit's proximity. Atmospheric drag disrupts the orbit of the station	High debris probability. Atmospheric drag. Long term radiation exposure. End of life disposal will be Earth re-entry	Not very protected from solar and cosmic radiation. Rendezvous is harder for resupply missions. Regulatory bodies (ITU™ [31]) restrict GEO availability

A trade-off on the properties of the space environments considered in Table 3.2 was performed to decide on the suitable orbit for the Nexus. The lower ranges of LEO (SAO) offers maximum magnetic shielding from cosmic and solar radiation. This is a necessity for long term habitation of up to 30 years at a time (The ASPA group aim). LEO also offers a lower parking orbit, which reduces launch cost, and increases launch frequency. This is the ideal for the build and operational phase of the station. However the level of debris around LEO is the highest in Earth orbits. As an extension to this report, the station's unique shielding design has been generated by author Abaas Nunow[9] and future works (chapter 6) on debris modelling for collision avoidance will be investigated. GEO has opposing properties to LEO, with high radiation exposure and low debris levels. With a station design that can combat the radiation levels, the technology is still years ahead. Hence the final choice for the station orbit is set at the current ISS orbit, which is the **SAO**.

3.2.3 Nexus Orbit Parameters (SAO)

The station orbit parameters chosen are outlined in Table 3.3. These are the current ISS parameters[30] at an epoch of 25 Apr 2025. Using the Python™found in section A.3, the variations of the orbital radius and orbital velocities of the stations are plotted in Figure 3.6 and Figure 3.7. These are some of the details necessary in mission planning to the station and station keeping.

TABLE 3.3. The Nexus station design orbital parameters[30]

Parameter	Value	Units
SMA (a)	6789	km
Perigee	417	km
Apogee	420	km
Eccentricity (e)	0.00023	°
Inclination (i)	51.6367	°
RAAN (Ω_o)	82.7408	°
AoP (ω_o)	209.5298	°
Revolutions	15.5	per day
Period	90 - 93	minutes

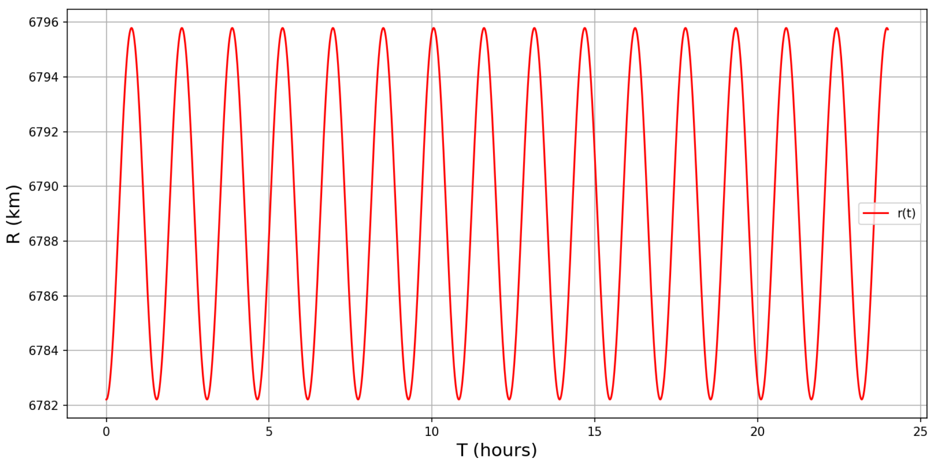

FIGURE 3.6. Station position magnitude variation over 24 hours[13]

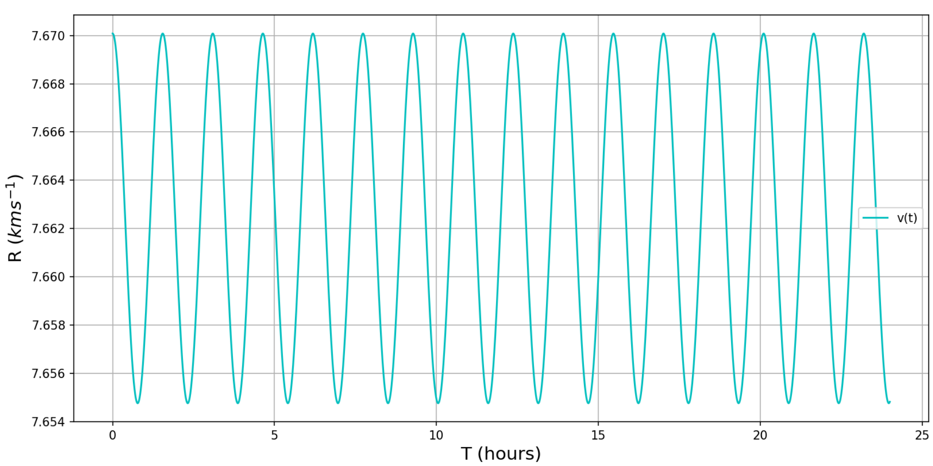

FIGURE 3.7. Station velocity magnitude variation over 24 hours[13]

The NASA™ General Mission Analysis Tool (GMAT™) is capable of propagating the orbit visually. After testing the orbital parameters, the resulting station orbit and ground track are presented in Figure 3.8 and Figure 3.9 respectively. Note that the orbit is a prograde orbit.

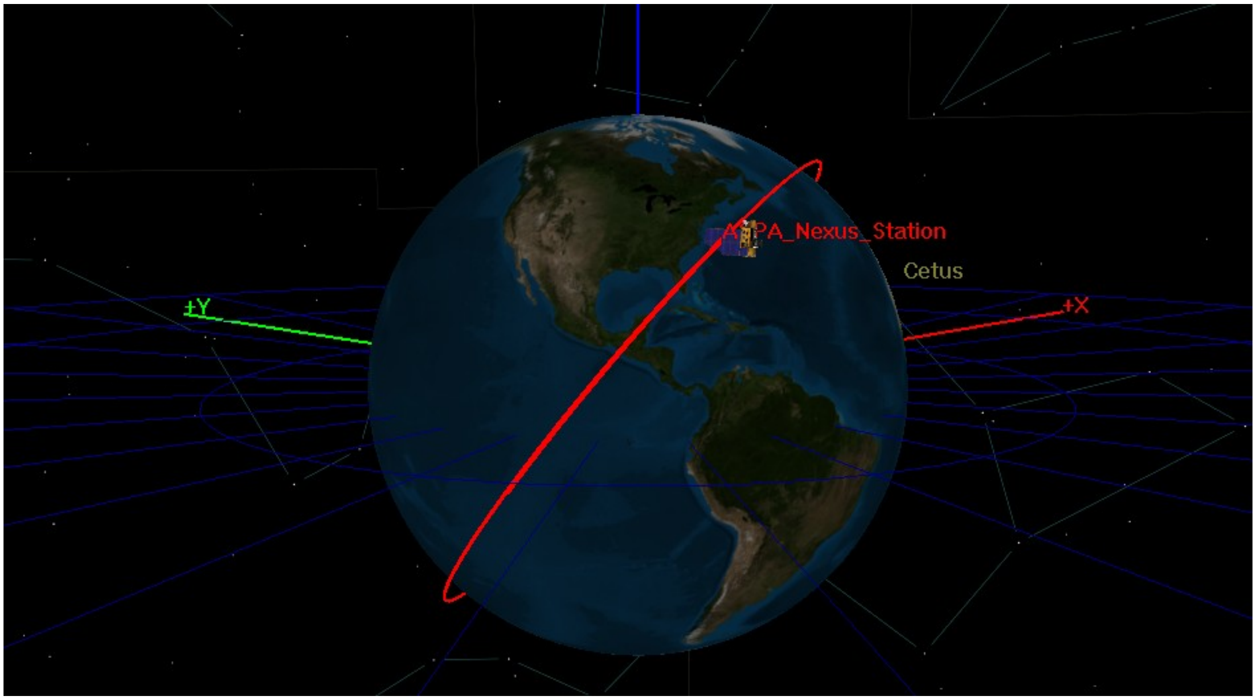

FIGURE 3.8. Nexus station orbit around earth using GMAT™.[13]

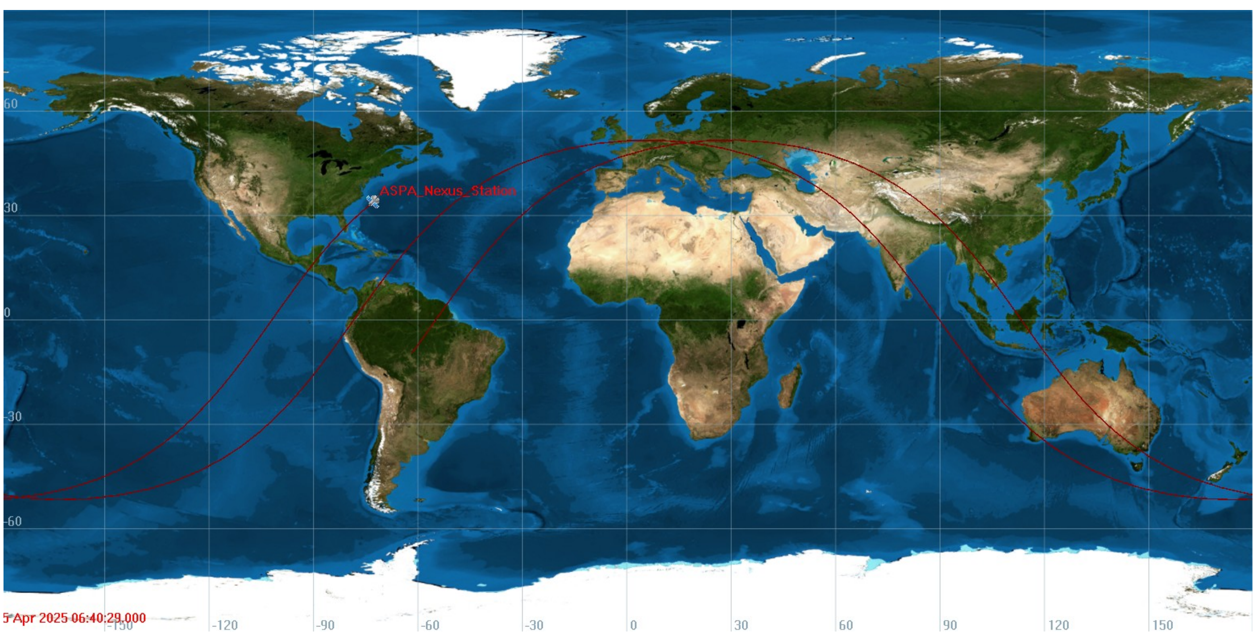

FIGURE 3.9. Nexus station groundtracking on earth using GMAT™.[13]

Chapter 4

Station Keeping and Electric Propulsion

The mode of propulsion chosen for the Nexus station are electric propulsion systems. These are chosen over chemical propulsion systems due to having less thrust to fuel requirement, less pollutions (thrust plumes[34]) and less cost to maintain. In this chapter, factors of keeping the station operational, and the optimum electric propulsion system will be discussed.

4.1 Station Keeping

Satellite and spacecrafts in orbit experience orbit degradation. These are due to the external forces that arise due to the space environment. Examples include;

- J_2 **perturbation**: This is an effect that arises due to the oblateness of the earth.[35] The oblateness of the earth refers to the unevenness of the Earth's surface. J_2 causes changes in the torque experienced by the station along its axis of rotation (Figure 2.2). This causes a disruption to the attitude of the station, along with degrading the orbit. The J_2 becomes stronger, the lower the altitude of the station. Hence, the Nexus will be greatly affected by it.
- **Atmospheric drag**: The density of the atmosphere increases the closer a satellite is to Earth. Given that the Nexus station has a drag profile of: $100\,m \times 450\,m = 45000\,m^2$, and the standard drag coefficient (ISS) of 2.2, the drag forces due to the atmosphere can be determined.
- **Solar pressure**: The solar winds and photons ejected from the surface of the sun exert a pressure on satellites and in turn, the Nexus station.

Internal forces that are part of control systems such as the **spin up and spin down** procedures and **required thrust** are also essential in maintaining station stability, attitude and orbit.

4.1.1 Spin Up and Spin Down time (max of $58.4\,s$)

The Nexus station requires the outermost rings and habitation modules to spin, in order to generate artificial gravity. The time it takes to spin up and down these rings are important to consider. When spinning up to reach the target rpm of 2, the time taken can affect the crew within the habitation modules if this occurs too fast. With spinning down, the same effect applies and there is the potential for an emergency spin down to occur. In which the spin down rate can be up to four times as fast as nominal values. The final maximum velocity at the station edge is calculated below:

$$V_{T(max)} = \Omega \times R = 0.2094 \times 223 = 46.70\,m/s \tag{4.1}$$

Using Python™, the target rpm of 2 and final maximum station edge velocity (Equation 4.1) ($V_{T(max)}$) of 46.70 m/s are used to determine the time for spin-up or spin-down. The required constant tangential acceleration required for the duration is also determined

(Equation 4.2) and shown on Table 4.1.

$$V_{T(max)} = U_T + (a_T \times t_s) \rightarrow a_T = \frac{(V_{T(max)} - U_T)}{t_s}(m/s^2) \tag{4.2}$$

TABLE 4.1. Station spin-up and spin-down time with corresponding tangential acceleration required towards a target rpm = 2 and a target tangential velocity of 46.70 m/s using Equation 4.2

Time (t_s) (hours)	**Tangential acceleration (a_T)** (m/s^2)
0.5	0.0259
1	0.0130
2	0.0065
3	0.0043
4	0.0032

Equation 4.2 can also be used to model the maximum tangential acceleration that can be used when spinning down for station emergencies. In an emergency situation, avoiding further damages on human life is crucial, hence the maximum acceleration that can be handled by a human[21] remains at 0.8 m/s^2. This brings the fastest spin-down time ($t_{s(E)}$) (or spin-up time) as:

$$t_{s(E)} = \frac{(V_{T(max)} - U_T)}{a_T} = \frac{(0 - 46.70)}{0.8} = |-58.357| = 58.4\,s \tag{4.3}$$

A nominal spin-up/spin-down time of 1 hour presents a low enough acceleration when considering potential electric propulsion systems.

4.2 Station Electric Propulsion

Electric thrusters[36373839] utilise voltage, current, fuel and a magnetic field to generate a relatively low thrust but high thrust to weight ratio. The thruster design for the station involves strategically placing these electrical thrusters around the external ring of the station (or on the habitation modules). Generating the required thrust to spin the station, perform orbital corrections and avoid debris. The thrusters will be generating tangential accelerations, and hence would be placed tangentially on the station.

4.2.1 A Literature Review of Electric Thrusters

A decision matrix (Table 4.2) has been generated to compare 10 important thruster requirements for the Nexus station. These requirements are;

(1) **Response Time**: At maximum isp, what is the fastest time taken to perform an operation. Weighting (5): Very important for emergency systems
(2) **Thrust Level**: isp range. Weighting (4): An important parameter when designing manoeuvres

(3) **Operational Lifetime**: Expected service life before maintenance or replacement. Weighting (5): Due to length of station operation
(4) **Power Requirements**: Power consumption relative to station resources (higher score = lower power needs). Weighting (3): There will be sufficient power sources such as solar and nuclear
(5) **Mass Efficiency**: Propellant efficiency (specific impulse) and overall system mass. Weighting (4)
(6) **Integration Complexity**: Ease of integration with station systems (higher is simpler). Weighting (3)
(7) **Impact on Station Dynamics**: Minimal influence on station's rotational stability (higher is better). Weighting (5): The aim is to minimise disturbances to the system
(8) **Plume Contamination**: Risk of thruster exhaust contaminating sensitive surfaces (how much Contamination is produced, and it/s inert-ness.) Weighting (3)
(9) **Thrust Variation**: Ability to vary thrust precisely for different manoeuvres. Weighting (4)
(10) **Technology Readiness**: Flight heritage and reliability.[40] Weighting (4)

Table 4.2. Decision matrix for comparing thruster systems for ASPA Nexus space station applications[36][37][38][39]

Requirements	**Weighting**	**Gridded Ion Engine (GIE)**	**Field Emission Electric Propulsion (FEEP)**	**Electrode less Thrusters**	**Colloid / Electrospray**	**Pulsed Plasma Thruster (PPT)**
Response Time	5	3 (15)	4 (20)	2 (10)	5 (25)	5 (25)
Thrust Level	4	4 (16)	1 (4)	4 (16)	2 (8)	2 (8)
Operational Lifetime	5	5 (25)	3 (15)	4 (20)	3 (15)	2 (10)
Power Requirements	3	2 (6)	5 (15)	1 (3)	4 (12)	4 (12)
Mass Efficiency	4	5 (20)	5 (20)	4 (16)	4 (16)	2 (8)
Integration Complexity	3	3 (9)	2 (6)	1 (3)	3 (9)	4 (12)
Impact on Station Dynamics	5	4 (20)	5 (25)	3 (15)	5 (25)	3 (15)
Plume Contamination	3	3 (9)	2 (6)	4 (12)	2 (6)	2 (6)
Thrust Variation	4	4 (16)	4 (16)	5 (20)	4 (16)	2 (8)
Technology Readiness	4	5 (20)	3 (12)	2 (8)	3 (12)	4 (16)
Total Scores		156	139	123	144	120

4.2.2 Conclusions on Electric Propulsion systems

Two out of the five electrical thrusters presented on the decision matrix were selected to be compared. These were the Gridded Ion Engine (GIE) and Colloid/Electrospray (C/ES) thrusters.

The NASA™ NEXT-C GIE[37] (156) is the strongest overall option with a thruster system using Xenon propellant, designed to produce 236 mN thrust. It also has a specific impulse of 4,190 seconds. The grid configuration, discharge chamber and cathodes are are prone to wear over time, hence require maintenance and replacing once avery few years. The Thruster does not come with an attitude control system, and is chosen as the main tangential thrusters for the station spin up and down. These are to be fixed at their locations, without much adjustments required. This thruster type is also flight proven, increasing its reliability in the field.

The C/ES[39] (144) provides high efficiency with a lower thrust to power ratio when compared with GIE. It has a isp range of 500-5000s isp, low power requirements and is fitted in arrays. It does not require a robust thermal protection system due to low thermal loading. The Propellants can be ionic liquids or conductive fluids. The downsides of this system is its limited flight heritage and required complex manufacturing methods. Hence why it is chosen as alternating thrusters in clusters to enable rapid precise adjustments during debris avoidance and station attitude corrections.

Lastly, a control system that integrates both primary (GIE) and secondary (C/ES) propulsion systems is required to improve overall station response time.

Chapter 5

Conclusions

The results obtained in this report on the feasibility of a rotating space station design have shown that the Nexus is feasible, but limited. With the aim of maximising comfort to allow mission on the station to be more accessible, the station design is mainly limited by human average tolerances. These are the coriolis forces ($< 6\%$), and accelerations that can cause dizziness and nausea (anything $> 0.8\, m/s^2$). With the Earth like $1G$ target, and comfort levels, the station radius is set at $R = 223\, m$ with the target rpm of 2.

An important limitation determined was the maximum movement speed within the station, which is set at $1.9\, m/s$. This only becomes a limitation for running and elevator movements. To expand on this the radius of the rotating space station would needs to be increased. However building a large space structure is already a design challenge.

The orbital elements for the ISS SAO that was selected reflects the ease of access and increased shielding from radiation. This further increases the habitability of the station compared to other orbits considered. A difficulty encountered when modelling the orbital elements is accounting for changes to the orbit perturbations due to disturbances in the space environment. As a result, more work should be conducted to best model the orbit of the station over it's lifespan.

Emergency scenario under spin-up and spin-down were considered for the station to ensure that the crew are able to safely evacuate in any emergency. This opens the opportunity to investigate other safety systems that can be put in place on the station.

The literature review on electric thrusters resulted in selecting a primary and secondary propulsion system, the GIE and C/ES respectively. The Primary system for localised station adjustments, while the secondary for orbital adjustments.

Overall, the preliminary studies into the AODS for the ASPA Nexus station, has produced viable results for the station design feasibility. This will go on to serve as the foundation for a broader and more in-depth analysis on the system.

Chapter 6

Future Work Considerations

More in-depth studies can be performed in certain aspects of the AODS. Some of these are included in this chapter.

6.1 Orbit Degradation and Orbit Prediction Models

Continuing From chapter 4, station keeping requires a robust control system to make course corrections at intervals over time. Combined with the choice of electric propulsion, the thruster firing frequency can be determined. From which thruster longevity can also be approximated. Drag equations on j_2, atmospheric drag and solar pressure will also be presented in future future works, as they play an important role in Orbit Degradation.

The base thruster parameters for the selected GIE and C/ES propulsion systems can be determined. These will open discussions on thermal effects of thrusters, reliability and longevity. Calculations that can justify the station's spin-up and spin-down ability can then be performed. Overall, the feasibility of the station's ability to use electric thrusters can be determined. The orbit parameters chosen for the Nexus station are the same as the ISS, as has been presented in chapter 3. Due to station precession, these parameters are expected to change constantly. Hence, apart from course corrections, course planning can be covered in further works.

6.2 Drag and Debris Avoidance

Further work on developing the control system that detects and avoids debris encounted in the SAO of the station. Engineering software such as Debris Risk Assessment and Mitigation Analysis (DRAMA™), FREEFLYER™and GMAT™ are useful in determining debris probability using historical data. Debris contact scenarios have been conducted by the head of the Nexus SPS (Abaas Nunow).

Debris avoidance could also result in station motion along all of its axis, which would require complex calculations to perform. The station mass distribution is an important consideration for this, and will be determined in further works by the ASPA group.

6.3 Crew Adaptability and End of life

The Nexus station has been designed to maximise crew comfort and accessibility by providing gravity conditions that do not require long term training for the missions. Studies can be conducted on how the crew adapts to the station in future work.

There are regulatory bodies[41] such as the Civil Aviation Authority (CAA) and internally, the Inter-Agency Space Debris Coordination Committee (IADC) play key roles in satellite disposals and other aspects of space missions. Future works into the feasibility of placing a satellite the size and mass of the Nexus station in SAO can be conducted.[42]

Bibliography

[1] NASA, *RACE TO SPACE Background*. NASA. [Online]. Available: https://www.nasa.gov/wp-content/uploads/2019/08/466720main_AP_ST_Hist_RacetoSpace_09-17-09.pdf
[2] [Online]. Available: https://now.northropgrumman.com/how-technology-from-the-space-race-changed-the-world
[3] F. E. Tilton, J. Degioanni, and V. Schneider, "Long-term follow-up of skylab bone demineralization." *Aviation, space, and environmental medicine*, vol. 51, no. 11, pp. 1209–1213, 1980.
[4] S. Trappe, D. Costill, P. Gallagher, A. Creer, J. R. Peters, H. Evans, D. A. Riley, and R. H. Fitts, "Exercise in space: human skeletal muscle after 6 months aboard the international space station," *Journal of applied physiology*, vol. 106, no. 4, pp. 1159–1168, 2009.
[5] L. DeLucas, "international space station," *Acta Astronautica*, 1996. [Online]. Available: https://www.sciencedirect.com/science/article/pii/0094576596000562
[6] E. Airiofolo, "The aspa group webpage," 2025. [Online]. Available: https://a-s-p-a.github.io/ASPA-Website-Book/intro.html
[7] C. A. Jorgensen and J. Antol, "International space station evolution data book," NTRS Research Center: Langley Research Center (LaRC), Tech. Rep., 2000.
[8] W. Farooq, "Novel concept and structural design of a rotating space station," Queen Mary University of London 3rd Year Design Project Report Draft, Tech. Rep., 2025.
[9] A. Nunow, "Numerical and material investigation and optimisation of whipple shield layering against high-velocity impacts," Queen Mary University of London 3rd Year Design Project Report Draft, Tech. Rep., 2025.
[10] I. Sivagnanamoorthy, "Nexus: Rendezvous and resupply logistics assessment for a rotating space station habitat in leo," Queen Mary University of London 3rd Year Design Project Report Draft, Tech. Rep., 2025.
[11] [Online]. Available: https://byjus.com/jee/moment-of-inertia/
[12] H. Murakami, O. Rios, and T. J. Impelluso, "A theoretical and numerical study of the dzhanibekov and tennis racket phenomena," *Journal of applied mechanics*, vol. 83, no. 11, p. 111006, 2016.
[13] E. Airiofolo, "This result has was generated by the author using either python, matlab, gmat or powerpoint."
[14] S. Torney, "Human-research-program-overview," NASA, Tech. Rep., 2017. [Online]. Available: https://ntrs.nasa.gov/api/citations/20170003808/downloads/20170003808.pdf
[15] Z. Yin, Z. Zhu, P. Guo, Z. Wang, J. Yang, and Y. Song, "On-orbit space technology experiment and verification project outlook of china's tiangong space station," *Space: Science & Technology*, vol. 3, p. 0061, 2023.
[16] C. D. Hall, "Spacecraft attitude dynamics and control," *Lecture Notes posted on Handouts page [online]*, vol. 12, no. 2003, 2003.
[17] "Centripetal force and centrifugal force - definition, examples, differences between centripetal force and centrifugal force and faqs." [Online]. Available: https://byjus.com/physics/centripetal-and-centrifugal-force/
[18] N. D. Katopodes, *Chapter 10 - Geophysical Effects*. Butterworth-Heinemann, Jan. 2019, p. 710–779. [Online]. Available: https://www.sciencedirect.com/science/article/pii/B9780128154892000101
[19] A. Persson, "Back to basics: Coriolis: Part 1 — what is the coriolis force?" *Weather*, vol. 55, no. 5, pp. 165–170, 2000. [Online]. Available: https://rmets.onlinelibrary.wiley.com/doi/abs/10.1002/j.1477-8696.2000.tb04052.x
[20] ——, "How do we understand the coriolis force?" *Bulletin of the American Meteorological Society*, vol. 79, no. 7, pp. 1373–1386, 1998.
[21] M. Queijo, A. Butterfield, W. Cuddihy, C. King, R. Stone, and P. Garn, "Analysis of a rotating advanced-technology space station for the year 2025," The Bionetics Corporation Hampton, VA 23666, Tech. Rep., 1988.

[22] D. P. Rubincam, "Lageos orbit decay due to infrared radiation from earth," *Journal of Geophysical Research: Solid Earth*, vol. 92, no. B2, pp. 1287–1294, 1987.
[23] J. D. LAFONTAINE and S. C. GARG, "A review of satellite lifetime and orbit decay prediction," *Indian Acad. Sci. (Engg. Sci.)*, vol. Vol 5, p. 62, 1982. [Online]. Available: https://www.ias.ac.in/public/Volumes/sadh/005/03/0197-0258.pdf
[24] M. Chen, R. Goyal, M. Majji, and R. E. Skelton, "Review of space habitat designs for long-term space explorations," *Progress in Aerospace Sciences*, vol. 122, p. 100692, Apr. 2021. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0376042120301044
[25] A. Globus and T. Hall, "Space settlement population rotation tolerance," *NSS Space Settlement Journal*, vol. 2, pp. 1–25, Jan 2017.
[26] K. N. Bretl, A. T. McCusker, S. O. Sherman, T. R. Mitchell, J. B. Dixon, and T. K. Clark, "Tolerable acclimation to the cross-coupled illusion through a 10-day, incremental, personalized protocol," *Journal of Vestibular Research*, vol. 29, no. 2-3, pp. 97–110, 2019.
[27] A. Bukley, W. Paloski, and G. Clement, "Physics of artificial gravity," 2006.
[28] M. K. Ewert and C. Stromgren, "Astronaut mass balance for long duration missions," in *International Conference on Environmental Systems (ICES 2019)*, no. ICES-2019-126, 2019.
[29] M. C. Angadh Nanjangud, Emmanuel Airiofolo. [Online]. Available: https://www.angadhn.com/SpacecraftDynamics/weekly-outline.html
[30] [Online]. Available: https://heavens-above.com/orbit.aspx?satid=25544
[31] S. Gorove, "Major legal issues arising from the use of the geostationary orbit," *Mich. YBI Legal Stud.*, vol. 5, p. 3, 1984.
[32] [Online]. Available: https://www.esa.int/Enabling_Support/Space_Transportation/Types_of_orbits#LEO
[33] W. L. Stefanov and C. A. Evans, "The international space station: A unique platform for remote sensing of natural disasters," *ARES Biennial Report 2012 Final*, Jan. 2014. [Online]. Available: https://ntrs.nasa.gov/citations/20150003831
[34] K. H. Lee and S. W. Choi, "Interaction effect analysis of thruster plume on leo satellite surface using parallel dsmc method," *Computers & Fluids*, vol. 80, pp. 333–341, 2013.
[35] E. A. Angadh Nanjangud. [Online]. Available: https://www.angadhn.com/SpacecraftDynamics/orbital-mechanics/Lecture12/Lecture12.html
[36] K. Holste, P. Dietz, S. Scharmann, K. Keil, T. Henning, D. Zschätzsch, M. Reitemeyer, B. Nauschütt, F. Kiefer, F. Kunze *et al.*, "Ion thrusters for electric propulsion: Scientific issues developing a niche technology into a game changer," *Review of Scientific Instruments*, vol. 91, no. 6, 2020.
[37] [Online]. Available: https://www1.grc.nasa.gov/space/sep/gridded-ion-thrusters-next-c/
[38] M. Coletti, P. Gessini, and S. Gabriel, "A 4-gridded ion engine for high impulse mission," *Space Propulsion*, 2010.
[39] N. M. Uchizono, A. L. Collins, A. Thuppul, P. L. Wright, D. Q. Eckhardt, J. Ziemer, and R. E. Wirz, "Emission modes in electrospray thrusters operating with high conductivity ionic liquids," *Aerospace*, vol. 7, no. 10, p. 141, 2020.
[40] Sep. 2023. [Online]. Available: https://www.nasa.gov/directorates/somd/space-communications-navigation-program/technology-readiness-levels/
[41] [Online]. Available: https://www.esa.int/Enabling_Support/Preparing_for_the_Future/Discovery_and_Preparation/End-of-life_disposal_of_satellites
[42] S. Foundation, "Space oversight and regulatory bodies," Mar 2023. [Online]. Available: https://www.spacefoundation.org/space_brief/space-oversight-regulatory-bodies/

Chapter A

Appendix

A.1 Python code on gravity gradient calculations

```
    import math

def calculate_station_radius(desired_acceleration, angular_velocity):
    """
    Calculate the radius of a rotating space station wheel.

    :param desired_acceleration: Desired centripetal acceleration in m/s^2
    :param angular_velocity: Angular velocity of the wheel in rad/s
    :return: Radius of the wheel in meters
    """
    radius = desired_acceleration / (angular_velocity ** 2)
    return radius

def calculate_angular_velocity(target_rpm):
    """
    Convert target_rpm from RPM to rad/s.

    :param target_rpm: target_rpm in RPM
    :return: Angular velocity in rad/s
    """
    return (target_rpm * 2 * math.pi) / 60

def calculate_tangential_acceleration(target_rpm, time_to_reach_rpm, radius):
    """
    Calculate the tangential acceleration required to reach a target RPM in
    a given time.

    :param target_rpm: Target target_rpm in RPM
    :param time_to_reach_rpm: Time to reach target RPM in seconds
    :param radius: Radius of the rotating wheel in meters
    :return: Tangential acceleration in m/s^2
    """
    target_angular_velocity = (target_rpm * 2 * math.pi) / 60

    angular_acceleration = target_angular_velocity / time_to_reach_rpm

    tangential_acceleration = angular_acceleration * radius
```

```
    return tangential_acceleration

def calculate_final_velocity(target_rpm, radius):
    """
    Calculate the final tangential velocity at the edge of the wheel.

    :param target_rpm: Target target_rpm in RPM
    :param radius: Radius of the rotating wheel in meters
    :return: Final tangential velocity in m/s
    """
    angular_velocity = (target_rpm * 2 * math.pi) / 60
    return angular_velocity * radius

desired_acceleration = 9.7819  # m/s^2 (Earth's gravity)
target_rpm = 2  # RPM (typical comfortable target_rpm)
time_to_reach_rpm = 3600  # 1 hour = 3600 seconds
radius = 223  # Using the radius calculated in the previous example

angular_velocity = calculate_angular_velocity(target_rpm)

radius = calculate_station_radius(desired_acceleration, angular_velocity)

acceleration =
calculate_tangential_acceleration(target_rpm, time_to_reach_rpm, radius)

final_velocity = calculate_final_velocity(target_rpm, radius)

print('Calculate for different target_rpms')
for rpm in [1, 2]:
    angular_vel = calculate_angular_velocity(rpm)
    rad = calculate_station_radius(desired_acceleration, angular_vel)
    print(f"\nAt {rpm} RPM and a desired centripetal acceleration of
    {desired_acceleration} m/s^2:")
    print(f"Radius: {rad:.2f} m, Diameter: {2*rad:.2f} m")
    print(f"Angular velocity: {angular_vel:.4f} rad/s")

print(f"\nCalculate for different time periods to reach target_rpm of
{target_rpm} RPM")
for hours in [1, 2]:
    time_seconds = hours * 3600
    acc =
    calculate_tangential_acceleration(target_rpm, time_seconds, radius)
    print(f"\nFor {hours} hour to target_rpm of
    {target_rpm} RPM + Radius of {radius:.2f}m:{'s' if hours > 1 else ''}:")
```

```
    print(f"Tangential acceleration: {acc:.4f} m/s^2")
    print(f"Final tangential velocity at the edge: {final_velocity:.2f} m/s")

print(f"Plot for gravity gradient at {target_rpm} RPM generating 1 G with
the outer diameter being {radius:.2f} m")

import numpy as np
import matplotlib.pyplot as plt

def calculate_centripetal_acceleration(angular_velocity, radius):
    """
    Calculate centripetal acceleration.

    :param angular_velocity: Angular velocity in rad/s
    :param radius: Distance from center of rotation in meters
    :return: Centripetal acceleration in m/s^2
    """
    return angular_velocity**2 * radius

def rpm_to_angular_velocity(rpm):
    """
    Convert RPM to angular velocity in rad/s.

    :param rpm: Rotation rate in RPM
    :return: Angular velocity in rad/s
    """
    return rpm * 2 * np.pi / 60

station_radius = 223  # meters (from previous example)
rotation_rate = 2  # RPM

angular_velocity = rpm_to_angular_velocity(rotation_rate)

distances = np.linspace(0, station_radius, 1000)

accelerations =
calculate_centripetal_acceleration(angular_velocity, distances)


plt.figure(figsize=(12, 8))
plt.plot(distances, accelerations, color='blue', linestyle=':',
label=f"Gravity gradient: {accelerations[-1]/distances[-1]:.5f}")
plt.title(f"Centripetal Acceleration vs Distance from Center
\n(Rotation Rate: {rotation_rate} RPM)")
plt.xlabel("Distance from Center (m)")
```

```
plt.ylabel("Centripetal Acceleration (m/s²)")
plt.grid(True)

plt.axhline(y=9.81, color='m', linestyle='--', label='Earth
gravity (9.81 m/s²)')

mh = radius - 16
plt.axvline(x=223, color='g', linestyle='--', label = f'Station
Edge Radius (223 m), g = {accelerations[-1]:.2f}')

plt.axvline(x=mh, color='r', linestyle='--', label = f'Module
Height (207 m), g = 9.10')

th = mh - 20
plt.axvline(x=th, color='g', linestyle='--')

Or = th - 5
plt.axvline(x=Or, color='r', linestyle='--')

plt.axvline(x= Or - 2.5, color='g', linestyle='--')
plt.axvline(x= Or - 7.5, color='r', linestyle='--')


plt.axvline(x=152, color='g', linestyle='--')
plt.axvline(x=142, color='r', linestyle='--')

plt.annotate('Station Edge', xy=(station_radius,
accelerations[-1]), xytext=(station_radius-50, accelerations[-1]+1),
             arrowprops=dict(facecolor='black', shrink=0.05))

plt.annotate('Earth Gravity', xy=(0, 9.81), xytext=(-30, 10.5),
             arrowprops=dict(facecolor='red', shrink=0.05))

plt.annotate(
    "",
    xy=(223.64, 0.5),
    xytext=(207.64, 0.5),  # The start point of the arrow
    (text position)
    arrowprops=dict(
        arrowstyle="<->",
        color="black",
        lw=1  # Line width
    ),
    color="black",
    fontsize=8,
```

```
    ha='center',
    va='center',
)

plt.text(
    215.64,
    2.4,
    "Module Height",
    color="black",
    fontsize=12,
    ha='center',
    va='center',
    rotation=90
)

plt.annotate(
    "",
    xy=(187.64, 0.5),
    xytext=(182.64, 0.5),
    arrowprops=dict(
        arrowstyle="<->",
        color="black",
        lw=1  # Line width
    ),
    color="black",
    fontsize=8,
    ha='center',
    va='center',
)

plt.text(
    185.14,
    3.4,
    "Outer Rotating Ring Height",
    color="black",
    fontsize=12,
    ha='center',
    va='center',
    rotation=90
)

plt.annotate(
    "",
    xy=(180.64, 0.5),
    xytext=(174.64, 0.5),
```

```
    arrowprops=dict(
        arrowstyle="<->",
        color="black",
        lw=1  # Line width
    ),
    color="black",
    fontsize=8,
    ha='center',
    va='center',
)

plt.text(
    177.64,
    3.4,
    "Middle Stationary Ring Height",
    color="black",
    fontsize=12,
    ha='center',
    va='center',
    rotation=90
)

plt.annotate(
    "",
    xy=(152.64, 0.5),
    xytext=(142, 0.5),
    arrowprops=dict(
        arrowstyle="<->",
        color="black",
        lw=1  # Line width
    ),
    color="black",
    fontsize=8,
    ha='center',
    va='center',
)

# Add the text on top of the arrow
plt.text(
    147.64,
    3.4,
    "Inner Stationary Ring Height",
    color="black",
    fontsize=12,
    ha='center',
```

```
    va='center',
    rotation=90
)

print(f"Acceleration at station edge: {accelerations[-1]:.2f} m/s²")
print(f"Distance for Earth-like gravity:
{np.interp(9.81, accelerations, distances):.2f} m")
print("Gravity gradient:", 9.81/radius)

plt.legend()

plt.tight_layout()
plt.show()
```

A.2 Excel table of data used in chapter 3

FIGURE A.1. Excel data used in chapter 3

Property	Value	Unit
1G Gravity on Nexus	9.7800	m/s^2
0.035G Gravity on Nexus	0.3423	m/s^2
Lowest possible station rim speed	6.0000	m/s
Minimum rim speed for Nexus (@ R = 223 m)	8.7360	m/s

Figure A.2. Excel data used in chapter 3

	1G values		0.035G values		6 m/s rim speed	min rim speed
(rpm)	Rotational Radius (m)	Tangential Velocity (m/s)	Rotational Radius (m)	Tangential Velocity (m/s)	Rotational Radius (m)	Rotational Radius (m)
0.1	89182.91	933.92	3121.40	32.69	572.96	834.23
0.2	22295.73	466.96	780.35	16.34	286.48	417.11
0.3	9909.21	311.31	346.82	10.90	190.99	278.08
0.4	5573.93	233.48	195.09	8.17	143.24	208.56
0.5	3567.32	186.78	124.86	6.54	114.59	166.85
0.6	2477.30	155.65	86.71	5.45	95.49	139.04
0.7	1820.06	133.42	63.70	4.67	81.85	119.18
0.8	1393.48	116.74	48.77	4.09	71.62	104.28
0.9	1101.02	103.77	38.54	3.63	63.66	92.69
1	891.83	93.39	31.21	3.27	57.30	83.42
1.1	737.05	84.90	25.80	2.97	52.09	75.84
1.2	619.33	77.83	21.68	2.72	47.75	69.52
1.3	527.71	71.84	18.47	2.51	44.07	64.17
1.4	455.01	66.71	15.93	2.33	40.93	59.59
1.5	396.37	62.26	13.87	2.18	38.20	55.62
1.6	348.37	58.37	12.19	2.04	35.81	52.14
1.7	308.59	54.94	10.80	1.92	33.70	49.07
1.8	275.26	51.88	9.63	1.82	31.83	46.35
1.9	247.04	49.15	8.65	1.72	30.16	43.91
2	222.96	46.70	7.80	1.63	28.65	41.71
2.1	202.23	44.47	7.08	1.56	27.28	39.73
2.2	184.26	42.45	6.45	1.49	26.04	37.92
2.3	168.59	40.61	5.90	1.42	24.91	36.27
2.4	154.83	38.91	5.42	1.36	23.87	34.76
2.5	142.69	37.36	4.99	1.31	22.92	33.37
2.6	131.93	35.92	4.62	1.26	22.04	32.09
2.7	122.34	34.59	4.28	1.21	21.22	30.90

A.3 Python code on orbit simulation

```
    import numpy as np
from scipy.integrate import solve_ivp
from math import pi, sin, cos, sqrt, acos, asin, tan, atan
import matplotlib.pyplot as plotter
from mpl_toolkits.mplot3d import Axes3D
from matplotlib.patches import Patch

def twobody_dynamics_first_order_EoMs(t, states, mu, r_earth):
    r[0], r[1], r[2], v[0], v[1], v[2] = states
    r_x_dot = v[0]
    r_y_dot = v[1]
    r_z_dot = v[2]
    v_x_dot = (-mu/(np.linalg.norm(r))**3)*r[0]
    v_y_dot = (-mu/(np.linalg.norm(r))**3)*r[1]
    v_z_dot = (-mu/(np.linalg.norm(r))**3)*r[2]
    return (r_x_dot, r_y_dot, r_z_dot, v_x_dot, v_y_dot, v_z_dot)


def coe_to_rv(a, e, i, raan, arg_periapsis, true_anomaly, mu):
    # Step 1: Compute the distance (radius)
    p = a * (1 - e**2)
    r = p / (1 + e * np.cos(true_anomaly))

    r_pqw = np.array([
        r * np.cos(true_anomaly),
        r * np.sin(true_anomaly),
        0
    ])

    v_pqw = np.array([
        -np.sqrt(mu/p) * np.sin(true_anomaly),
        np.sqrt(mu/p) * (e + np.cos(true_anomaly)),
        0
    ])

    cos_raan, sin_raan = np.cos(raan), np.sin(raan)
    cos_i, sin_i = np.cos(i), np.sin(i)
    cos_argp, sin_argp = np.cos(arg_periapsis), np.sin(arg_periapsis)

    R = np.array([
        [
            cos_raan * cos_argp - sin_raan * sin_argp * cos_i,
            -cos_raan * sin_argp - sin_raan * cos_argp * cos_i,
```

```
            sin_raan * sin_i
        ],
        [
            sin_raan * cos_argp + cos_raan * sin_argp * cos_i,
            -sin_raan * sin_argp + cos_raan * cos_argp * cos_i,
            -cos_raan * sin_i
        ],
        [
            sin_argp * sin_i,
            cos_argp * sin_i,
            cos_i
        ]
    ])

    r_vec = R @ r_pqw
    v_vec = R @ v_pqw

    return r_vec, v_vec



import math
mu = 3.986*10**5 * 3600**2 #km^3/hour^2 (convert by multiplying by 3600^2)
r_earth = 6378.14 #km

constants = (mu, r_earth)

a = 6789          # km
e = 0.001
i = np.radians(51.64)
raan = np.radians(209)
arg_periapsis = np.radians(67)
true_anomaly = np.radians(0)

r, v = coe_to_rv(a, e, i, raan, arg_periapsis, true_anomaly, mu)

print("Position vector (km):", r)
print("Velocity vector (km/s):", v)

X = np.array([r[0], r[1], r[2], v[0], v[1], v[2]])

dp = 8640
start_time = 0.0
simulation_end_time = 24 #one day in hrs
t_span = (start_time, simulation_end_time)
```

```
t_eval = np.linspace(start_time, simulation_end_time, dp)

initial_conditions = X

numerical_solution_to_differential_equations =
solve_ivp(twobody_dynamics_first_order_EoMs, t_span,
initial_conditions, t_eval=t_eval, args=constants,
rtol = 1e-12, atol = 1e-12)
#units: t,r,v = hr, km, km/hr


time_values = numerical_solution_to_differential_equations.t

r_x_components = numerical_solution_to_differential_equations.y[0, :]
r_y_components = numerical_solution_to_differential_equations.y[1, :]
r_z_components = numerical_solution_to_differential_equations.y[2, :]

position_vector_absolute_values = (r_x_components**2 + r_y_components**2
+ r_z_components**2)**0.5

plotter.plot(time_values, position_vector_absolute_values, 'r', label='r(t)')
plotter.legend(loc='best')
plotter.xlabel('T (hours)', fontsize = 15)
plotter.ylabel('R (km)', fontsize = 15)
plotter.title('Station orbital radius variation in 24 hours', fontsize = 15)
plotter.grid()
plotter.show()

time_values = numerical_solution_to_differential_equations.t

v_x_components = numerical_solution_to_differential_equations.y[3, :]
v_y_components = numerical_solution_to_differential_equations.y[4, :]
v_z_components = numerical_solution_to_differential_equations.y[5, :]

velocity_vector_absolute_values = (v_x_components**2 + v_y_components**2
+ v_z_components**2)**0.5

plotter.plot(time_values, velocity_vector_absolute_values/3600, 'c', label=r'v(t)') #vel
plotter.legend(loc='best')
plotter.xlabel('t (hours)', fontsize = 15)
plotter.ylabel(r'r ($kms^{-1}$)', fontsize = 15)
plotter.title('Station velocity magnitude variation in 24 hours',
fontsize = 15)
plotter.grid()
plotter.show()
```

```
fig = plotter.figure(figsize=(25,15))
ax = fig.add_subplot(projection='3d')

u = np.linspace(0, 2 * np.pi, 300)  # was 100
v = np.linspace(0, np.pi, 300)      # was 100

x_e = r_earth * np.outer(np.cos(u), np.sin(v))
y_e = r_earth * np.outer(np.sin(u), np.sin(v))
z_e = r_earth * np.outer(np.ones(np.size(u)), np.cos(v))

ax.plot_surface(x_e, y_e, z_e, color='royalblue', alpha=0.6,
edgecolor='k', linewidth=0.1)

ax.set_aspect('equal')

ax.plot(r_x_components, r_y_components, r_z_components, 'R')


ax.set_xlabel(r'$R_{x}$ (Km)', fontsize = 15)
ax.set_ylabel(r'$R_{y}$ (Km)', fontsize = 15)
ax.set_zlabel(r'$R_{z}$ (Km)', fontsize = 15)

ax.set_xlim(-8000, 8000)
ax.set_ylim(-8000, 8000)
ax.set_zlim(-8000, 8000)

earth_legend = Patch(color='royalblue', label='Earth')

orbit_line, = ax.plot(r_x_components, r_y_components, r_z_components,
label='Nexus Orbit', color='orange')
ax.legend(handles=[earth_legend, orbit_line], loc='upper left')

plotter.title('Trajectory of Satellite in orbit of Earth')
plotter.show()
```