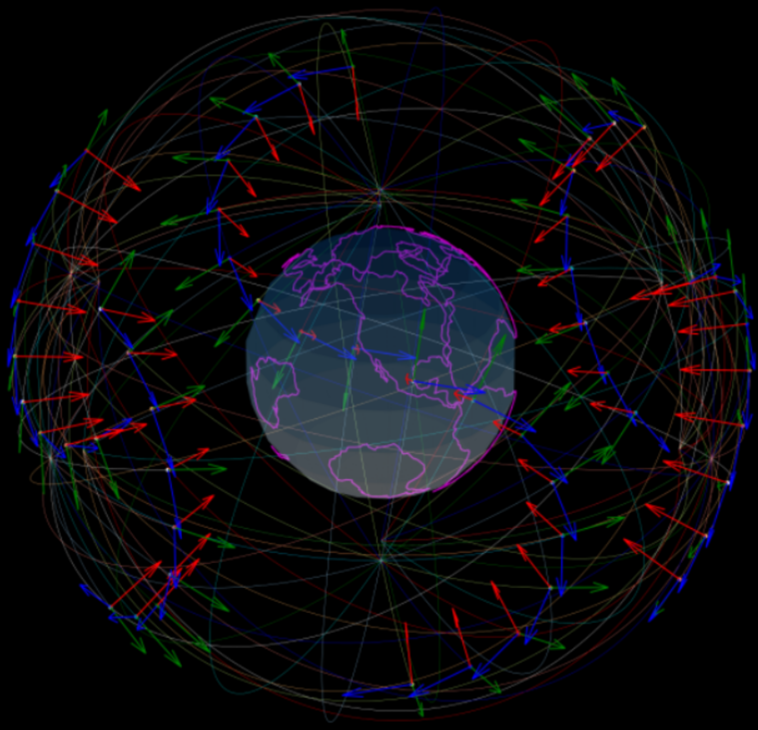
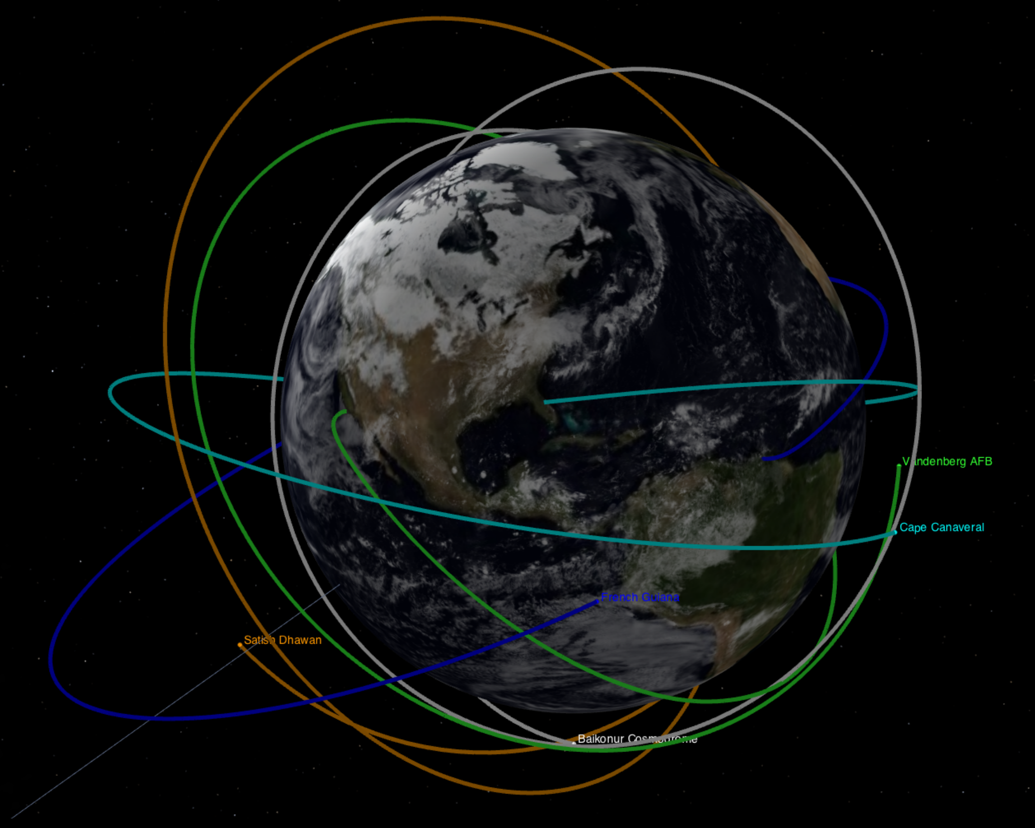
Astrodynamics with Python

Alfonso Gonzalez





To: Mom (Veronica), Dad (Carl), Brother (Alberto) and all past, present, and future humans of Earth, Earth's Moon, Mars, and Beyond. Original writing began in year 2021.

Contents

1 Preface

The Astrodynamics with Python book, YouTube videos, and GitHub repository are all products of the simple belief that all information should be free to anyone with access to the internet. They are collectively my attempt at providing useful information to the world.

Also because of that belief, if you'd like to help me by translating this project to your native language, don't hesitate to contact me at: spaceengineeringpodcast@gmail.com

This book is unlike other books, given that (for now) it is solely electronic, is being released as its being written (chapter by chapter), and will be a very iterative process (hence why it is being version controlled via Git). This is for multiple reasons:

- Free to anyone with access to the internet
- Easy to publish (git push, merge to main)
- This is a collaboration with other engineers who contribute by translating
- This is a collaboration with readers (you)
  - If you see a mistake or are confused by an explanation, reach out via email or open up Git Issue, so that when the book is updated, your Git Issue will be attached to the fix/improvement git commit, thus you will have directly contributed to this project!
  - This applies to the book as well as the software in this repository.

Now lets get to the technical work.

2 Chapters and Material

The following are general guidelines of how this book will be written:

- Visuals and software will be at the center of every explanation / derivation
  - In general, I don't consider myself to truly understand a problem until I can solve it on paper **AND** implement it in software.

The current plan is to separate the book by the following topics:

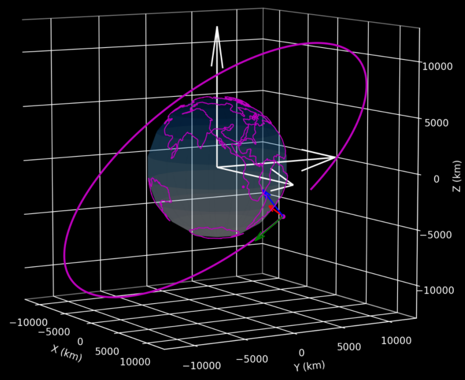
- Orbital Mechanics
- Rocket Trajectories
- Numerical Methods
- Spacecraft Attitude Control
- Trajectory Optimization / Optimal Control
- SPICE
- Prerequisites

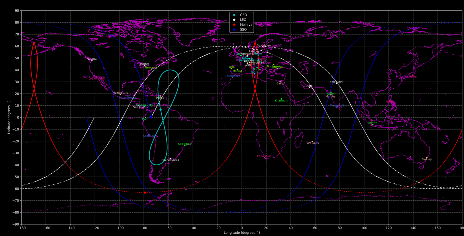
The book, videos, and software will all be complementing each other, and will be continuously updated as needed / requested from the readers.

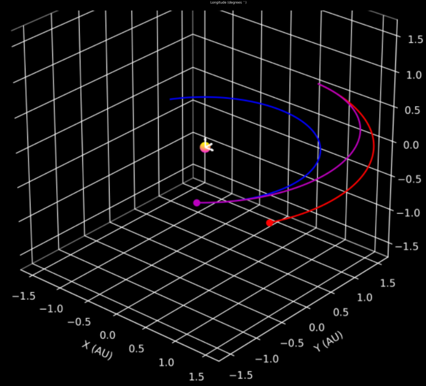
2.1 Orbital Mechanics

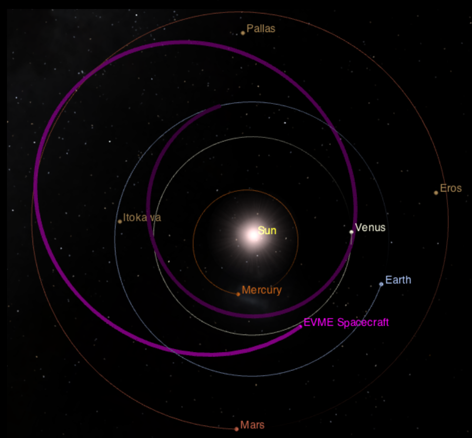
This section of the book will be organized in the same order as the Fundamentals of Orbital Mechanics video series (link to YouTube playlist)
The following are the planned topics:

- The two-body problem / Newton's universal law of gravitation (link)
- Ordinary differential equations (ODEs) (link)
- Introduction to ODE solvers (Runge-Kutta 4) (link)
- Solving 2nd Order ODEs with 1st Order ODE Solvers / Propagating Orbits (link)
- Introduction to the Keplerian / Classical Orbital Elements
- How to Identify Keplerian Orbital Elements in 3D Orbit Plots
- Earth Inertial and Body Fixed Reference Frames
- Introduction to SPICE (Spacecraft Planet Instrument C-matrix Events)
- Converting between Earth Centered Inertial (EME2000) and Earth Centered Earth Fixed (IAU EARTH) Frames
- Groundtracks calculations
- How to Identify Keplerian Orbital Elements in Groundtracks Plots
- Two-Line Element Sets (TLEs)
- Hohmann Transfers
- Introduction to Lambert's Problem
- Universal Variables Lambert's Solver
- Interplanetary Trajectories (Synodic Periods, Earth to Mars, Earth to Jupiter, etc.)
- Porkchop Plots
- Sphere of Influence
- Patched Conics
- Gravity Assist Trajectory Design (Zero-Sphere of Influence V-Infinity Matching) (link)
- Circular Restricted 3 Body Problem (CR3BP), (Lagrange Points, Invariant Manifolds, Earth-Moon Trajectories, etc.)
- Orbital Perturbations (J2, N-body, SRP, Higher Order Spherical Harmonics)
- Orbit Determination





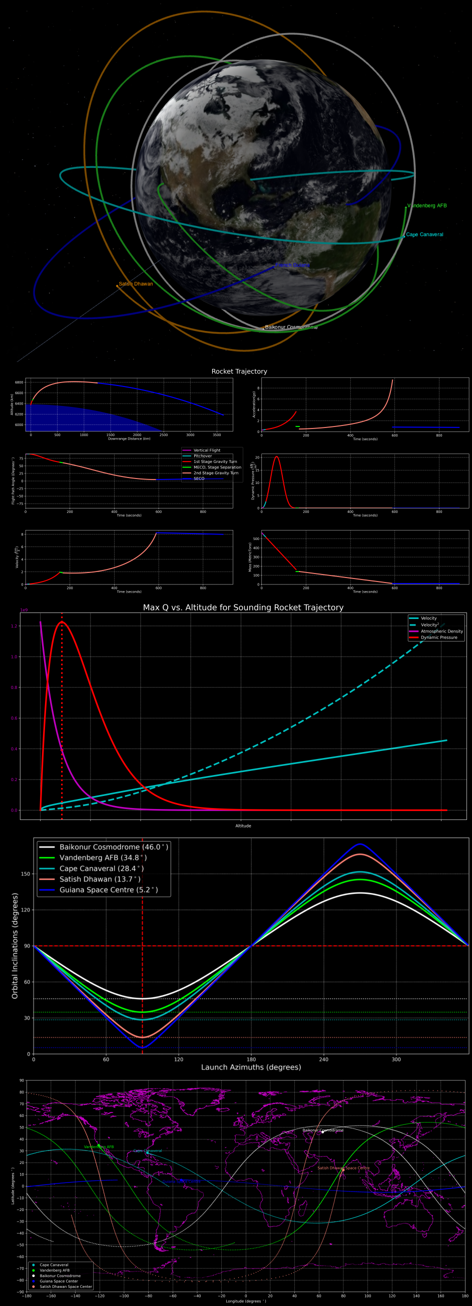




2.2 Rocket Trajectories

This section of the book will be organized in the same order as the Rocket Trajectories video series (link to YouTube playlist)
The following are the planned topics:

- Ideal Rocket Equation Derivation, Definition of Specific Impulse (link)
- Sounding Rocket Trajectories (1D motion) (link)
- Maximum Dynamic Pressure and Aerodynamic Drag (link)
- Gravity Turn Rocket Trajectories (2D motion) (link)
- Thrust Throttling to Reduce Maximum Dynamic Pressure
- Introduction to Rocket Trajectories in 3D (link)
- Relationship Between Launch Site Latitude, Target Orbital Inclination, and Launch Azimuth Vector
- Targeting Orbital Inclination from Launch Sites Around the World
- Calculating Inertial Velocity Vector of Rocket on Launch Pad as a Function of Latitude / Longitude Coordinates
- Guidance Relative to IAU EARTH (Body Fixed Frame) vs. EME2000 (Inertial Frame)
- Targeting Orbital Eccentricity
- Targeting Right Ascension (Instantaneous Launch Windows)
- Targeting Specific Orbits (Geostationary Transfer Orbit (GTO), ISS Rendezvous, Sun-Synchronous, etc.)



2.3 Numerical Methods

This section as of now does not directly follow any video playlists, but videos will be made as this section gets written that corresponds to the material. For now though there is still a Numerical Methods with Python playlist.
Also, there are lots of topics in this playlist that will be pre-requisities to the other sections of this book, and will be referenced from those sections.
The following are the planned topics:

- Derivative Estimations by Finite Differences
- Single Variable Root Solving Methods (Newton, Secant)
- Principal Rotation Matrices (X,Y,Z Rotations)
- Active vs Passive Rotation Matrices (Transposes)
- Axes of Rotation
- Euler Angles (with Matrices)
- Quaternions
- Converting Between Axes of Rotation, Rotation Matrices, and Quaternions
- Inertial and Non-Inertial Reference Frames
- Jacobian Matrix
- Newton Root Solver Method for Multivariable Functions (uses Jacobian)
- Numerically Calculate Jacobian Matrix
- Partial Derivatives for Multivariable Functions
- Hessian Matrix
- Numerically Calculate Hessian Matrix
- Shooting Methods (Overlaps with Trajectory Optimization)

2.4 Spacecraft Attitude Control

This section as of now does not directly follow any video playlists, but videos will be made as this section gets written that corresponds to the material. For now though there is a video playlist with a bunch of example simulations: (link).
The following are the planned topics:

- Defining Reference Frames (Primary and Secondary Vectors)
- LVLH Frame (Nadir and Zenith)
- Calculate Target Attitudes from Spacecraft State Vector $(\vec{r}, \vec{v})$, (Inertial Frame, LVLH, Earth Pointing, Moon Pointing, Sun Pointing, etc.)
- Rigid Body Dynamics (Inertia Tensor)
- Euler's Equation for Angular Acceleration $\dot{\vec{\omega}}$
- Adding Attitude Quaternion and Angular Velocity to Spacecraft State Vector
- Torque Free Motion Simulations
- Intermediate Axis Rotation Dynamics (T-Handle Effect)
- Introduction to PID Control
- Integrating Attitude Control Laws to Spacecraft Class

2.5 Trajectory Optimization / Optimal Control

As of now, there are no videos specifically on the topic of Trajectory Optimization. So far, I've only gotten through simple multivariable unconstrained minimzation in the learning process of Optimal Control. The examples in this section will mostly be applied to Orbital Mechanics.
The following are the planned topics. Note that there are a lot of prerequisites to this section in the Numerical Methods section.

- Newton Method for Single Variable Minimization (also with Derivative Estimations via Finite Differences)
- Newton Method for Multivariable Minimizations (also with Jacobian Estimations via Finite Differences)
- Unconstrained Optimization
- Constrained Optimization (Equality and Inequality)
- Quadratic Programming
- Nonlinear Programming
- Optimal Control
- Brachistochrone
- Bang-Bang Control
- Examples (2 Burn Orbit Transfers, Low Thrust Orbit Transfers, Attitude Control, Lunar Swingby Trajectories, Aero-Assisted Orbit Transfer)

Check out "Practical Methods for Optimal Control Using Nonlinear Programming" by John T. Betts.

2.6 Prerequisites

This section will be left open to any requests from the readers (you) that don't exactly fit into any of the other sections. Topics like what are vectors, derivatives, integrals, derivatives of vectors ($\vec{a} = \frac{d^2\vec{r}}{dt^2} = \frac{d\vec{v}}{dt}$), etc.