Design Project Uranus

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“A human being born at one of Uranus's poles would be a middle-aged man at sunset and a very old man before it was time for a second sunrise.”
— Isaac Asimov, The Relativity of Wrong

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Part 1 - Mission Details

a. ***Mission objective:***
   i. Utilizing a gravity assist off of Jupiter, deliver the Design Project Uranus and it's 502.9 kg payload into an elliptical orbit around Uranus within a 10 year transfer time.
      1. Target perigee: 200,420 km
      2. Target apoapsis: 601,620 km.
   ii. The scientific goal of this mission is to observe and gather data on Uranus and its 27 moons, in an effort to better understand the complexities and unsolved questions surrounding Uranus, and the possible origins to these features.

b. ***Spacecraft specs:***
   i. *Launch Vehicle:*
      1. Lower Stage: Atlas V (RD-180)
         a. Isp = 311.3 s
         b. Thrust: 3,827 kN
         c. m_f = 21,054 kg
         d. m_{FUEL} = 150,000 kg
         e. Length = 32.46 m
         f. Diameter = 3.81 m
      2. Upper Stage: SEC-III (RL10C-1)
         a. Isp = 450.5 s
         b. Thrust: 99.2 kN
         c. m_f = 2,245 kg
         d. m_{FUEL} = 10,212.1 kg
         e. Length = 11.7 m
         f. Diameter = 5.4 m
   ii. *Science payload:*
      1. Mass: 502.9 kg
      2. Instruments:
         a. 2 - CIA-grade Spy Telescopes
         b. Infrared Radiometer
         c. Ultraviolet Airglow Spectrometer
         d. Ultraviolet Occultation Spectrometer
         e. Magnetometer
         f. Charged Particle Telescope
         g. Plasma Analyzer
         h. High-Gain Antenna

Part 2 - Launch/Departure Details

a. ***Launch Site:***
   i. Location: Kennedy Space Center
   ii. Latitude: 28.5728722°
   iii. Longitude: -80.6489808°
   iv. Elevation: 3.00 m

b. ***JPL Horizons***
   i. Phasing angle: 97.4345°
      1. $J0$ = 2459334.5 days
   ii. 2-day launch window
      1. Open: JD_O = 2459333.5 days
      2. Close: JD_C = 2459335.5 days
      3. Effective Azimuth w.r.t. permissible range for the launch site
         a. IDL: 29 April 2021 / 2:00 - 2:30 PM UTC-4 DST

c. ***On IDL:* 29 April 2021 / 2:00 - 2:30 PM / UTC-4**

J_D	2459334.25 to 2459334.27083333 Days
T_D	0.213258042436687 to 0.213258612822272 Centuries
LS Sidereal Time: α_{LS}	7.01898837629° to 14.56005701416°
Mean Anomaly: θ	74.61365759547° to 74.63419093422°
Eccentric Anomaly	74.62873356298° to 74.64926434472°
Velocity Vector Declination: δv	-1.66163789962833° to -0.72627192653331°
Right Ascension: α_V	-43.396191289697° to -42.4553862536065°
Inertial Launch Azimuth:	45.4317428535927° to -20.991129855434°
Effective Azimuth: Az_{EFF}	44.8806172828433° to -21.7137392119138°

d. ***Launch trajectory***
   i. Launch Parameters
      1. *Az_{PO} = 108.2°*
      2. γ_{PO} = 84.621°
      3. Z_{PO} = 0.100 km
      4. T_{COAST} = 55 s
   ii. Parking orbit:
      1. V_{PARK} = 7.680 km/s
      2. $R_{P, LEO}$ = 380.0 km
   iii. Departure:
      1. Aiming Radius, Δ = 12,473.53 km

2. Direction of Periapsis, $\beta = 56.897°$
3. Assume inclination w.r.t Jupiter, $\iota \approx 0°$

Part 3 - Interplanetary Transfer Details

a. ***Arrival:***

i. Mean anomaly w.r.t Earth, $\theta = 146.775°$
ii. Phase angle, $\phi = 92.174°$
iii. Turn Angle, $\delta = 60.873°$
iv. $V_{ARR,\ HELIO}$ = 14.867 km/s
v. $V_{ARR,\ INF}$ = 1.811 km/s
vi. $V_{HYP,\ PER}$ = 11.915 km/s
vii. $R_{HYP,\ PER}$ = 913,490 km

b. ***Departure:***

i. Mean anomaly w.r.t Earth, $\theta = 207.648°$
ii. $V_{DEP,\ INF}$ = 1.811 km/s
iii. $V_{DEP,\ HELIO}$ = 15.693 km/s

Part 4 - Uranus Arrival Details

a. ***Arrival:***

i. $V_{INF,\ AR}$ = 2.257 km/s
ii. $V_{HYP,\ PER}$ = 19.303 km/s
iii. $R_{HYP,\ PER}$ = 31,560 km

b. ***Aerocapture:***

i. $R_{TARG,\ APO}$ = 601,620 km
ii. $V_{TARG,\ PER}$ = 18.680 km/s
iii. ΔV_{AERO} = 0.623 km/s

c. ***Final Burn (At target apoapsis)***

i. $R_{TARG,\ APO}$ = 601,620 km
ii. $R_{TARG,\ PER}$ = 200,420 km
iii. $V_{AERO,\ APO}$ = 0.980 km/s
iv. $V_{TARG,\ APO}$ = 2.195 km/s
v. ΔV = 1.215 km/s

Part 5 - *See next page.*

Part 5 - ∆V Requirements

#	Description	dV_{REAL} [km/s]	$dV_{FICTITIOUS}$ [km/s]	V_1 [km/s]	V_2 [km/s]	M_o [kg]	M_f [kg]	M_{FUEL} [kg]
1	Launch -> 150km	8.136	0.849 (drag+gra)	0	7.287	183,820	12,762	150,000
2	Coast -> LEO	0.393	------------	7.287	7.680	12,762	11,674	1,088
3	LEO -> Jupiter	5.242	-------------	7.680	12.922	11,674	3,621.2	8,252.8
4	Jupiter Fly-by	---------	0.826	14.867	15.693	---------	---------	------------
5	Uranus -> Aerobrake	---------	0.623	19.303	18.68	---------	---------	------------
6	Aerobrake -> Target	1.215	------------	.980	2.195	3621.2	2749.9	871.3
0	Total to Dest.	14.986	2.298	N/A	N/A	92,018	520.9	160,212.1

Part 6 - *See next page.*

Part 6 - Mission Summary

a. On April 30, 2021 / 18:20 UTC, an Atlas V rocket fitted with a single engine Centaur III upper stage will launch from Kennedy Space Center carrying 502.9kg of scientific payload to an elliptical target orbit around Uranus.
b. The Atlas V rocket will launch with a total wet mass of 183,816.2 kg, burning 150,000 kg of fuel to an altitude of ~150 km before MECO and separation of the Atlas V booster stage. Fifty-five seconds after MECO, SEC-III will ignite, burning prograde to transition from a hyperbolic trajectory to LEO.
c. Once SEC-III is at a parking orbit of 380 km and arrives at the injection point, SEC-III will fire prograde until the target hyperbolic trajectory and speed of 12.922 km/s is attained with respect to the Earth.
d. After departure from Earth, SEC-III will perform a gravity assist off of Jupiter's trailing edge at an altitude of 842,000km, gaining 0.826 dV in its heliocentric velocity.
e. We depart Jupiter on a hyperbolic trajectory to Uranus.
f. Upon arrival at Uranus, we pass through our hyperbolic perigee of 6,000km above Uranus' surface.
g. Flying into the atmosphere of Uranus induces an aerobraking effect and SEC-III receives 0.623 km/s of delta V. This reduction in velocity gives us our target apoapsis of 601,620 km.
h. Upon arrival to the target apoapsis, SEC-III makes one final prograde burn to reach a target perigee of 200,420 km. Once the target orbit is achieved, the SEC-III will detach from the payload, and the payload will continue to orbit around Uranus while collecting data from the planet and its moons.

Part 7 - Assumptions

a. Patched conics (neglect n-body mechanics)
b. Instantaneous impulses/maneuvers (burn-time = 0secs)
c. dV/Mass requirements are made assuming co-planar planets with circular orbits.
d. MATLAB codes used for calculations

Part 8 - Team member recognition

Team Member	Role
Matthieu H. Lu	Hyperbolic/Interplanetary parameter determination post-departure and pre-arrival
Darshan Sonawala	Arrival Phase and Aerobraking
Lance Kellerman	Launch Window and Geometry Determination
Derek M Waite	General chaos and confusion, mass budgeting, Jupiter Fly-by/Gravity Assist

References

[1] Inspiration for choice of payload
https://solarsystem.nasa.gov/missions/mariner-10/in-depth/

[2] Travel time of similar mission to Uranus
https://www.space.com/18709-uranus-distance.html

[3] Atmosphere Uranus
https://en.wikipedia.org/wiki/Atmosphere_of_Uranus

[4] Motivation for choice of target orbit around Uranus
https://www.britannica.com/place/Uranus-planet/Moons

[5] Motivation for exploration of ice giants
https://www.nasa.gov/feature/nasa-completes-study-of-future-ice-giant-mission-concepts

[6] Motivation for choice of Jupiter Fly-by altitude:
https://en.wikipedia.org/wiki/Voyager_2
https://en.wikipedia.org/wiki/New_Horizons

[7] SEC-III RL10C-1
https://en.wikipedia.org/wiki/Centaur_(rocket_stage)

[8] Atlas V RD-180
https://en.wikipedia.org/wiki/Atlas_V

[9] Figure 1: Astronomical Data for the Sun, the Planets, and the Moon

[10] Figure 2: Gravitational Parameter and SOI Radius for the Sun, the Planets, and the Moon

[11] Figure 3a - Atmosphere of Uranus
https://en.wikipedia.org/wiki/Atmosphere_of_Uranus#/media/File:Tropospheric_profile_Uranus_new.svg

[12] Figure 3b - Atmosphere of Uranus
https://en.wikipedia.org/wiki/Atmosphere_of_Uranus#/media/File:Uranian_stratosphere.png

[13] Figure 4 - dV map of Solar System
https://www.reddit.com/r/RealSolarSystem/comments/fq4ky5/slightly_upgraded_delta_v_map_of_the_solar_system/

[14] Figure 5a-c
MATLAB Code: Launch Trajectory - Credit: Marco Maggia

References Cont.

[15] Figure 6a-d
MATLAB Code: Gravity Assist - Credit: Marco Maggia

Appendix A - Matlab Code

A.1 - Gravity Assist (editable section only):

```
% MATLAB code for interplanetary transfer using one gravity assist
% maneuver. The following code does not account for planets phasing.
%
% Written by Marco Maggia, March 2016.

clc;clear;close all

%% %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%                             EDITABLE SECTION
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% (1) Set altitude of parking orbit (circular)
hc_parking = 380; % [km]

% (2) Set Planets: Planet_1-->flyby planet, Planet_2-->target planet
Planet_1 = 'Jupiter';
Planet_2 = 'Uranus';

% (3) Set flyby side
side = 'Trailing';

% (4) Set altitude flyby at Planet_1
if strcmp(Planet_1,'Jupiter')
    h_flyby = 842000; % [km]
    %default  22400000
end

% (5) Set periapsis and apoapsis radius for target orbit around Planet_2
if strcmp(Planet_2,'Uranus')
    rp_targ = 200420; % [km]
    ra_targ = 601620; % [km]
end
```

A.2 - Launch Trajectory (editable section only):

```
clc;clear
close all

%% (EDIT)
%~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
%  ROCKET parameters (ATLAS V - modified)
% gross weight of fully fueled Atlas V: 305,143 [kg]

mfuel = 150000; % Mass of fuel for Atlas V (variable)

mf = 21054; % Dry mass of AtlasV (fixed) [kg]
mpayload = 12762.16; % SEC-III+fuel for cirularization & mission +
%                      scientific payload [kg] (fixed)
m_wet    = mf+mfuel+mpayload;  %[kg]
m_dry    = mpayload;    %[kg]      Dry mass
d        = 3.8E-3;     %[km]      Rocket diameter
T        = 3827;     %[kN]
Isp      = 311.3;    %[s]

% Launch Parameters
Az_po    = 108.2;      %[deg]    Azimuth at pitchover (inertial)
gam_po   = 84.621 ;     %[deg]     FPA at pitchover
z_po     = 0.100;      %[km]    Altitude at pitchover


% Launch Window Data
alphLS = 10.789;
alphaV = -42.926;
D_Lam    = (alphLS-alphaV)/180*pi;
d_vinf   = -1.19396/180*pi; % Declination of v_inf

% Launch Site
phi_LS   =  28.57;  %[deg]    Launch site latitude
Lam_LS   = -80.65;  %[deg]    Launch site longitude
z_LS     =      3;  %[m]      Launch site altitude Actually correct for KSC

t_Coast  = 55;     %[s]      Coasting time after b/o, SpaceX launch was 14s
z_park   = 380;     %[km]     Parking orbit altitude

R_Planet  = 778.6E6; %[km]  Radius of Juipter's orbit from sun

% Show plots ('y'=yes;'n'=no)
plots='y';
```

A.3 - Launch Window Determination:

```matlab
clear, clc;
J0 = 2459334.5; %Value of J0 for 2021 - 04 - 30
e = 0.0167; % Eccentricity
ThetaEQ = 75.92305; % Degrees
Epsilon = 23.44; % Degrees
PhiLS = 28.5728722; % KSC launch site latitude, degrees
LamdaLS = -80.6489808; % KSC launch site longitude, degrees
VEquator = 0.460; % km/s
MuE = 398600; % km^3/s^2
rP = 380; % parking orbit radius, km
Vrot = VEquator*cos(PhiLS); % km/s
V = sqrt(MuE/rP); %km/s
% Part B: Theta_EQ = 75.92305 degrees at the vernal equinox of 2021/03/20
%                               at 9:37:00 UT
for n = 0:96
    i(n+1,:) = [n];
    % Part C:
    DeltaUT(n+1,:) = [-24+(n/2)];
    JD(n+1,:) = [J0+(DeltaUT(n+1,1)/24)];
    TD(n+1,:) = [(JD(n+1,1)-2451545)/36525];
    % Part D:
    aG(n+1,:) = [(100.4606184+(36000.77004*(TD(n+1,1)))+(0.000387933...
        *((TD(n+1,1))^2))-((2.583*(10^(-8)))*((TD(n+1,1))^3)))+...
        (360.98564724*(DeltaUT(n+1,1))/24)]; %Greenwich sidereal time
    aLS(n+1,:) = [(aG(n+1,1)+LamdaLS)];
    % Part E:
    Me(n+1,:) = [((100.464572+(35999.3725*TD(n+1,1)))-(102.937682+...
        (0.32327364*TD(n+1,1))))];
    E(n+1,:) = [Me(n+1,1)+(e*sind(Me(n+1,1)))+(((e^2)/2)*sind(2*Me...
        (n+1,1)))+(((e^3)/8)*((3*sind(3*Me(n+1,1)))-sind(Me(n+1,1))))];
    Theta(n+1,:) = [2*atand((sqrt((1+e)/(1-e)))*(tan(E(n+1,1)/2)))];
    UDeltav(n+1,:) = [atand(2*(((-sind(Epsilon)*sind(ThetaEQ)*...
        sind(Theta(n+1,1)))-((e+cosd(Theta(n+1,1)))*sind(Epsilon)*...
        cosd(ThetaEQ)))/(sqrt((((cosd(ThetaEQ)*sind(Theta(n+1,1)))-...
        ((e+cosd(Theta(n+1,1)))*sind(ThetaEQ))))^2)+(((-cosd(Epsilon)*...
        sind(ThetaEQ)*sind(Theta(n+1,1)))-((e+cosd(Theta(n+1,1)))*...
        cosd(Epsilon)*cosd(ThetaEQ)))^2))))]; % Uppercase delta v
    alphav(n+1,:) = [atand(2*(((-cosd(Epsilon)*sind(ThetaEQ)*...
        sind(Theta(n+1,1)))-((e+cosd(Theta(n+1,1)))*cosd(Theta(n+1,1))*...
        cosd(ThetaEQ)))/((cosd(ThetaEQ)*sind(Theta(n+1,1)))-((e+...
        cosd(Theta(n+1,1)))*sind(ThetaEQ)))))];
    % Part F:
    dLambda(n+1,:) = [aLS(n+1,1)-alphav(n+1,1)];
    Az(n+1,:) = [(cosd(UDeltav(n+1,1))*sind(dLambda(n+1,1)))/...
        ((-cosd(PhiLS)*sind(UDeltav(n+1,1)))+(sind(PhiLS)*...
        cosd(UDeltav(n+1,1))*cosd(dLambda(n+1,1))))];
    I(n+1,:) = [acosd(cosd(PhiLS)*sind(Az(n+1,1)))];
    Vrel(n+1,:) = [sqrt((V^2)+(Vrot^2)+(2*V*Vrot*sind(Az(n+1,1))))];
    AzEff(n+1,:) = [(Az(n+1,1)-acosd(sqrt(1-(((Vrot/Vrel(n+1,1))^2)*...
        ((cosd(Az(n+1,1)))^2)))))];
    M = [i, DeltaUT, JD, TD, aG, aLS, Me, E, Theta, UDeltav, alphav,...
        dLambda, I, Vrel, Az, AzEff]; % Matrix with all desired variables
    %                                         at each value of n
end
```

A.4a - Interplanetary 1of2:

```
clear
clc

%Variables: Sun
mu_S = 132712000000;

%Variables: Earth
mu_E = 398600;
r_E = 6371;
r_ES = 149.6E6;
T_ES = 365.256*24*60*60;
V_ES = sqrt(mu_S/r_ES);

%Variables: Jupiter
mu_J = 126686000;
r_J = 71490;
r_JS = 778.6E6;
T_JS = 11.86*365*24*60*60;
V_JS = sqrt(mu_S/r_JS)

%Variables: Uranus
mu_U = 5794000;
r_U = 25560;
r_US = 2.872E9;
T_US = 84.01*365*24*60*60;
r_U_p = 200420;
r_U_a = 3*r_U_p;
V_US = sqrt(mu_S/r_US);

%Gravity Assist
%Variables: Gravity Assist
DV1 = 5.242; %km/s
DV2 = 2.257; %km/s
DVtot = 7.499; %km/s
t = 10*365; %mission time in days

%Phasing Angle
Phi_0 = 180*(1-((r_ES + r_JS)/(2*r_JS))^1.5) %degrees

%Interplanetary Travel

%Hohmann Transfer (Earth to Jupiter)
r_Hohmann_p = r_ES; %periapses radius for Hohmann transfer
r_Hohmann_a = r_JS; %apoapses radius for Hohmann transfer
mu_Hohmann = mu_S;
a_Hohmann = (r_Hohmann_p + r_Hohmann_a)/2 %semimajor axis for Hohmann Transfer
En_Hohmann = -mu_Hohmann/(2*a_Hohmann) %Energy of Elliptical Orbit
V_SC_J = sqrt((En_Hohmann + (mu_Hohmann/r_Hohmann_a))*2) %V of SC at edge of Jupiter SOI (heliocentric RF)
V_SC_E = sqrt((En_Hohmann + (mu_Hohmann/r_Hohmann_p))*2) %V of SC at edge of Earth SOI (heliocentric RF)

%Departure
r_E_parking = 400+r_E; %parking orbit radius
V_Departure_circ = sqrt(mu_E/r_E_parking); %parking orbit velocity
V_Departure_hyp = V_Departure_circ + DV1; %hyperbolic orbit velocity @ perigee
```

A.4b - Interplanetary 2of2:

```
V_Departure_hyp = V_Departure_circ + DV1; %hyperbolic orbit velocity @ perigee
V_Departure_inf = V_SC_E - V_ES %V_inf for hyperbolic orbit departure
a_Departure_hyp = mu_E / (V_Departure_inf^2)
e_Departure_hyp = (r_E_parking / a_Departure_hyp) + 1 %eccentricity of hyperbolic orbit departure
ar_Departure_hyp = a_Departure_hyp*sqrt(e_Departure_hyp^2 - 1) %aiming radius for departure orbit
ta_Departure_hyp = 2*asind(1/e_Departure_hyp) %turning angle for departure orbit

%Arrival
r_U_capture = 240000;
a_Capture = (r_U_p + r_U_a)/2
En_Capture = -mu_U/(2*a_Capture) %Energy of capture orbit
V_Capture_ell_p = sqrt((En_Capture + (mu_U/r_U_p))*2)
V_Capture_ell_a = sqrt((En_Capture + (mu_U/r_U_a))*2)
V_Arrival_hyp_p = V_Capture_ell_p + DV2 %V @ hyperbolic perigee
%Fuel
%Rocket:
syms I_sp thrust m_0 real
% I_sp = ;
% thrust = ;
% m_0 = ;
m_f = 1500;
g_0 = 9.8/1000; %km/s^2
```

A.5 - Aerobraking:

```
% Assumption: One burn that needs to be done at the intended apoapsis radius.

mu_U = 5794000;
rP = 200420; %% Intended Periapsis Radius
rA = 3*rP; %% Intended Apoapsis Radius
a = 0.5*(rP + rA);
e = (rA - rP)/(rP + rA);
Energy_ell = -1*mu_U/(2*a);
vP = sqrt(2*(Energy_ell+(mu_U/rP)));
vA = sqrt(2*(Energy_ell+(mu_U/rA)));

rP_aero = 6000+25559; %Periapsis Radius of Aerobraking Orbit
a_aero = 0.5*(rA+rP_aero);
e_aero = (rA - rP_aero)/(rA+rP_aero);
Energy_aero = -mu_U/(2*a_aero);
vA_aero = sqrt(2*(Energy_aero+(mu_U/rA)));
delta_v_aero = abs(vA - vA_aero)
```

Appendix B - Tables and Figures

Figure 1: Table A.1 (from textbook: Orbital Mechanics for Engineering Students 3rd Edition)

Table A.1 Astronomical Data for the Sun, the Planets, and the Moon

Object	Radius (km)	Mass (kg)	Sidereal Rotation Period	Inclination of Equator to Orbit Plane	Semimajor Axis of Orbit (km)	Orbit Eccentricity	Inclination of Orbit to the Ecliptic Plane	Orbit Sidereal Period
Sun	696,000	1.989×10^{30}	25.38 d	7.25°	—	—	—	—
Mercury	2440	330.2×10^{21}	58.65 d	0.01°	57.91×10^{6}	0.2056	7.00°	87.97 d
Venus	6052	4.869×10^{24}	243 d*	177.4°	108.2×10^{6}	0.0067	3.39°	224.7 d
Earth	6378	5.974×10^{24}	23.9345 h	23.45°	149.6×10^{6}	0.0167	0.00°	365.256 d
(Moon)	1737	73.48×10^{21}	27.32 d	6.68°	384.4×10^{3}	0.0549	5.145°	27.322 d
Mars	3396	641.9×10^{21}	24.62 h	25.19°	227.9×10^{6}	0.0935	1.850°	1.881 y
Jupiter	71,490	1.899×10^{27}	9.925 h	3.13°	778.6×10^{6}	0.0489	1.304°	11.86 y
Saturn	60,270	568.5×10^{24}	10.66 h	26.73°	1.433×10^{9}	0.0565	2.485°	29.46 y
Uranus	25,560	86.83×10^{24}	17.24 h*	97.77°	2.872×10^{9}	0.0457	0.772°	84.01 y
Neptune	24,760	102.4×10^{24}	16.11 h	28.32°	4.495×10^{9}	0.0113	1.769	164.8 y
(Pluto)	1195	12.5×10^{21}	6.387 d*	122.5°	5.870×10^{9}	0.2444	17.16°	247.7 y

*Retrograde

Figure 2: Table A.2 (from textbook: Orbital Mechanics for Engineering Students 3rd Edition)

Table A.2 Gravitational Parameter (μ) and Sphere of Influence (SOI) Radius for the Sun, the Planets, and the Moon

Celestial Body	μ (km^3/s^2)	SOI Radius (km)
Sun	132,712,000,000	–
Mercury	22,030	112,000
Venus	324,900	616,000
Earth	398,600	925,000
Earth's moon	4903	66,100
Mars	42,828	577,000
Jupiter	126,686,000	48,200,000
Saturn	37,931,000	54,800,000
Uranus	5,794,000	51,800,000
Neptune	6,835,100	86,600,000
Pluto	830	3,080,000

Table A.3 Some Conversion Factors

1 ft	= 0.3048 m
1 mile (mi)	= 1.609 km
1 nautical mile (n mi)	=1.151 mi = 1.852 km
1 mi/h	= 0.0004469 km/s
1 lb (mass)	= 0.4536 kg
1 lb (force)	= 4.448 N
1 psi	= 6895 kPa
1 astronomical unit (AU)	= 149,597,870.700 km

Figure 3a: Atmosphere of Uranus

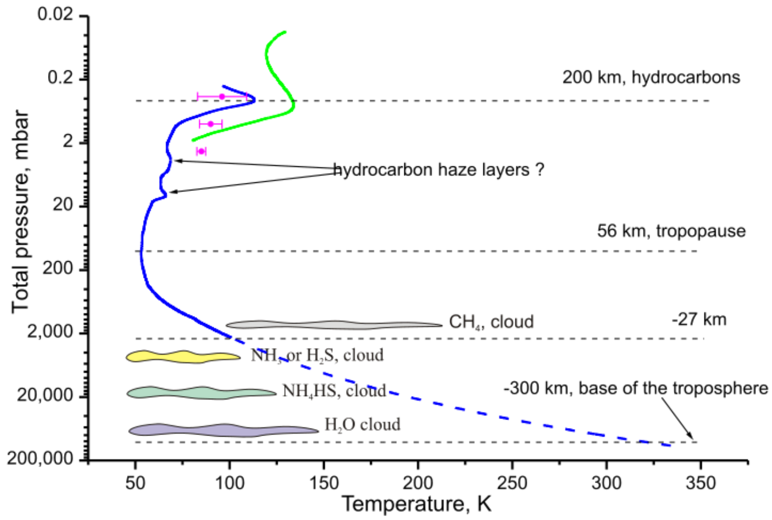


Figure 3b: Atmosphere of Uranus

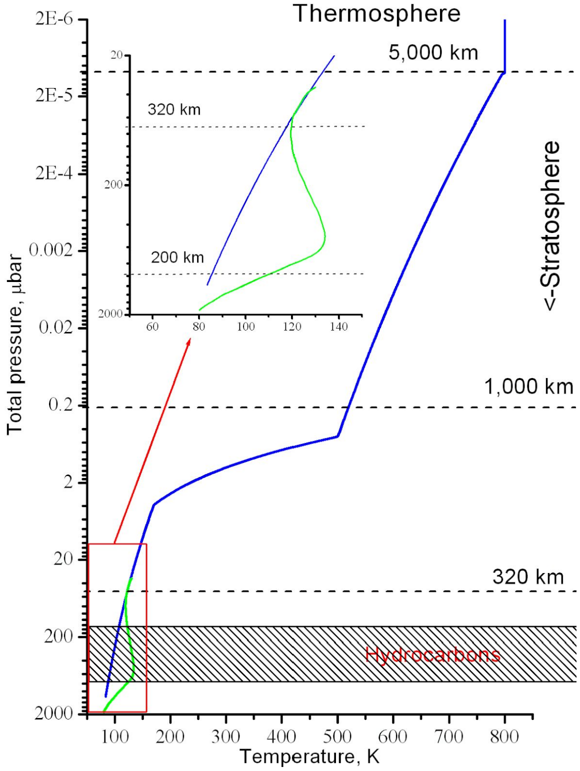


Figure 4: Minimum deltaV map of the solar system

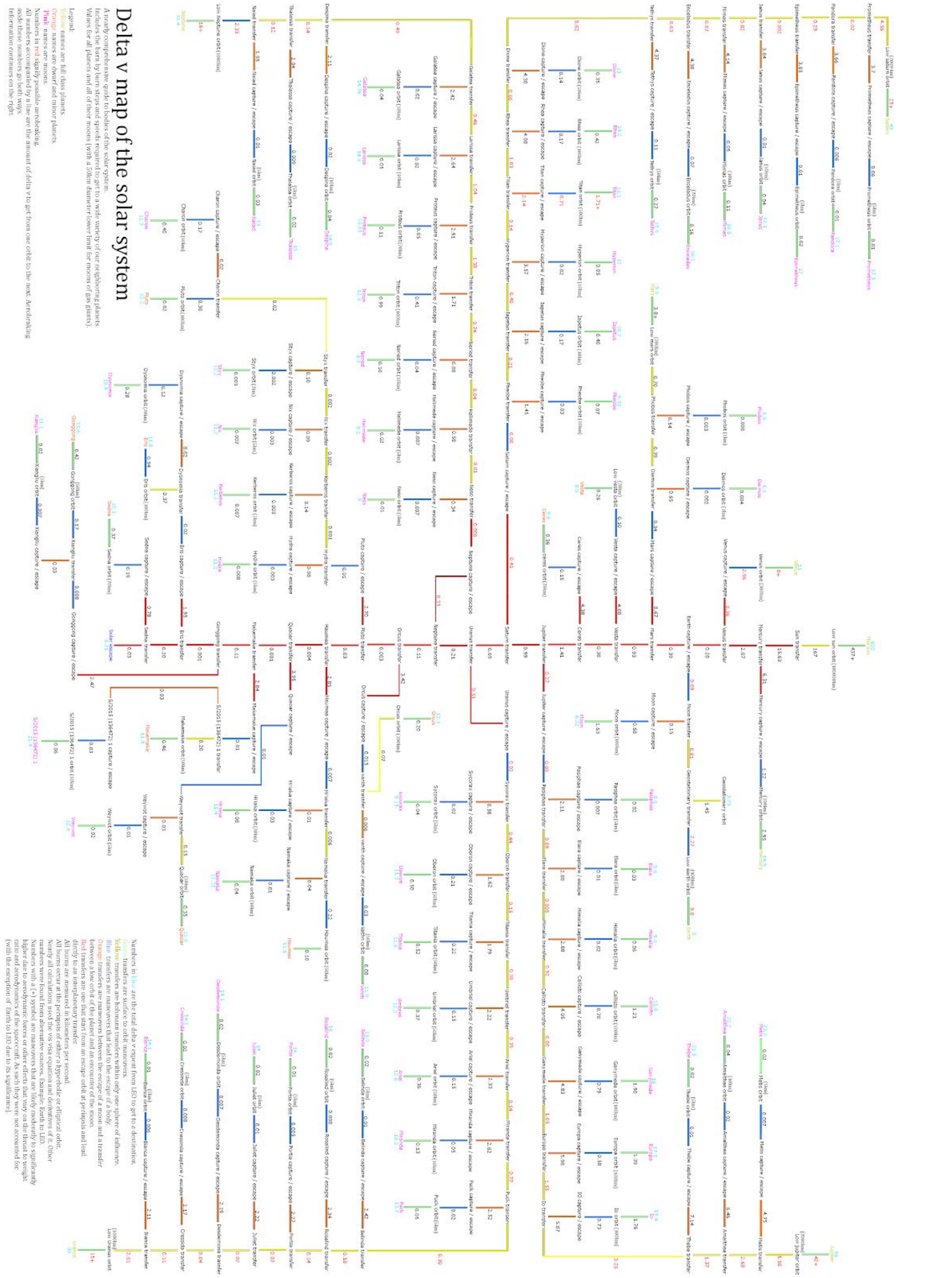


Figure 5a: Launch Trajectory

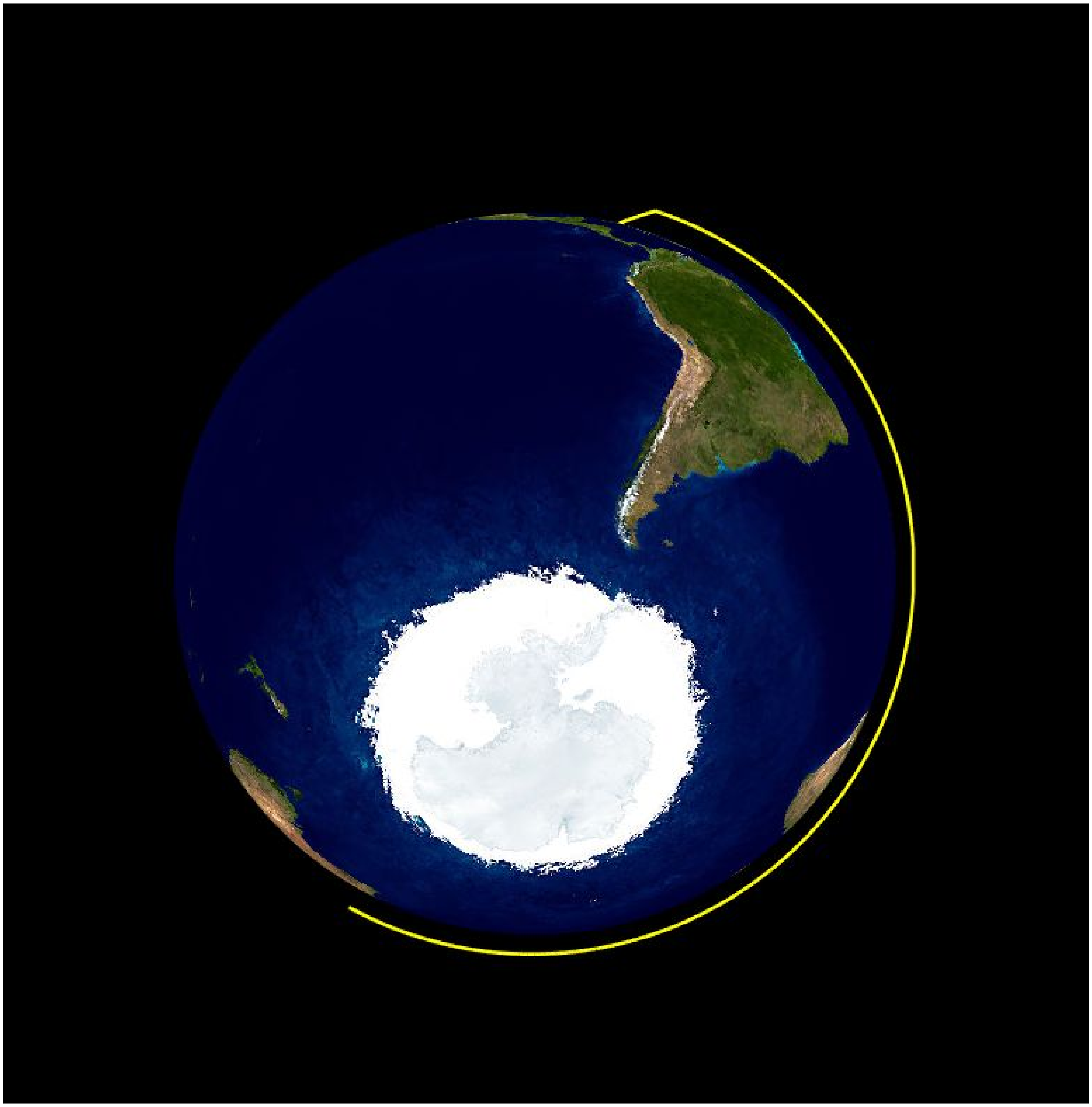


Figure 5b: Launch Trajectory

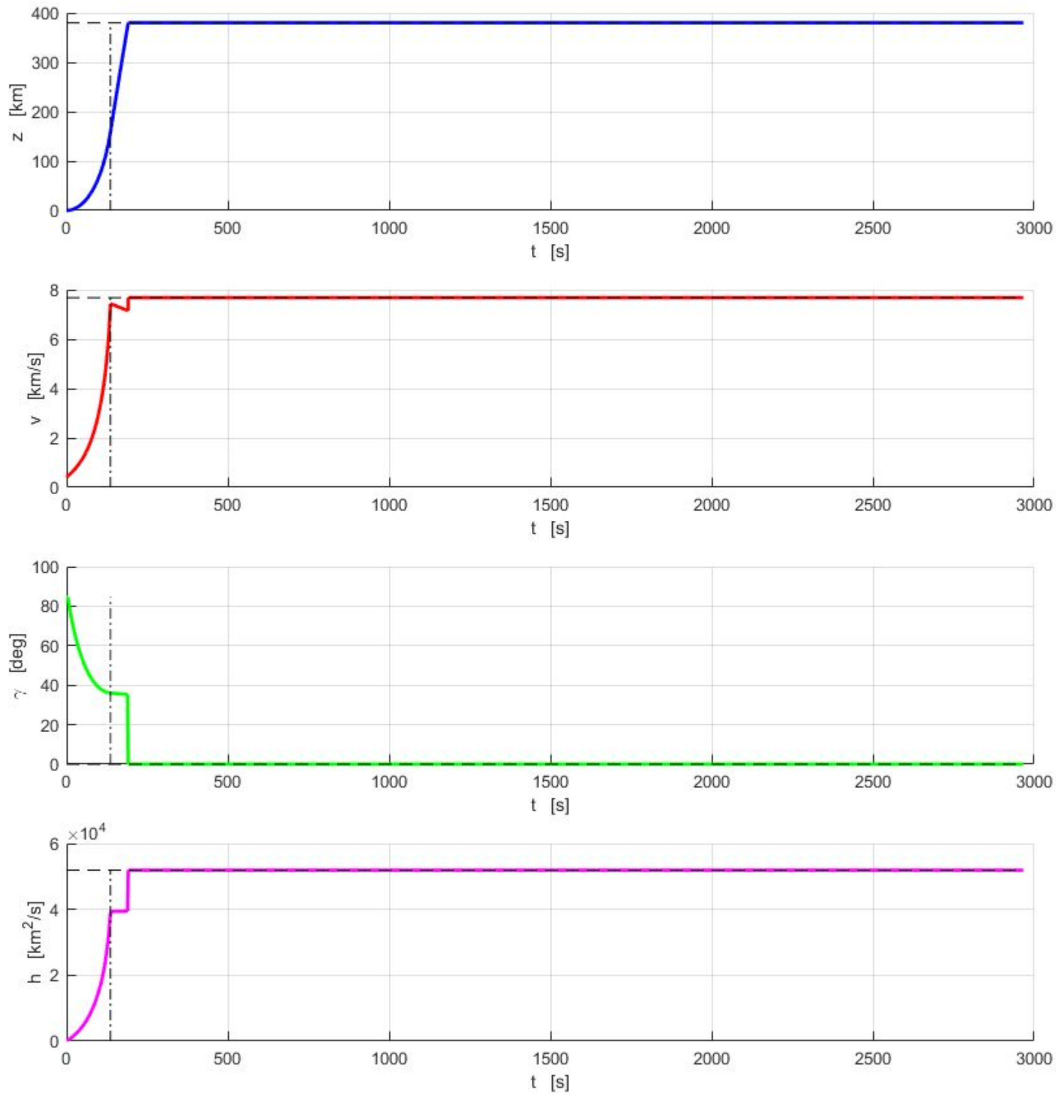


Figure 5c: Launch Trajectory

Figure 6a: Gravity Assist

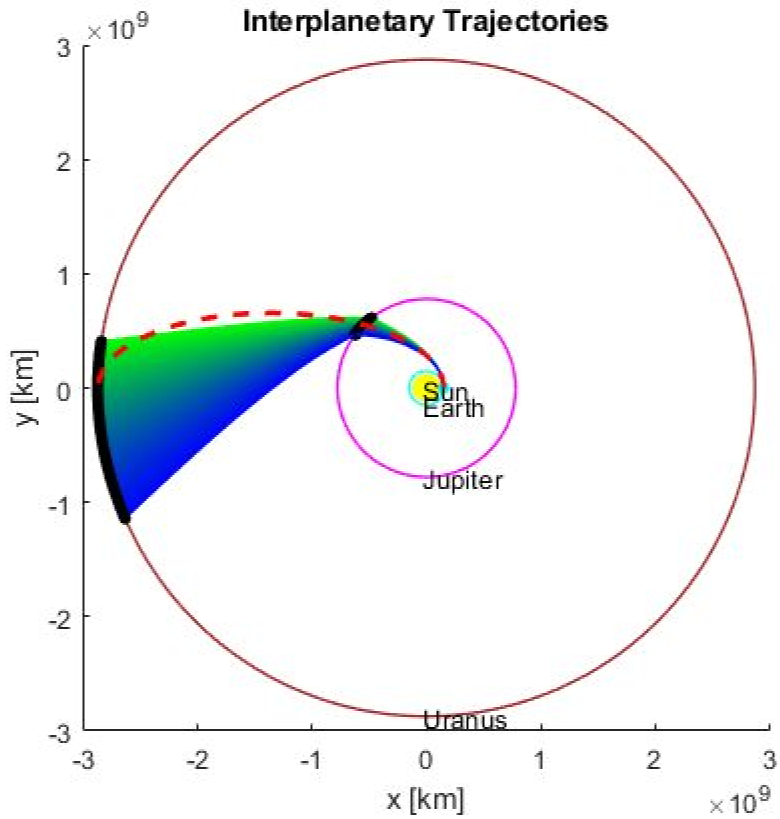


Figure 6b: Gravity Assist

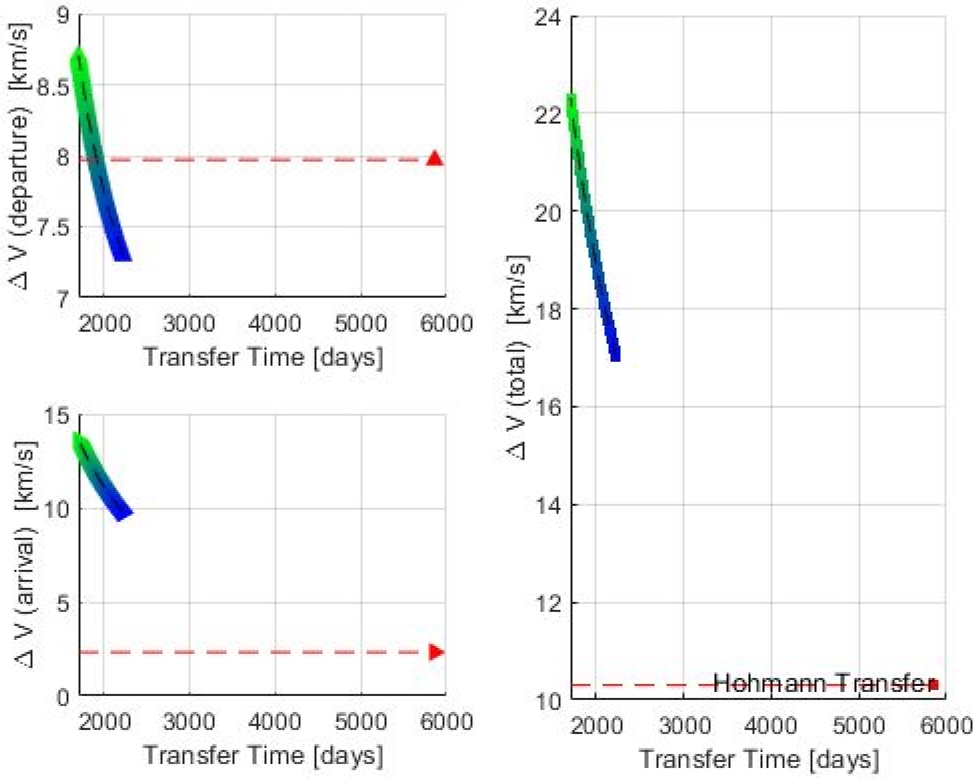


Figure 6c: Gravity Assist

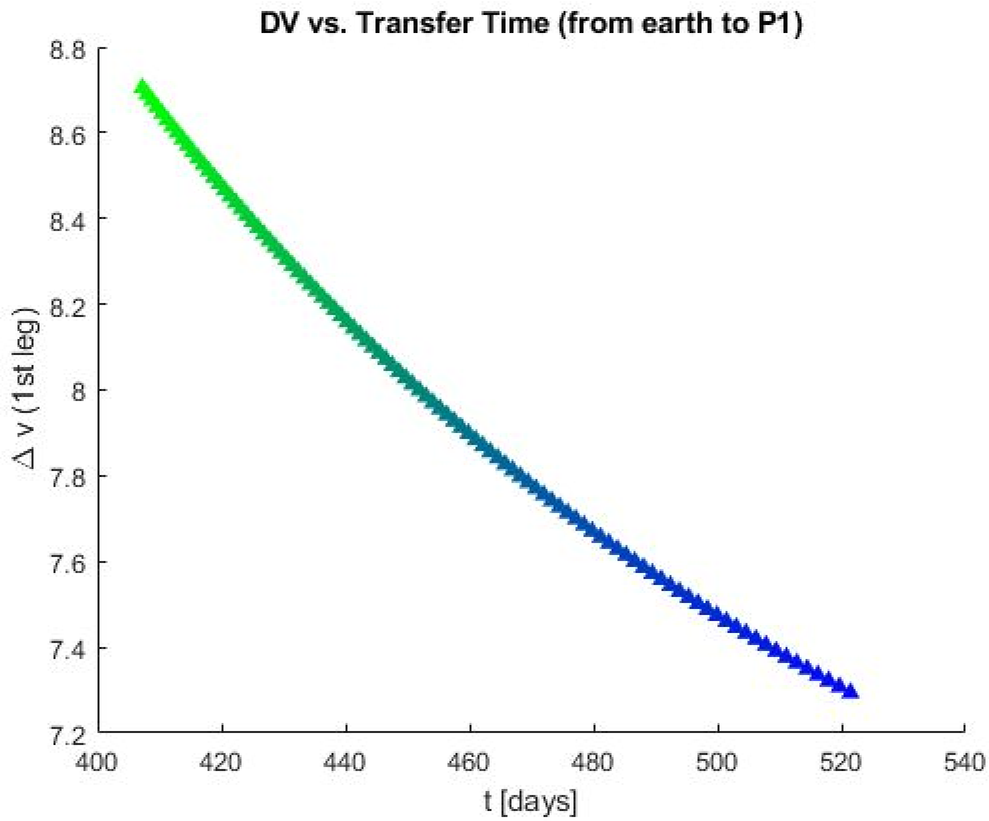
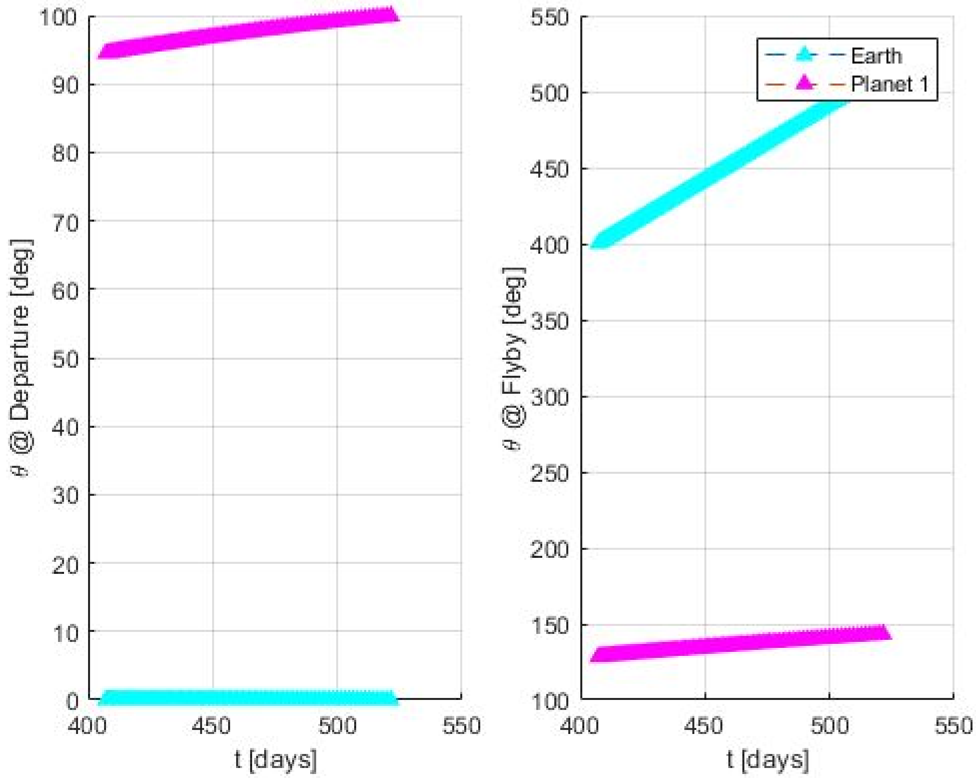
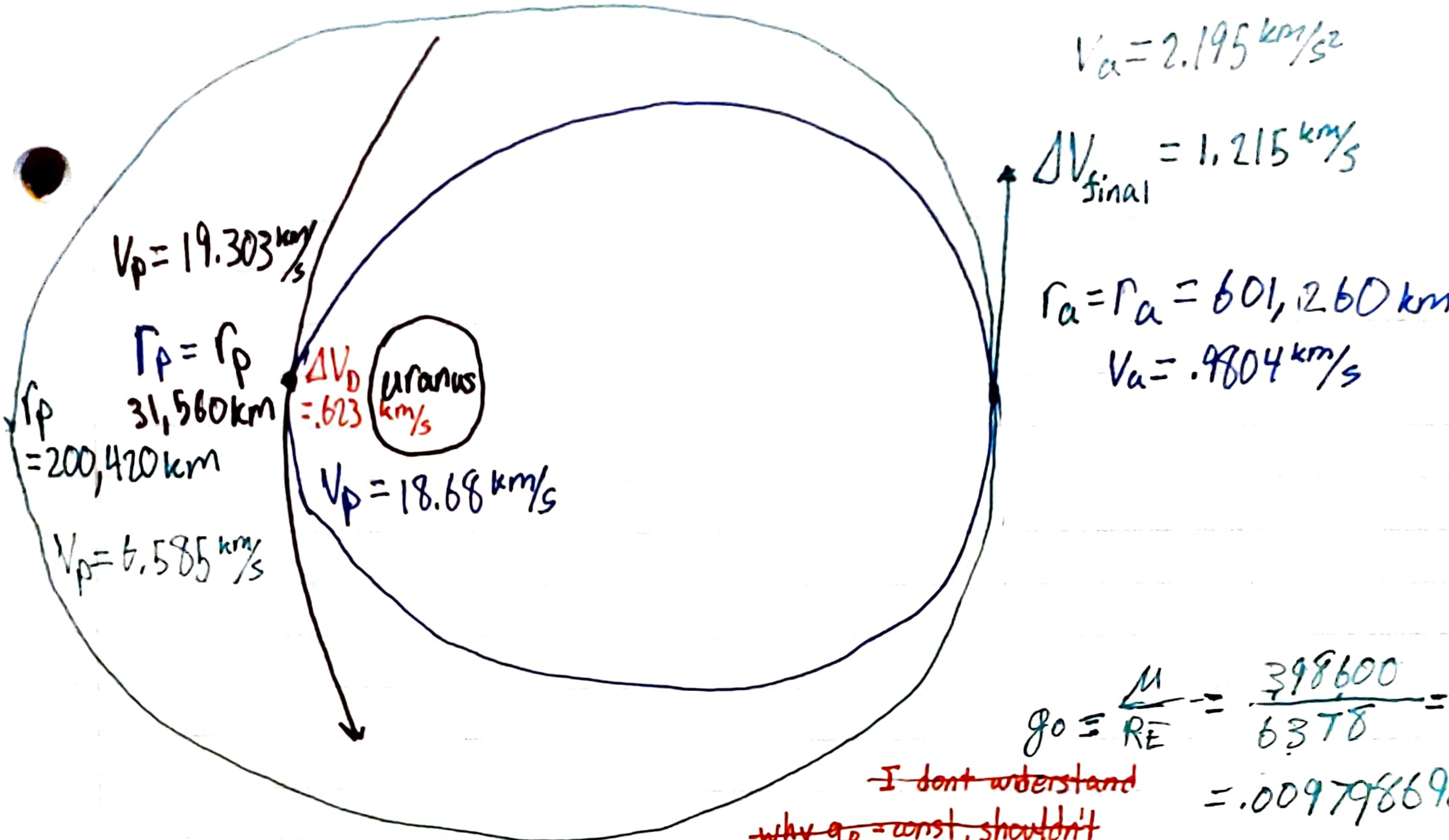


Figure 6d: Gravity Assist



Appendix C - Hand Calculations

See next page.



$$g_0 = \frac{\mu}{R_E} = \frac{398600}{6378} = .009798696 \, \frac{km}{s^2}$$

~~I dont understand~~
~~why g_0 = const, shouldn't~~
~~we use g_0 @ distance from planet?~~

At target orbit: $m_{s/c}$ = dry mass (centaur + scientific payload)

$$= 2247 \, kg + 502.9 \, kg = 2749.9 \, kg$$

$$m_0 = m_{s/c} \, e^{\frac{\Delta V_{final}}{I_{sp} \, g_0}} = 2749.9 \, e^{\frac{1.215}{450.5(.00978)}}$$

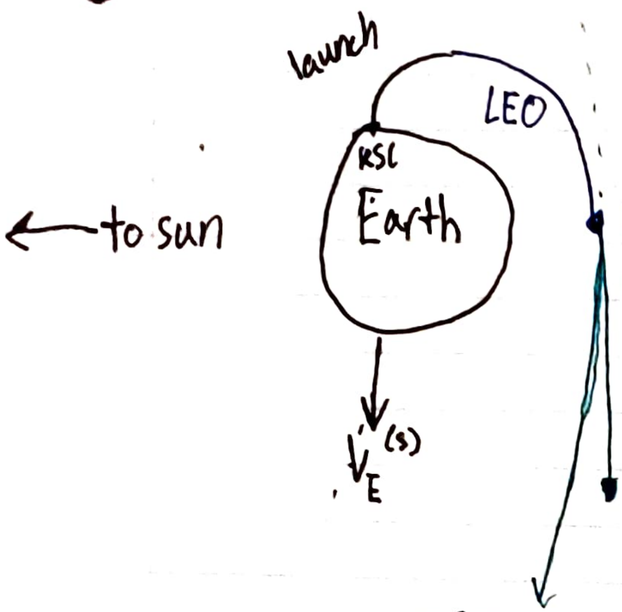
$$= 3621.2 \, kg$$

From grav assist: $dV_{dep} = 5.242^{3}$ km/s

$V_{cir,earth} = \sqrt{\frac{\mu_{sun}}{r}} = \sqrt{\frac{132,712,000,000}{149.6E6}} = 29.784$ km/s

$V_{cir} = \sqrt{\frac{\mu_e}{r}} = \sqrt{\frac{398,600}{6378+380}}$

$= 7.67997$ km/s



$r_p = r_a = 380$ km

$r_{p,Hyp} = 380$ km

$V_{p,Hyp} = 12.92197$ km/s $= V_{cir} + \Delta V_{dep}$

$V_\infty = \frac{\mu}{h}\sqrt{e^2-1}$, $\mu = 398,600$, $h = r_p V_{p,Hyp}$, $e = \frac{V_{p,Hyp}^2 r_p^2}{\mu} = \frac{12.922^2(380)}{398,600} - 1$

$= 59.4889$

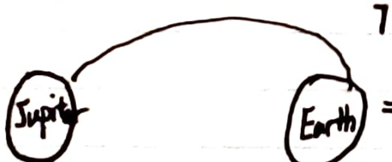
$\mathcal{E}_{Hyp} = \frac{V_{p,Hyp}^2}{2} - \frac{\mu_E}{r_p} = \frac{V_\infty^2}{2} = 24.50447$

$V_\infty = \sqrt{2(24.5045)} = 7.0006$ km/s wrt earth

$m_0 = m_{s/c}\, e^{\frac{\Delta V_{dep}}{I_{sp} g_0}}$, $m_{s/c}$ here is SEC III + payload + fuel for insertion into target orbit at Uranus.

.27563

$\boxed{= 11,874.28 \text{ kg}}$ Atlas V must deliver this much mass to 380km LEO



$V_{cir,jup} = 13.0556$ km/s

=>

778.6E6 $= r_a$

$V_a = 7.068$ km/s

$V_p = 36.785$ km/s $= V_\infty + V_E^{(s)}$

$r_p = 149.6E$

$L = 17m,\ D = 1.5m$ ISP 279.3 s Thrust = [illegible] kN

0–5 x AJ-60A Boosters $m_0 = 46{,}697kg$ $m_f = 4{,}057kg$, $m_{fuel} =$ [illegible]

$t_{bo} = 94s$

$L = 32.46m$ $D = 3.81m$

Common Core Booster $ISP = 311.3s$ sea-level $T = 3827kN$ L

$m_f = 21{,}054kg$ $m_0 = 305{,}143kg$ 337.8 s vacuum 4,152 kN V

$t_{bo} = 253s$

Atlas V LS→LEO = 8,250 kg – 20,520 kg (16,[illegible] – 45,[illegible] lb)

payload lift capability

RIOC-1 Centaur III Single Engine ← up to 12 restarts (12 dV maneuvers)

$m_f = 2247kg\ (4{,}954\ lb)$

→ $ISP = 450.5s$ → $t_{bo} = 842$ seconds

$T = 99.2kN$

→ $m_{pay} = 502.9kg$

→ can carry up to 18,273 kg (payload + fuel) → $m_{fuel,max} = 17{,}770.1kg$

constrained by Atlas V lift capacity (m_{tot} cannot exceed 20,520 kg)

max mass at LEO: 20,520 kg ($m_{0,SEC\ III} + m_{payload}$)

so we can take up to 17,770.1 kg LEO→Uranus target of fuel with us,

$$\Delta V = I_{sp}\, g_0 \ln\left(\frac{m_0}{m_f}\right)$$

April 30th, 2021 @ 7:21 am

- Uranus Target

$r_p = 200{,}420\,km$ $\quad \alpha = \frac{h^2}{\mu_{uranus}}$

$r_a = 601{,}260\,km$ $\quad e = \frac{r_a - r_p}{r_a + r_p} = \frac{601{,}260 - 200{,}420}{601{,}260 + 200{,}420} = .5$

$a = \frac{r_p + r_a}{2} = 400{,}840$

$h = \sqrt{a\mu(1-e^2)} = \sqrt{400{,}840(5{,}794{,}000)(1-.5^2)}$
$= 1{,}319{,}791.734$

$V_p = \frac{h}{r_p} = 6.585\ km/s$ wrt. uranus

$V_{cir,uranus} = \sqrt{\frac{\mu_{sun}}{r_{,uranus}}} = 6.798\ km/s$

$V_a = \frac{h}{r_a} = 2.195\ km/s$

$DV_{arrival} = 2.257\ km/s = V_\infty \rightarrow r_p = 200420$
$= 2.333\ km/s \rightarrow r_p = 31{,}560$

$V_{SOI,Uranus} = 4.541\ km/s \leftarrow V_{s/c}$ wrt uranus

$r_p: r_U + r_{s/c} = 31560\,km$ $\quad a = \frac{r_p + r_a}{2} = \frac{31{,}560 + 601260\,km}{2} = 316{,}410\ km$

$r_a = 601{,}260\,km$ $\quad e = \frac{r_a - r_p}{r_a + r_p} = .90002$, $\quad h = \sqrt{(316{,}410)(5{,}794{,}000)(1-.9^2)}$
$= 589472.8$

$\Rightarrow V_p = 18.68\ km/s \leftarrow$ elliptical

$V_a = .9804\ km/s$

$V_{p,Hyp} = \sqrt{V_\infty^2 + \frac{2\mu_p}{r_p}} = 19.303\ km/s$, need $\Delta V_{Drag} = .623\ km/s$ to close orbit.

$\Delta V_{final\ burn} = 1.215\ km/s$

4,000,000 km

Transfer time → Jupiter 517.84 days $\Delta V_{Dep} = 7.325$

θ @ Departure 99.775° $\Delta V_{arr} = 1.478$

θ @ Flyby: 142.775° $\Delta V_{tot} = 8.803$

$\Delta V = V_{pHyp} - V_{park}$ $V_{park} = \sqrt{\frac{398600}{6758}} = 7.68$

$V_{pHyp} = 12.922 \text{ km/s}$ $V_\infty = \frac{\mu_E}{h}\sqrt{e^2-1}$, $h = V_p r_p = 12.922(6758)$

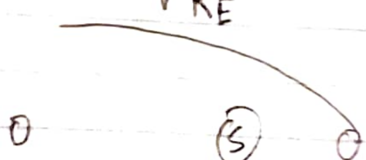
$= 7.001 \text{ km/s}$ $= 87,326.9$

$e = \frac{V_{pH}^2 r_p}{\mu_E} - 1 = \frac{(12.922)^2(6758)}{398600} - 1 = 1.831 \Rightarrow \beta = \cos^{-1}\frac{1}{1.831}$

$= 56.897°$

$\Delta = r_p \frac{\sqrt{e^2-1}}{e-1} = 6758\left(\frac{\sqrt{1.831^2-1}}{1.831-1}\right) = 12,473.53 \text{km}$

$\sqrt{\frac{\mu_{sun}}{R_E}} =$



$V(\theta) = \frac{\mu_{sun}}{h}\sqrt{1+e^2+2e\cos\theta}$

$r_p = 149.6E6$ $V(142.775°) = \frac{132,712,000}{5.5031E9}\sqrt{1+(.678)^2+2(.678)\cos(\theta)}$

$V_p = 29.78 + 7.001 \text{ km/s}$ $= 14.867 \text{ km/s}$

$= 36.785$

$h = v_p r_p = 149.6E6(36.785)$

$=$

$e = \frac{r_a - r_p}{r_a + r_p} = \frac{778.6E6 - 149.6E6}{778.6E6 + 149.6E6} = .6777$

$\sqrt{\frac{\mu_{sun}}{R_J}} = 13.056 \text{ km/s}$ $V_\infty = 1.811 \text{ km/s}$

$V_{p,Hyp} = \sqrt{V_\infty^2 + \frac{\mu_{JUP}}{R_p}} = 11.915 \text{ km/s}$

$$V_{s/c}^{(s)} = \sqrt{V_p^{(s)} + V_\infty^2 - 2V_p^{(s)} V_\infty \cos(\delta + \phi)}$$

$$= 15.693 \text{ km/s}$$