SLS Block 2C with Pyrios Boosters and 2xJ–2X optimised upper stage. Payload to 200 km LEO = 129.0 t. 23 Nov. 2013. Author: Steven S. Pietrobon, PhD.

RSRMV thrust curve obtained from page 56 of [1]. There is a discrepancy in that Loaded Mass minus Burnout Mass in [1] is 650,743 kg compared to 633,233 kg in [2] and 628,701 kg in [3]. Therefore, we have adjusted the propellant mass and impulse in [1] to match the values in [2].

The dimensions of the Pyrios LOX/RP–1 booster and F–1B nozzle diameter were estimated from Figure 6 of [4]. The Isp of the F–1B is not given, so this was estimated from the available values. The F–1A [5] nozzle efficiency of $\eta = 0.973$ allowed an estimation of the chamber pressure of P_c = 7456.5 kPa and the sea level thrust coefficient of C_f = 1.667 using the formula $F_{sl} = P_c A_t C_f \eta$ and an Isp calculation program [6], where F_{sl} is the sea level thrust and A_t is the throat area. The estimated F–1B chamber pressure is 5% less than the F–1A at 7846 kPa. The F–1A Isp efficiency of 90.25% was then used to estimate the F–1B Isp of 2,932.7 m/s. This is 2% less than the F–1A Isp due to the lower chamber pressure and reduced area ratio (12 instead of 16).

Figure 3 of [4] allowed an estimation of the Pyrios useful propellant mass of 800.1 t and total mass of 924.09 t. To understand what these values mean, we used the Saturn 1C–1 graph point to give a 2103.1 t propellant mass and 2273.6 t total mass for the Saturn V S–1C stage. Using the Apollo 14 launch vehicle report [7], the closest values were the 2113.8 t propellant mass and 2283.3 t total mass at lift–off. Both these values are 0.5% less than the values obtained from the graph, which is within the range of measurement error. Therefore, we interpreted the useful propellant mass and total mass to be the values at liftoff. The startup and reserve propellant masses were estimated using the same proportions as for the S–1C.

Boosters	1C4J2.2	2C4J2
Booster Name	RSRMV	Pyrios
Number of Boosters	2	2
Engine Name	–	F–1B
Number of Engines per Booster	1	2
Aft Skirt Diameter (m)	5.156	9.340
Booster Diameter (m)	3.711	5.486
Nozzle Diameter (m)	3.875	3.185
Sea Level Thrust at 0.2 s (N)	15,599,386	8,029,040
Maximum Vacuum Thrust (N)	17,866,606	8,836,221
Vacuum Isp (m/s)	2,622.3	2,932.7
Total Mass (kg)	733,776	942,030
Startup Propellant (kg)	0	17,940
Usable Propellant (kg)	632,791	787,311
Residual/Reserve Propellant (kg)	442	12,789
Burnout/Dry Mass (kg)	100,543	123,990
Action Time (s)	131.9	131.8

The simulations have no thrust bucket and reduced the thrust rating to 109%, as reported in [8].

Core Stage: 4xRS–25 Engines	1C4J2.2	2C4J2
Stage Diameter (m)	8.407	8.407
Nozzle Diameter (m)	2.304	2.304
Vacuum Isp (m/s)	4,436.5	4,436.5
Engine Thrust (N)	2,278,824	2,278,824
Engine Thrust Rating (%)	109	109
Thrust Bucket (%)	109	109
Total Mass (kg)	1,091,525	1,091,525
Usable Propellant (kg)	966,061	966,061
Reserve Propellant (kg)	8,210	8,210
Fuel Bias Propellant (kg)	1,678	1,678
Startup Propellant (kg)	7,439	7,439
Dry Mass (kg)	115,575	115,575

The size of the upper stage was optimised to maximise payload delivered into a 200 km orbit. The interstage mass was adjusted according to total maximum weight carried by the core. Ullage motors were added to ensure propellant settling, similar to that used by the Saturn V.

Upper Stage:	1C4J2.2	2C4J2
Engines	J–2X	J–2X
Number of Engines	2	2
Stage Diameter (m)	8.407	8.407
Nozzle Diameter (m)	3.048	3.048
Vacuum Isp (m/s)	4,275.7	4,275.7
Single Engine Thrust (N)	1,281,088	1,281,088
Single Engine Mass (kg)	2,472	2,472
Total Mass (kg)	147,516	156,359
Usable Propellant (kg)	125,292	133,184
Reserve Propellant (kg)	2,114	2,247
Startup Propellant (kg)	771	771
Residual Propellant (kg)	0	0
RCS Propellant (kg)	102	116
Dry Mass (kg)	19,005	19,748
Ullage Motors Propellant (kg)	115	148
Ullage Motors Dry Mass (kg)	117	145
Ullage Motors Action Time (s)	3.87	3.87
Ullage Motors Thrust (N)	65,032	83,178
Ullage Motors Offset Angle (°)	30	30
Interstage Mass (kg)	5,944	8,910

The LAS/SAJ jettison time was obtained from [9]. Simulation results for 2C4J2 are shown in Figures 1–4. The higher impulse of the Pyrios boosters compared to the RSRMV allows for an increase of payload of 26.2 t or 25.5% from 102.8 t to 129.0 t.

	1C4J2.2	2C4J2
Orbit (km)	200 ± 0.4	200 ± 0.4
Liftoff Thrust at 0.2 s (N)	38,623,742	39,541,132
Liftoff Mass (kg)	2,823,613	3,242,240
Liftoff Acceleration (m/s^2)	13.69	12.20
MaxQ (Pa)	21,877	28,287
Maximum Acceleration (m/s^2)	23.80	31.65
LAS/SAJ Jettison Time (s)	330	330
Launch Abort System (kg)	7,394	7,394
Orion Jettisoned Adaptors (kg)	920	920
Other Spacecraft (kg)	102,762	128,953
Remaining Propellant (kg)	0	0
Total Payload (kg)	102,762	128,953
Total Delta–V (m/s)	9,905	9,689

[1] Alliant Techsystems Inc., “ATK space propulsion products catalog,” Aug. 2012.

[2] B. Donahue and J. Bridges, “The Space Launch System capabilities for enabling crewed Lunar and Mars exploration,” *63rd Int. Astronautical Congress*, Naples, Italy, IAC–12–D2.8.7, Oct. 2012.

[3] P. Phillips, “Ground systems development and operations,” NASA, July 2012.

[4] S. Cook, K. Doering, A. Crocker and R. Bachtel, “Enabling an affordable advanced liquid booster for NASA’s Space Launch System,” *63rd Int. Astronautical Congress*, Naples, Italy, IAC–12–D2.8.10, Oct. 2012.

[5] NASA, “Liquid engine comparison,” Slide PD24, 12 Jan. 1992.

[6] C. Selph, “United States Air Force chemical equilibrium specific impulse (Isp) code,” Mar. 1992. http://www.dunnspace.com/isp.htm

[7] Saturn Flight Evaluation Working Group, “Saturn V launch vehicle flight evaluation report AS–509 Apollo 14 mission,” *George C. Marshall Space Flight Center*, MPR–SAT–FE–71–1, Apr. 1971.

[8] M. Davidson, “RS–25: The Clark Kent of engines for the Space Launch System,” 13 Sep. 2013. http://www.nasa.gov/exploration/systems/sls/rs25–engine–powers–sls.html

[9] S. Creech, J. Holladay and D. Jones, “SLS dual use upper stage (DUUS) opportunities,” NASA, Apr. 2013.

Figure 1: Altitude versus time for SLS Block 1C

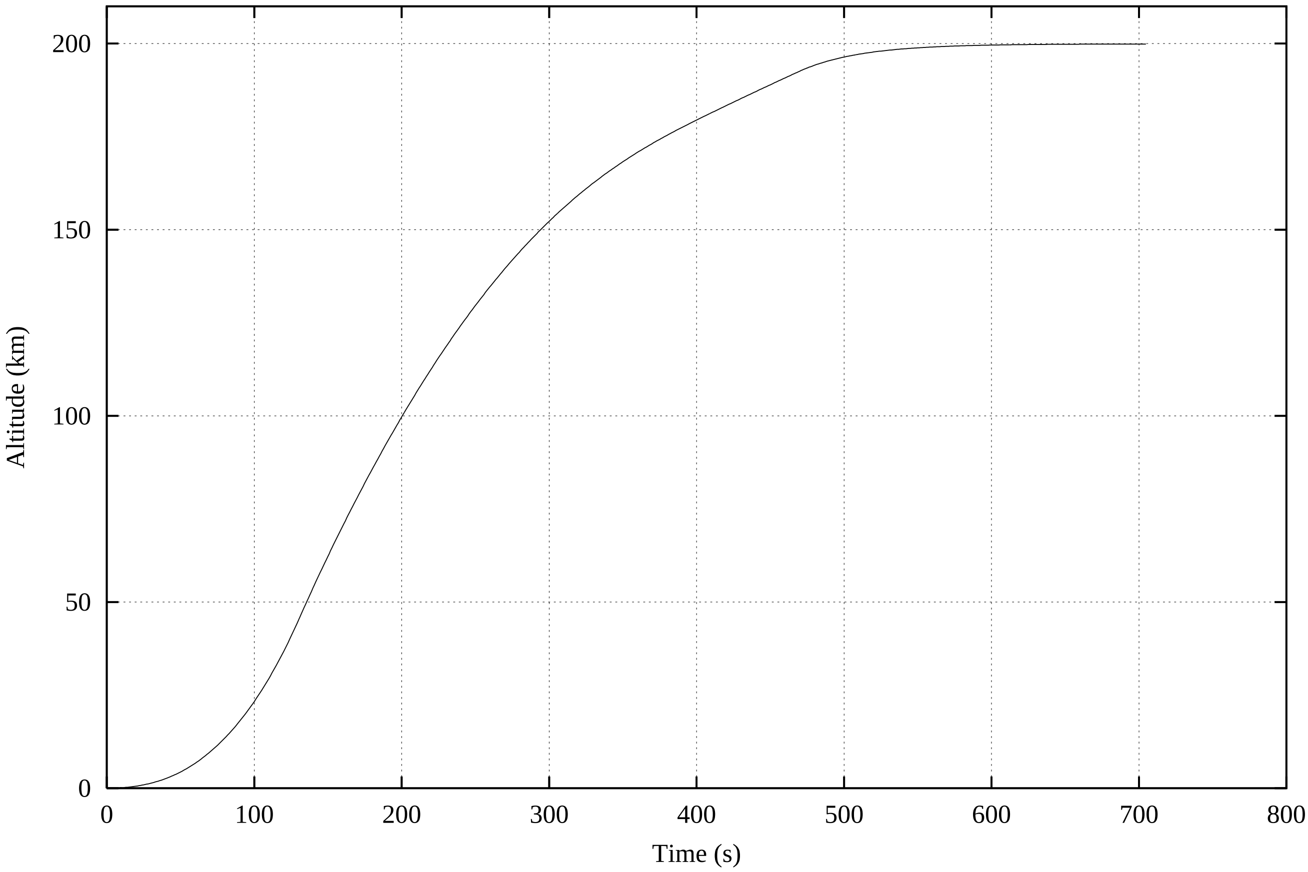

Figure 2: Speed versus time for SLS Block 1C

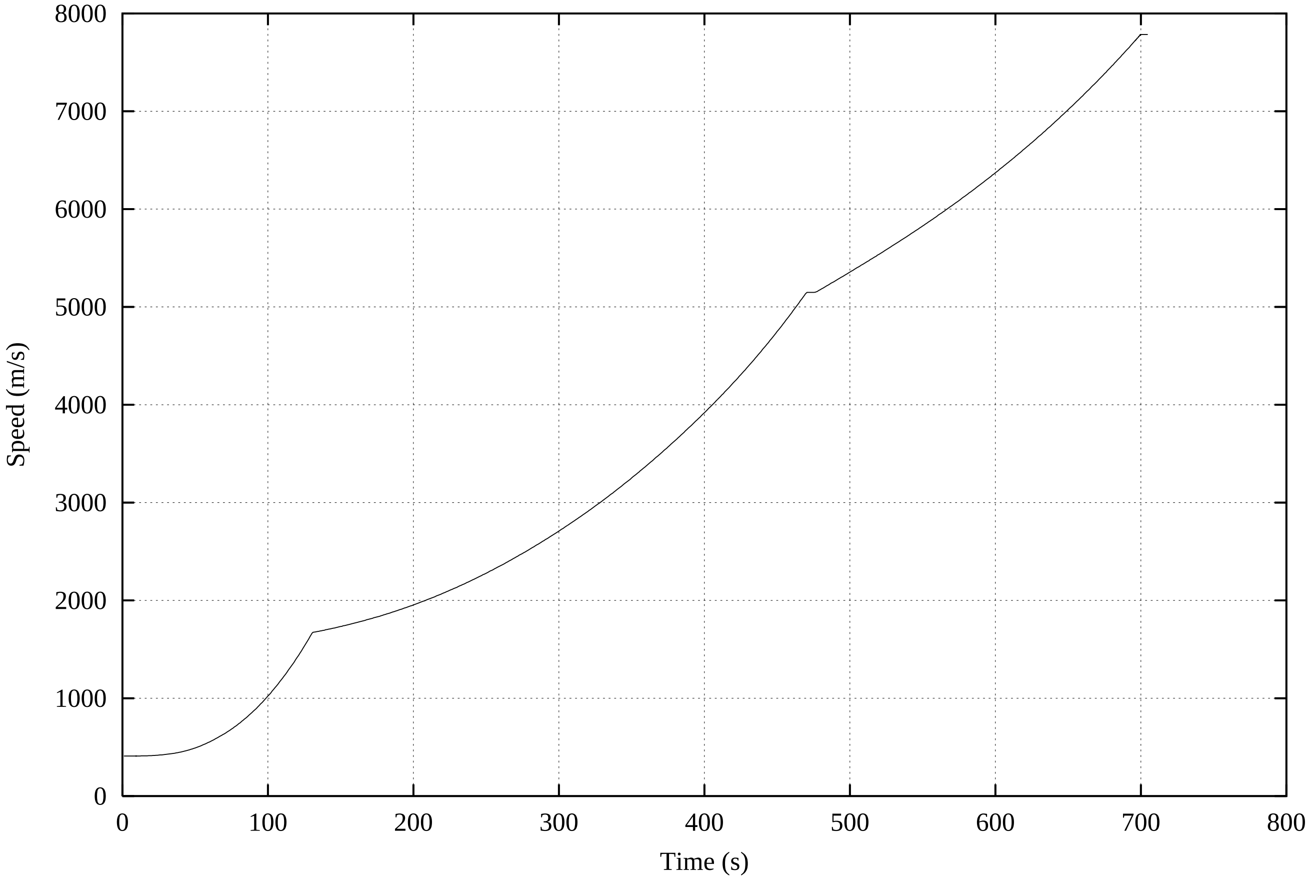

Figure 3: Acceleration versus time for SLS Block 1C

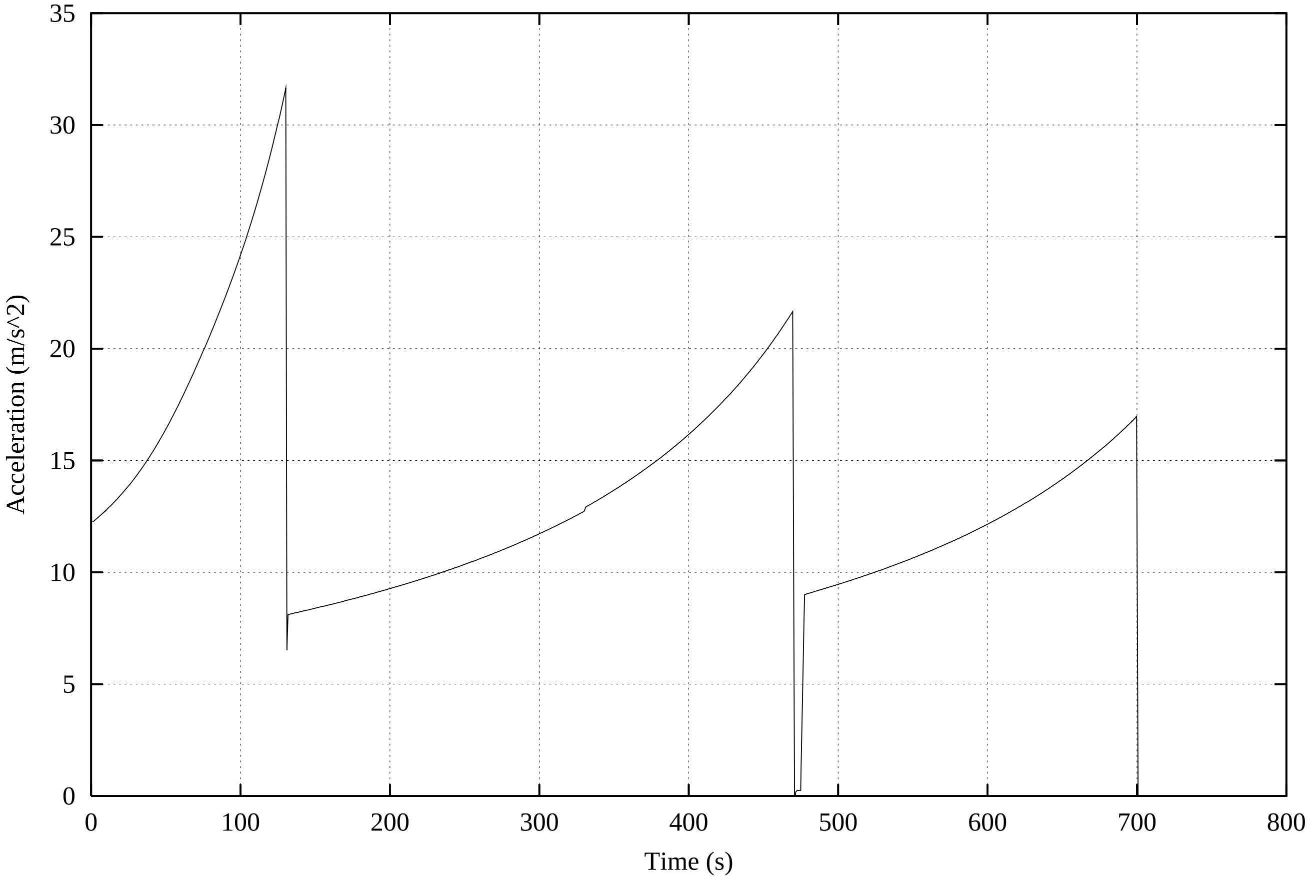

Figure 4: Dynamic pressure versus time for SLS Block 1C