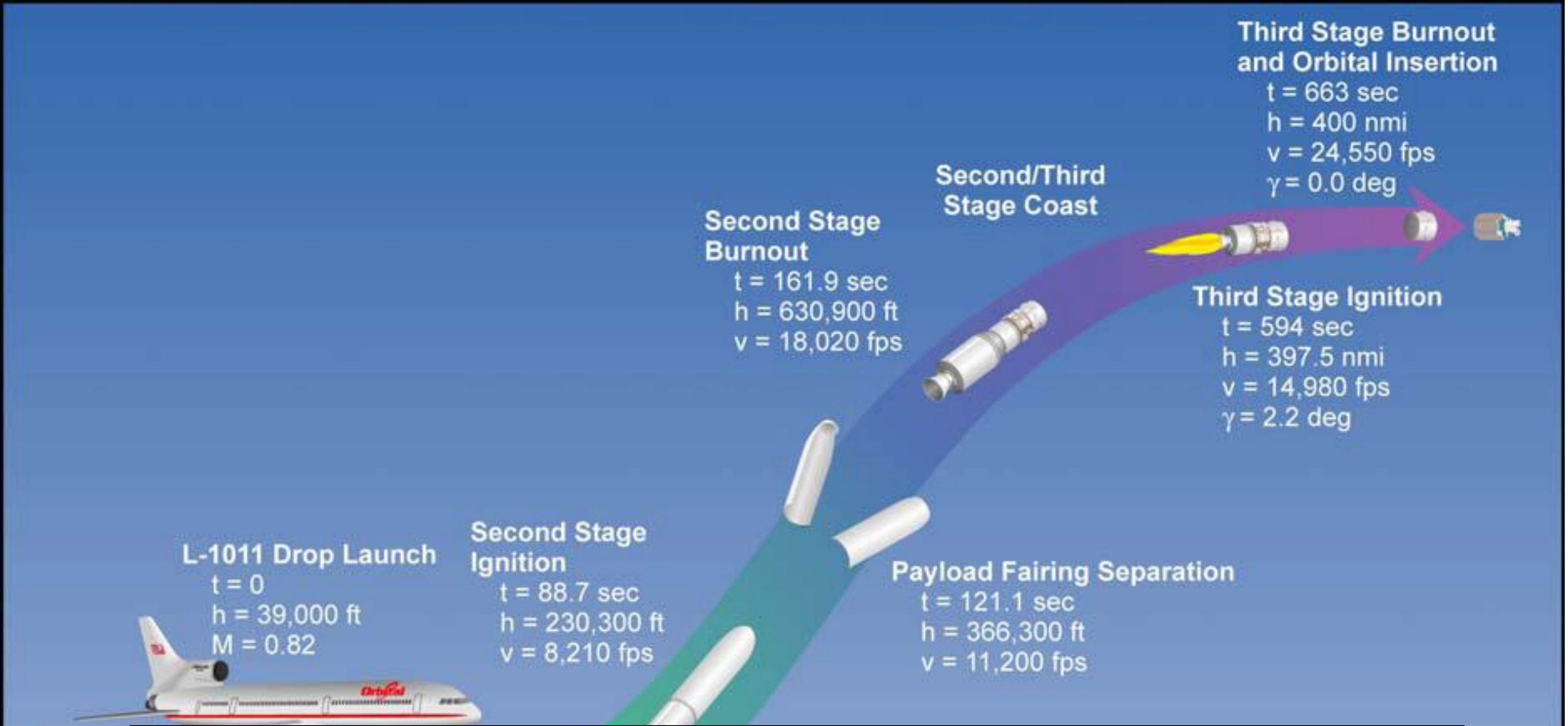
Flight and Orbital Mechanics

Lecture slides



Flight and Orbital Mechanics

AE2-104, lecture hours 25+26: Launchers

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Example: Ariane 5

Questions:
- what is the payload of this launcher?
- why does it have 2 stages and 2 boosters?
- what are the characteristics of each stage?
- ....

[Arianespace, 2010]

Overview

- Ideal single-stage launcher
- Ideal multi-stage launcher
- Real single-stage launcher (gravity, atmosphere)
- Real multi-stage launcher (idem)
- Overall performance (Pegasus)
- Design (Pegasus)

Learning goals

The student should be able to:

- derive, describe and explain Tsiolkovsky's equation
- describe and explain the concept of a multi-stage launcher and quantify its performance
- describe and quantify the performance of a launcher in realistic conditions, *i.e.*, under the influence of gravity and drag
- make a 1st-order design of a new launcher from scratch
- ….

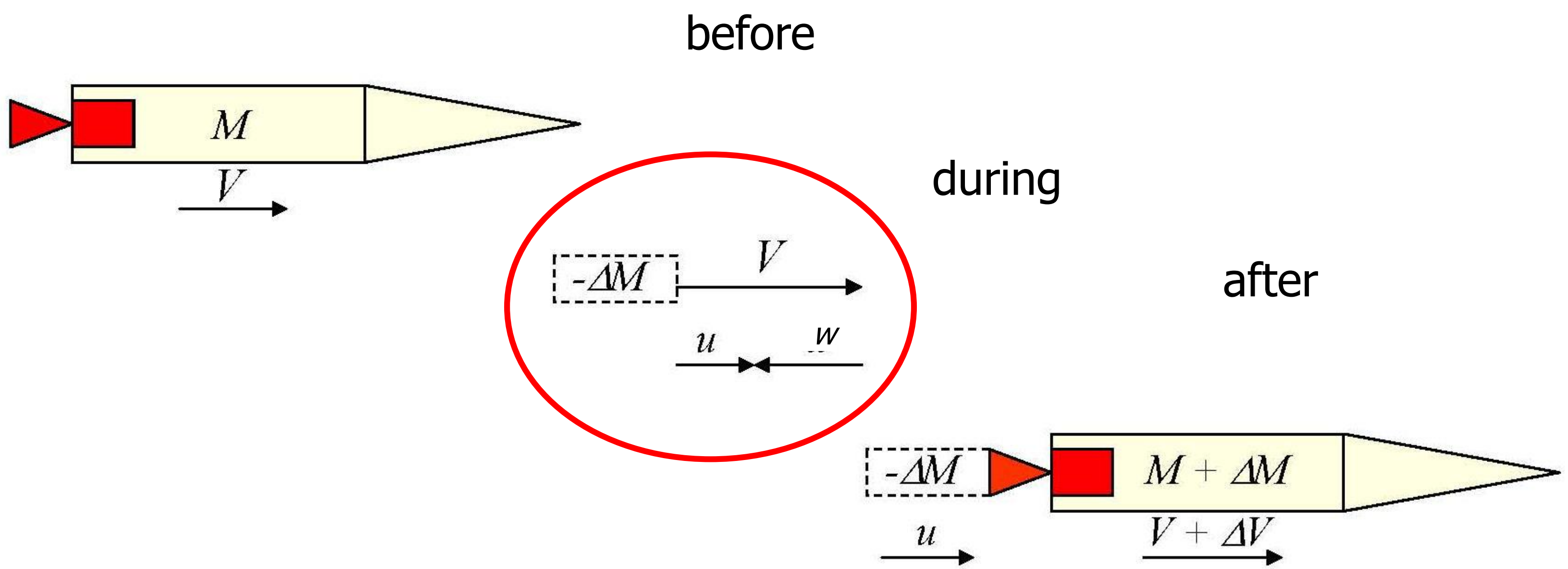
Lecture material:

- these slides (incl. footnotes)

Principles

Principles + performance ideal rocket: partial recap of ae1-102

Principles (cnt'd)



- vehicle contains payload, structure, propellant
- exhaust velocity propellant w
- conservation of momentum of system
- vehicle accelerates

Principles (cnt'd)

- system = launcher + expelled propellant
- momentum system = constant

$$M \frac{dV}{dt} = -\frac{dM}{dt} w$$

Solidification Principle:

$$F = M\,a = M \frac{dV}{dt} = m\,w$$

- M = instantaneous mass of rocket [kg]
- m = expelled (gaseous) mass per unit of time, or mass flow [kg/s]
- V = <u>inertial</u> velocity of launcher [m/s]
- w = <u>relative</u> exhaust velocity of expelled propellant [m/s]

Ideal single stage rocket

Equation of motion (vacuum, no gravity):

$$M\frac{dV}{dt} = -\frac{dM}{dt}w$$

Integration:

$$\Delta V = w\ln\left(\frac{M_{begin}}{M_{end}}\right)$$

Tsiolkovsky's Equation (a.k.a. "the rocket equation")

Note: $w = I_{sp}\, g_0$

Ideal single stage rocket (cnt'd)

Characteristic parameters:

- thrust-to-weight ratio:

$$\Psi_0 = \frac{F}{M_0\, g_0}$$

- mass ratio:

$$\Lambda = \frac{M_{begin}}{M_{end}}$$

So:

- burn time:

$$t_b = \frac{M_{begin} - M_{end}}{m} = \frac{I_{sp}}{\Psi_0}\left(1 - \frac{1}{\Lambda}\right)$$

- end velocity

$$V_{end} = I_{sp}\, g_0 \ln(\Lambda)$$

- burnout altitude:

$$s_{end} = \frac{g_0\, I_{sp}^2}{\Psi_0}\left(1 - \frac{\ln(\Lambda) - 1}{\Lambda}\right)$$

Ideal single stage rocket (cnt'd)

	"normal"	impulsive shot *
Λ	M_{begin} / M_{end}	
t_b	$(I_{sp} / \Psi_0)(1 - 1/\Lambda)$	0
Ψ_0	$F / (M_0 g_0)$	∞
V_{end}	$I_{sp} g_0 \ln(\Lambda)$	
s_{end}	$g_0 I_{sp}^2 / \Psi_0 (1 - (\ln(\Lambda)-1)/\Lambda)$	0

*: impulsive shot: all propellants are ejected in 1 instant

Ideal single stage rocket (cnt'd)

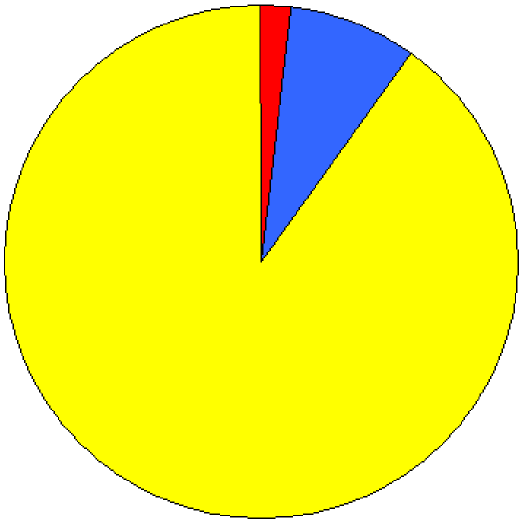
Do not forget (cf. ae1-102):

- $\Psi_0 > 1$
- structural loading at burnout

Ideal multi-stage rocket (cnt'd)

Definition of parameters:

- M_{total} = total mass (*i.e.*, before firing)
- $M_{payload}$ = payload mass (red)
- M_{constr} = construction mass (blue)
- M_{prop} = propellant mass (yellow)



- $M_{begin} = M_{total} = M_{payload} + M_{constr} + M_{prop}$
- $M_{end} = M_{payload} + M_{constr}$

Ideal multi-stage rocket

$$\Delta V = g_0 \, I_{sp} \ln\left(\frac{M_{total}}{M_{total} - M_{prop}} \right)$$

$$\Delta V = g_0 \, I_{sp} \ln\left(\frac{M_{total}}{M_{constr} + M_{payload}} \right)$$

$$\frac{M_{constr}}{M_{total}} + \frac{M_{payload}}{M_{total}} = \exp\left(\frac{-\Delta V}{I_{sp} \, g_0} \right)$$

Ideal multi-stage rocket (cnt'd)

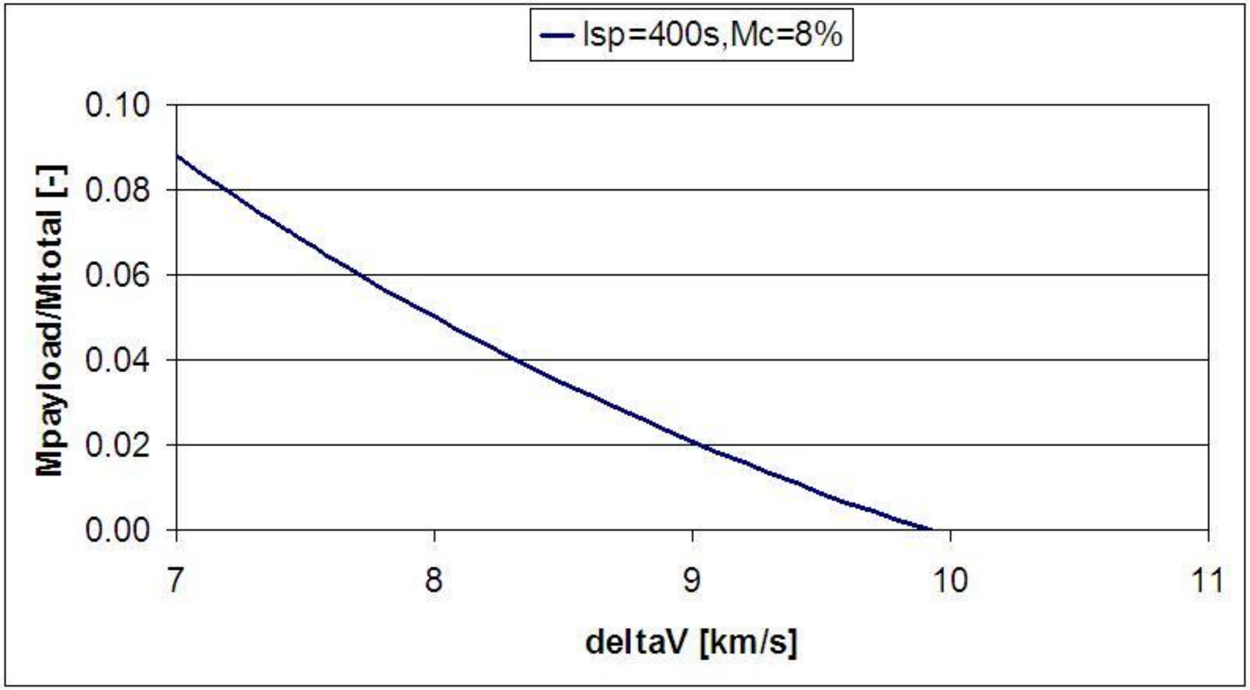
Example 1:

ΔV = 10 km/s, I_{sp} = 400 s, M_{constr}/M_{total} = 8 %, $M_{payload}$ = 500 kg ➔

- $M_{total} = M_{begin}$ = ???
- M_{prop} = ???
- M_{constr} = ???

Ideal multi-stage rocket (cnt'd)

Example 1 (cnt'd):



NO SOLUTION !

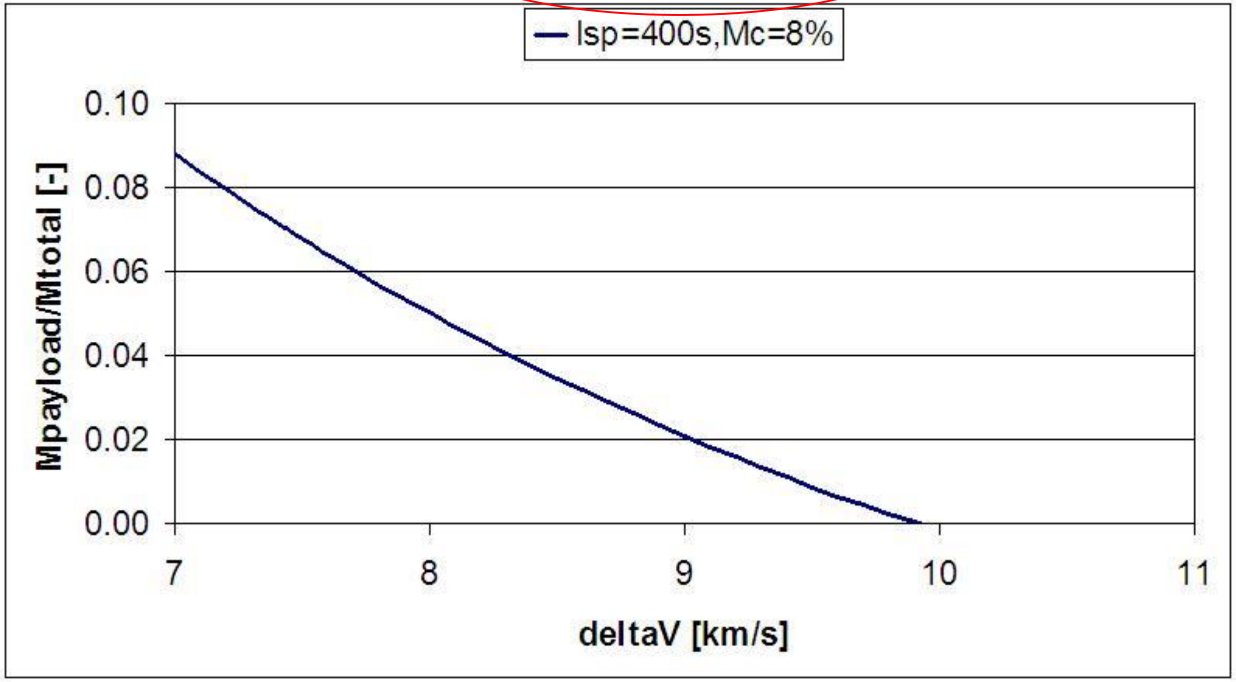
Ideal multi-stage rocket (cnt'd)

Options:

- reduce required $M_{payload}$
- use engine/propellant with higher I_{sp}
- use lighter construction
- multi-staging

Ideal multi-stage rocket (cnt'd)

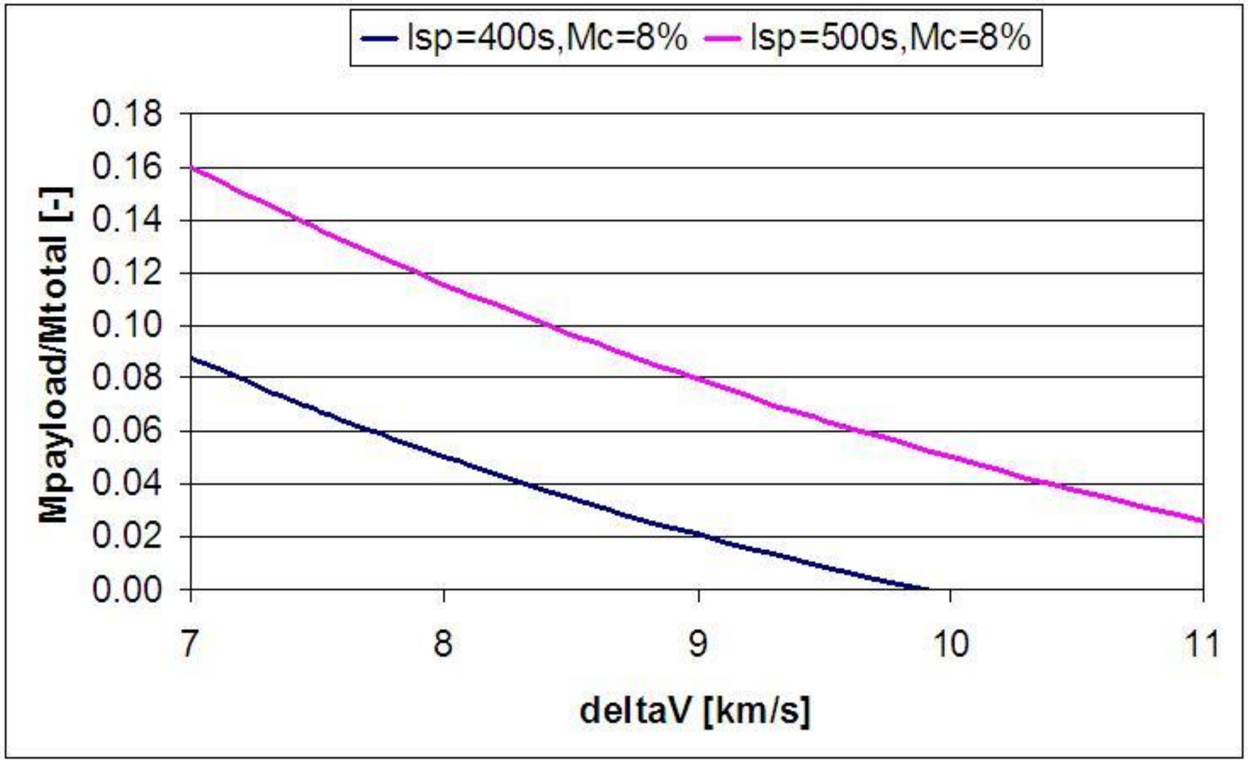
Example 2: ΔV = 10 km/s, I_{sp} = 400 s, M_{constr}/M_{total} = 8 %, $M_{payload}$ = 250 kg



Ideal multi-stage rocket (cnt'd)

Example 3:

ΔV = 10 km/s, I_{sp} = 500 s, M_{constr}/M_{total} = 8 %, $M_{payload}$ = 500 kg ➔



Ideal multi-stage rocket (cnt'd)

Example 3 (cnt'd):

ΔV = 10 km/s, I_{sp} = 500 s, M_{constr}/M_{total} = 8 %, $M_{payload}$ = 500 kg ➔

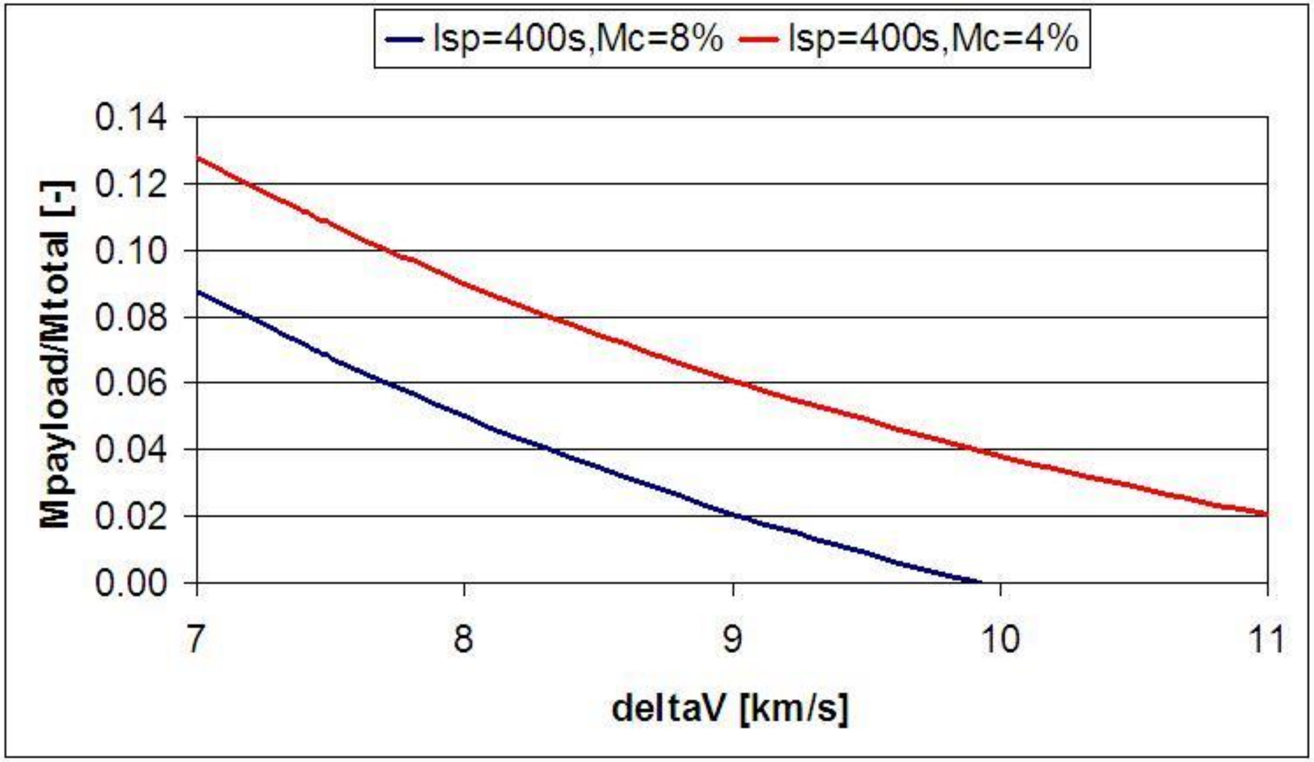
- $M_{payload}/M_{total}$ = 0.0502
- $M_{total} = M_{begin}$ = 9960 kg
- M_{constr} = 797 kg
- M_{prop} = 8663 kg
- M_{prop}/M_{total} = 87.0 %

OPTIMAL SOLUTION? FEASIBLE SOLUTION?

Ideal multi-stage rocket (cnt'd)

Example 4:

ΔV = 10 km/s, I_{sp} = 400 s, M_{constr}/M_{total} = 4 %, $M_{payload}$ = 500 kg ➔



Ideal multi-stage rocket (cnt'd)

Example 4 (cnt'd):

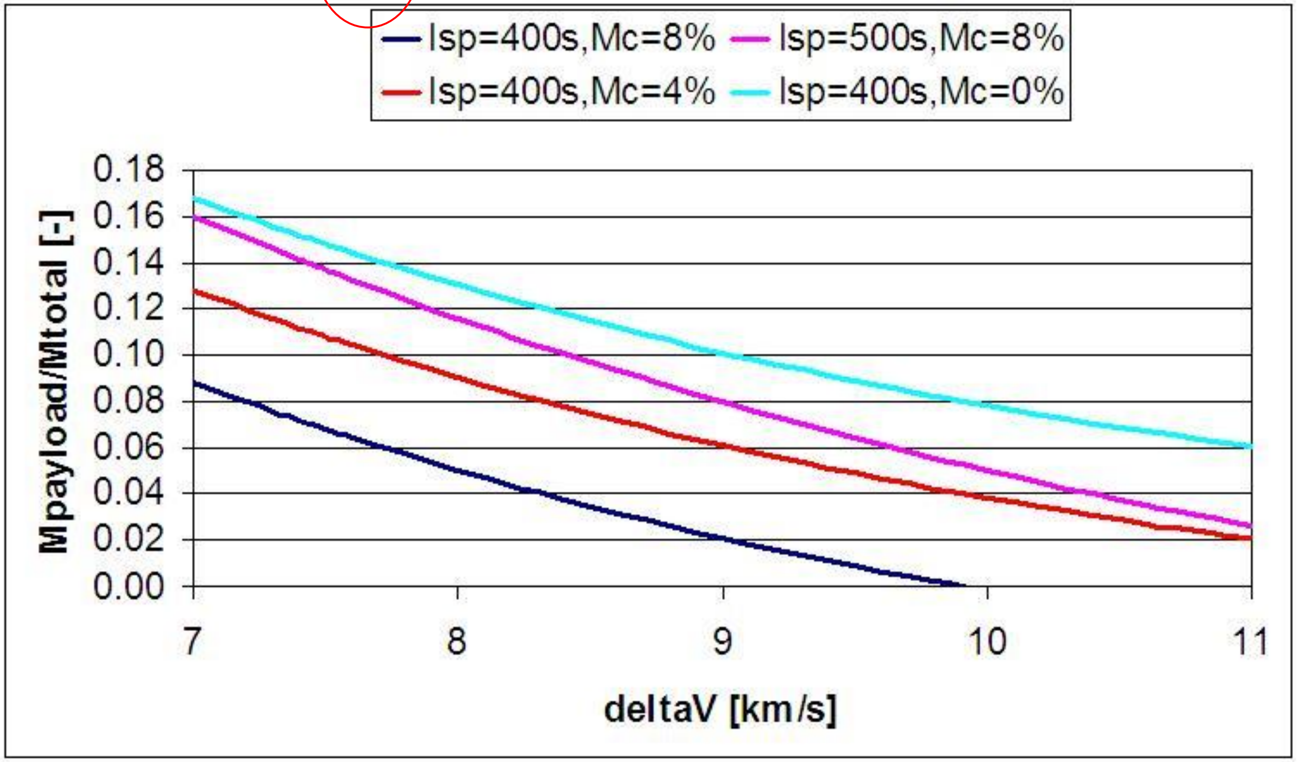
ΔV = 10 km/s, I_{sp} = 400 s, M_{constr}/M_{total} = 4 %, $M_{payload}$ = 500 kg ➔

- $M_{payload}/M_{total} = 0.0382$
- $M_{total} = M_{begin}$ = 13089 kg
- M_{constr} = 524 kg
- M_{prop} = 12065 kg
- M_{prop}/M_{total} = 92.2 %

OPTIMAL SOLUTION? FEASIBLE SOLUTION?

Ideal multi-stage rocket (cnt'd)

Example 5: no construction mass ……….

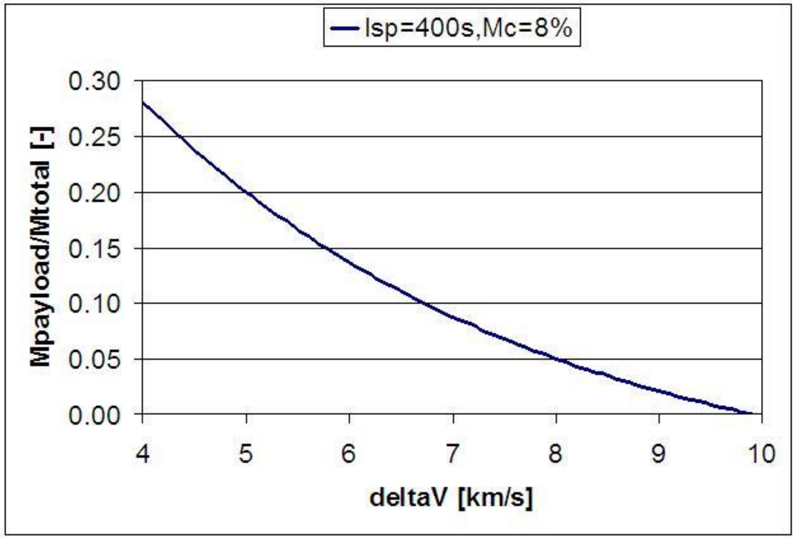


Ideal multi-stage rocket (cnt'd)

Example 6a:

ΔV = 5 km/s, I_{sp} = 400 s, M_{constr}/M_{total} = 8 %, $M_{payload}$ = 500 kg ➔

- $M_{payload}/M_{total}$ = 0.1997
- M_{total} = M_{begin} = 2504 kg
- M_{constr} = 200 kg
- M_{prop} = 1804 kg
- M_{prop}/M_{total} = 72.0 %



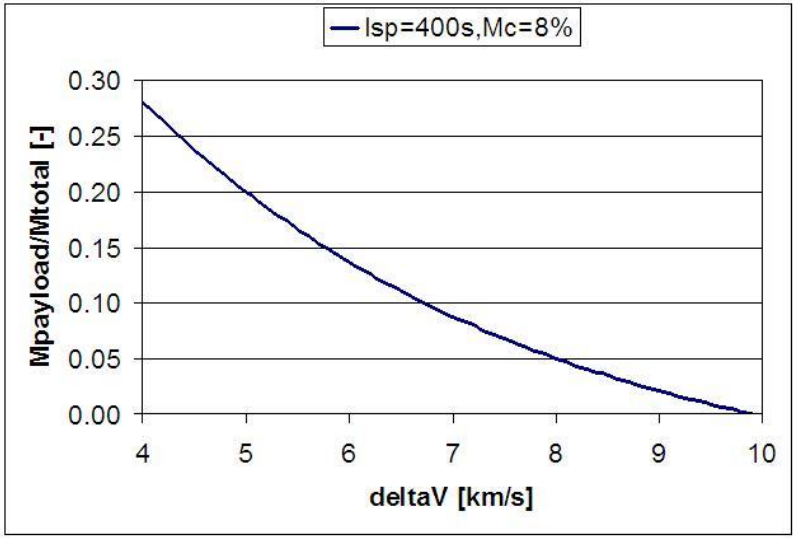
OPTIMAL SOLUTION? FEASIBLE SOLUTION?

Ideal multi-stage rocket (cnt'd)

Example 6b:

ΔV = 5 km/s, I_{sp} = 400 s, M_{constr}/M_{total} = 8 %, $M_{payload}$ = 2504 kg ➔

- $M_{payload}/M_{total}$ = 0.1997
- M_{total} = M_{begin} = 12,539 kg
- M_{constr} = 1003 kg
- M_{prop} = 9032 kg
- M_{prop}/M_{total} = 72.0 %



OPTIMAL SOLUTION? FEASIBLE SOLUTION?

Ideal multi-stage rocket (cnt'd)

Add numbers examples 6a+b:

	Example 6a	Example 6b	total
ΔV [km/s]	5.0	5.0	10.0
M_{prop} [kg]	1804	9032	10836
M_{constr} [kg]	200	1003	1203
$M_{payload}$ [kg]	500	2504	500
M_{total} [kg]	2504	12539	12539
	stage 2	stage 1	

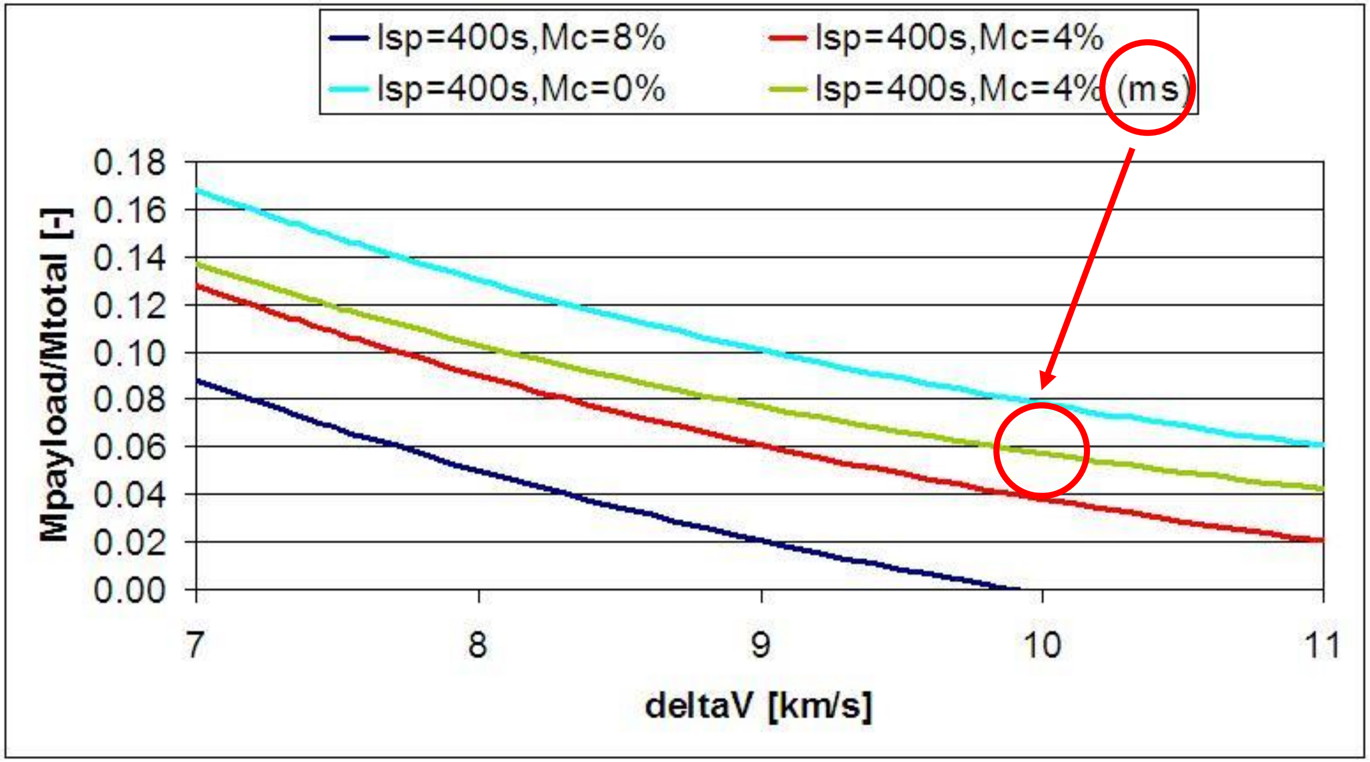
Ideal multi-stage rocket (cnt'd)

Compare examples:

	Example 1	Example 3	Example 4	Example 6a+b
ΔV [km/s]	10.0			
$M_{payload}$ [kg]	500			
I_{sp} [s]	400	500	400	400
M_{constr}/M_{total} [%]	8	8	4	8
# stages	1	1	1	2
M_{prop} [kg]	n.a.	8663	12065	10836
M_{constr} [kg]	n.a.	797	524	1203
M_{total} [kg]	n.a.	9960	13089	12539

Ideal multi-stage rocket (cnt'd)

Compare examples:



Conclusion: 50% gain in payload (ratio) !!

Ideal multi-stage rocket (cnt'd)

Multi-staging:

Advantages:

- no need to accelerate total construction mass until final velocity → upper stages perform more efficiently
  - more payload capacity
  - more ΔV capacity

Disadvantages:

- more complexity (engines, piping, …)
- more risk (jettison, ignition, …)

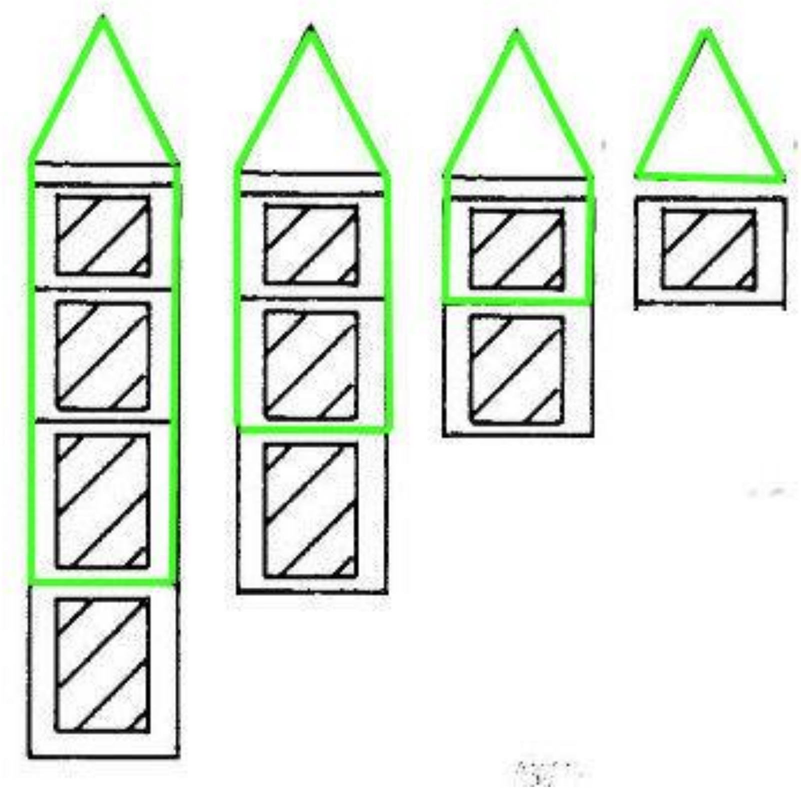
Ideal multi-stage rocket (cnt'd)

Definition of parameters:

- $M_{total,i}$ = total mass of stage "i" (*i.e.*, before firing)
- $M_{payload,i}$ = payload mass of stage "i"
- $M_{constr,i}$ = construction mass of stage "i"
- $M_{prop,i}$ = propellant mass of stage "i"

- Note: $M_{payload,i} = M_{total,i+1}$

Ideal multi-stage rocket (cnt'd)



green = payload

Stage 1 2 3 4

Ideal multi-stage rocket (cnt'd)

Tsiolkovsky, single stage:

$$\Delta V = I_{sp}\, g_0 \ln\left(\frac{M_{begin}}{M_{end}}\right)$$

define

$$p = M_{payload} / M_{begin}$$

$$\sigma = M_{constr} / M_{prop}$$

then

$$\frac{M_{begin}}{M_{end}} = \frac{M_{payload} + M_{constr} + M_{prop}}{M_{payload} + M_{constr}} = \frac{1+\sigma}{p+\sigma}$$

so

$$\Delta V = I_{sp}\, g_0 \ln\left(\frac{1+\sigma}{p+\sigma}\right)$$

(after [Fortescue, Stark & Swinerd, 2003])

Ideal multi-stage rocket (cnt'd)

Derivation of 4th equation on previous sheet:

$$M_{payload} = p\,M_{begin} \quad \text{and} \quad M_{constr} = \sigma\,M_{prop}$$

so

$$M_{begin} = p\,M_{begin} + M_{constr} + M_{prop}$$

which becomes

$$(1-p)\,M_{begin} = M_{constr} + M_{prop} = (\sigma+1)\,M_{prop}$$

or

$$M_{begin} = \frac{1+\sigma}{1-p}\,M_{prop}$$

mass ratio for Tsiolkovsky's equation :

$$\frac{M_{begin}}{M_{end}} = \frac{\dfrac{1+\sigma}{1-p}\,M_{prop}}{p\,\dfrac{1+\sigma}{1-p}\,M_{prop} + \sigma\,M_{prop}} = \frac{\dfrac{1+\sigma}{1-p}}{p\,\dfrac{1+\sigma}{1-p} + \sigma} = \frac{1+\sigma}{p(1+\sigma)+\sigma(1-p)} = \frac{1+\sigma}{p+p\sigma+\sigma-p\sigma} = \frac{1+\sigma}{p+\sigma}$$

Ideal multi-stage rocket (cnt'd)

stage "i" only :

$$\Delta V_i = I_{sp,i}\, g_0 \ln\left(\frac{1+\sigma_i}{p_i+\sigma_i}\right)$$

total launcher :

$$\Delta V_{tot} = \sum \Delta V_i = \sum I_{sp,i}\, g_0 \ln\left(\frac{1+\sigma_i}{p_i+\sigma_i}\right)$$

assume

$$I_{sp,i} = I_{sp}$$

$$\sigma_i = s$$

so

$$\Delta V_{tot} = \sum I_{sp}\, g_0 \ln\left(\frac{1+s}{p_i+s}\right)$$

(after [Fortescue, Stark & Swinerd, 2003])

Ideal multi-stage rocket (cnt'd)

by definition :

$$P_{tot} = p_1 \times p_2 \times p_3 \times .....\times p_N = \prod p_i$$

optimal solution (w.o.derivation):

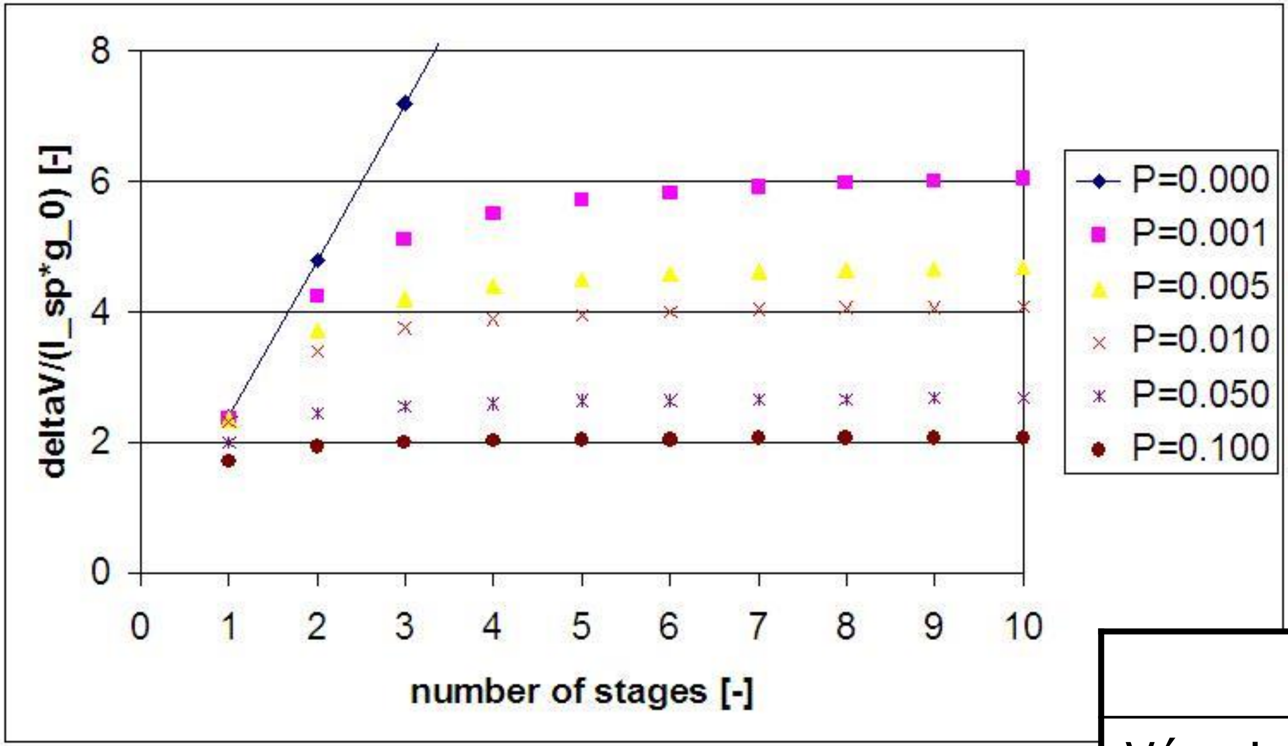
$$p_i = \sqrt[N]{P_{tot}}$$

so

$$\Delta V_{tot} = I_{sp}\ g_0\ N\ \{\ln(1+s) - \ln(s + \sqrt[N]{P_{tot}})\}$$

(after [Fortescue, Stark & Swinerd, 2003])

Ideal multi-stage rocket (cnt'd)



	N	P
Véronique	1	0.044
Ariane-4	2	0.02-0.03

- #stages typically 3 or 4
- single stage: $\Delta V/(I_{sp}g_0)$ 1.7 – 2.4 (factor 1.4)
- 4 stages: $\Delta V/(I_{sp}g_0)$ 2.0 – 5.5 (factor 2.8)
- staging very attractive (for modest P)
- high P: gain multi-staging limited (→ 2 stages for Ariane-5, Delta IV, Titan V, …) real challenge!

Ideal multi-stage rocket (cnt'd)

Question 1

The performance of a rocket (*i.e.*, the ΔV that can be obtained) is determined by the ratio M_{begin}/M_{end}, amongst others. New parameters "p" and "σ" can be defined: $p = M_{payload}/M_{begin}$ and $\sigma = M_{constr}/M_{prop}$.

Derive the following equation:

$$M_{begin}/M_{end} = (1+\sigma)/(p+\sigma)$$

Ideal multi-stage rocket (cnt'd)

Question 2

The performance of a rocket (*i.e.*, the ΔV that can be obtained) is determined by the ratio M_{begin}/M_{end}, amongst others. New parameters "p_i" and "σ_i" can be defined for each possible stage "i": $p_i=M_{payload,i}/M_{begin,i}$ and $\sigma_i=M_{constr,i}/M_{prop,i}$.

Derive the following equation which holds for an arbitrary number of stages N (where it is assumed that the parameters σ_i are equal to "s" for all stages, and the payload fractions of all stages p_i are equal to (N)$\sqrt{P_{tot}}$ (*i.e.*, the N^{th} root of P_{tot}):

$$\Delta V_{tot} = I_{sp}\, g_0\, N \{\ln(1+s) - \ln(s + \sqrt[N]{P_{tot}})\}$$

Ideal multi-stage rocket (cnt'd)

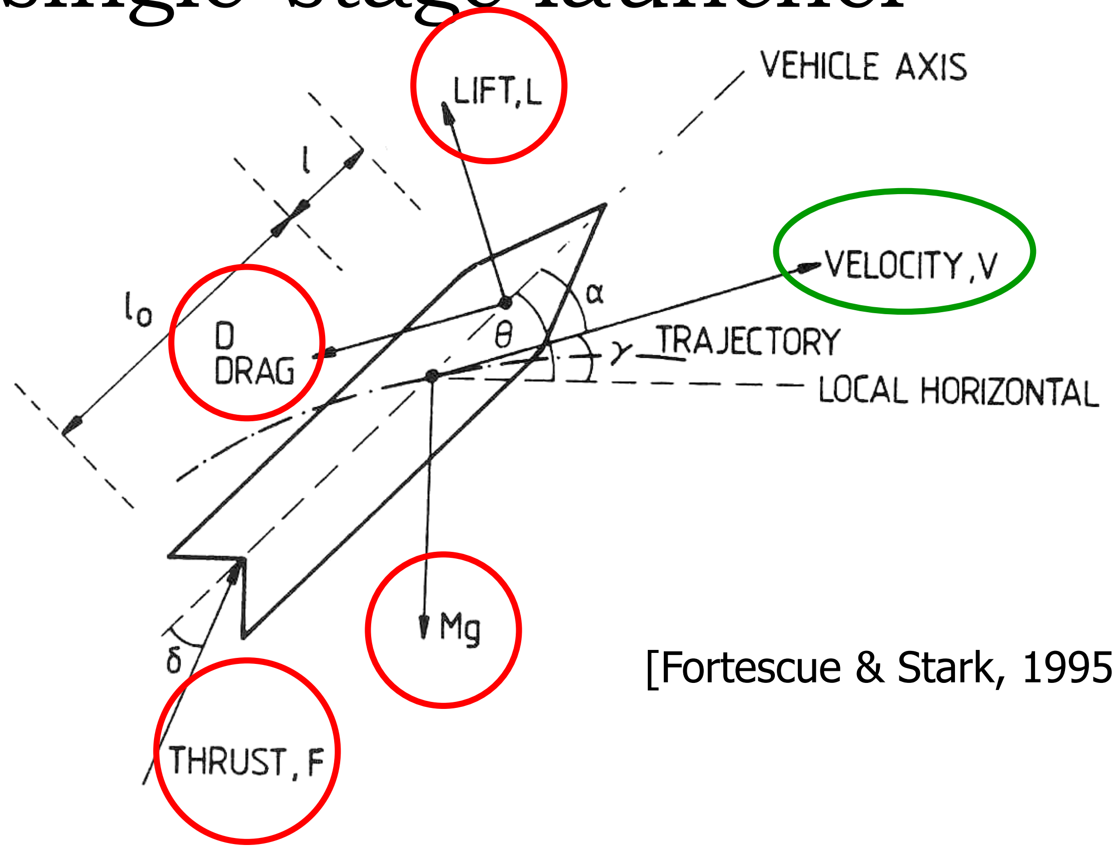
Question 3

Given the equation

$$\Delta V_{tot} = I_{sp}\, g_0\, N\, \{\ln(1+s) - \ln(s + \sqrt[N]{P_{tot}})\}$$

1. What do the various parameters represent?
2. What does the equation express?
3. Make a sketch of the behaviour of $\Delta V_{tot}/(I_{sp}\ g_0)$ as a function of parameter N, for the case P_{tot} = 0.001 and the case P_{tot} = 0.010 (parameter "s" is equal to 10%). Clearly indicate the (range of) numerical values for $\Delta V_{tot}/(I_{sp}\ g_0)$.
4. Discuss the consequences of increasing N for both cases of P_{tot}.

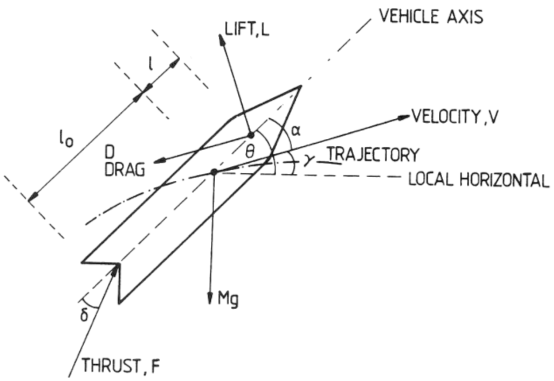
Real single-stage launcher



[Fortescue & Stark, 1995]

In direction of flight: M dV/dt = F cos(α+δ) – M g sin(γ) - D

Real single-stage launcher

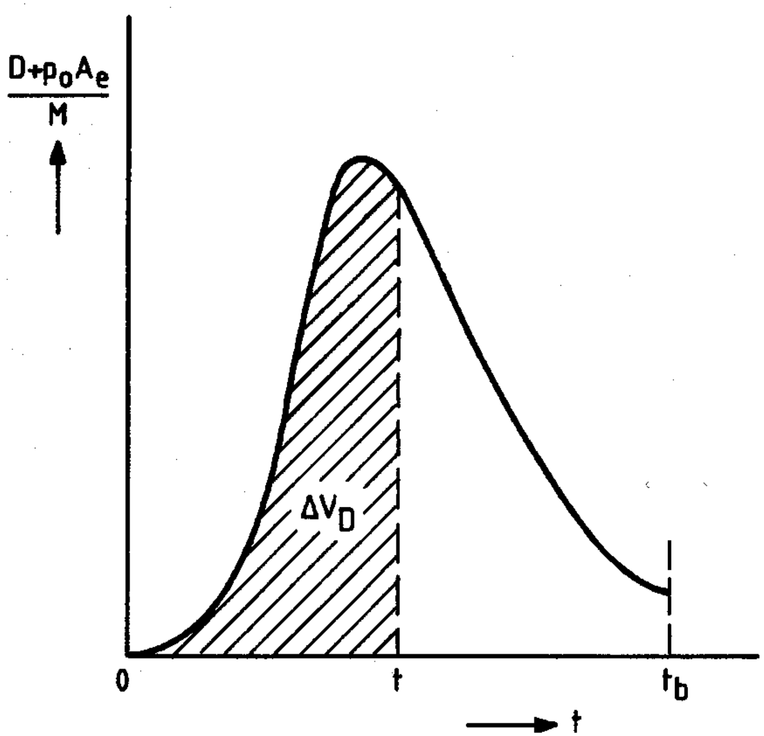


In direction of flight: $M\,dV/dt = F\cos(\alpha+\delta) - M\,g\sin(\gamma) - D$

1. Thrust misalignment: $\alpha+\delta \neq 0°$ (α needed to counteract gravity, δ for steering → cannot be avoided)

2. Gravity loss: $\gamma \neq 0°$ (launcher lifts off in vertical direction → unavoidable)

3. Drag loss: $D \neq 0$ (first part of trajectory through atmosphere → unavoidable)



Real single-stage launcher (cnt'd)

vertical flight :

$$dV = -w\frac{dM}{M} - g\,dt - \frac{D}{M}dt$$

integration :

$$V_{end} = -\int w\frac{dM}{M} - \int g\,dt - \int \frac{D}{M}dt =$$

$$= V_{end,ideal} - \Delta V_g - \Delta V_d$$

where

$$V_{end,ideal} = I_{sp}\, g_0 \ln(\Lambda)$$

$$\Delta V_g = g_0\, t_b$$

Real single-stage launcher (cnt'd)

velocity at burnout:

$$V_{burnout} = I_{sp}\, g_0 \left[\ln(\Lambda) - \frac{1}{\Psi_0}\left(1 - \frac{1}{\Lambda}\right) \right]$$

- including gravity losses
- w/o drag losses

altitude at burnout:

$$h_{burnout} = \frac{I_{sp}^2\, g_0}{\Psi_0} \left[\left(1 - \frac{\ln(\Lambda)+1}{\Lambda}\right) - \frac{1}{2\Psi_0}\left(1 - \frac{1}{\Lambda}\right)^2 \right]$$

altitude at culmination:

$$h_{culm} = \frac{I_{sp}^2\, g_0}{\Psi_0} \left(\frac{1}{2}\Psi_0 \ln^2(\Lambda) - \ln(\Lambda) - \frac{1}{\Lambda} + 1 \right)$$

time until culmination:

$$t_{culm} = I_{sp} \ln(\Lambda)$$

Real single-stage launcher (cnt'd)

Data:

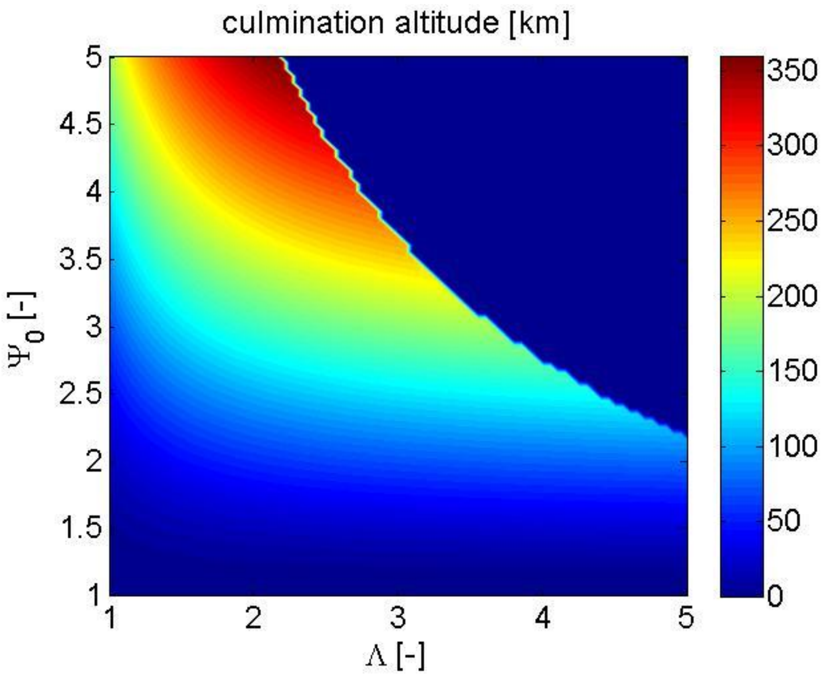
- specific impulse I_{sp} = 300 s
- $\Psi_0 = 1.5$
- $\Lambda = 5$

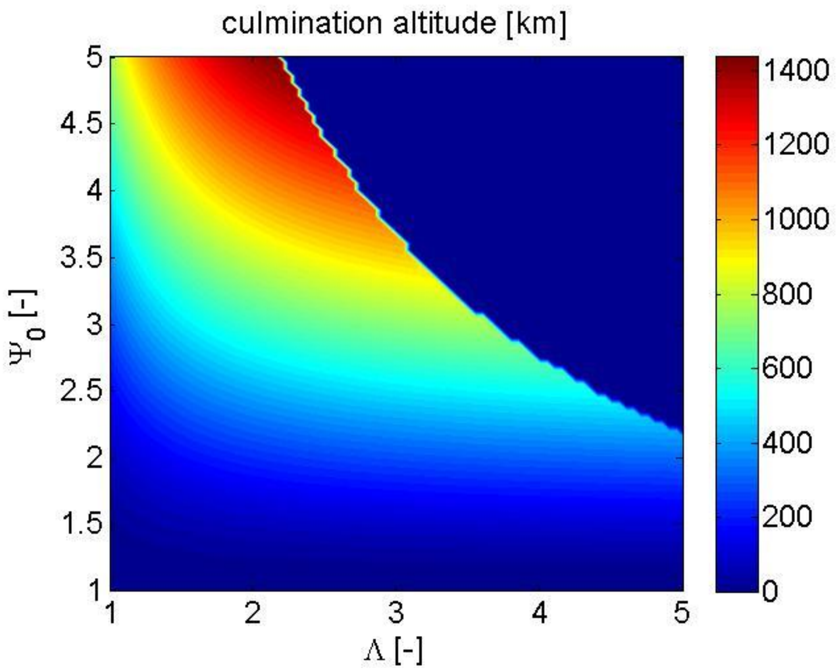
Results:

	w/o gravity	with gravity
burn time [s]	160.0	
burnout velocity [m/s]	4736.6	3167.0
burnout height [km]	281.4	155.8
culmination time [s]	-	482.8
culmination height [km]	-	667.0
culmination height for impulsive shot [km]	-	1143.5

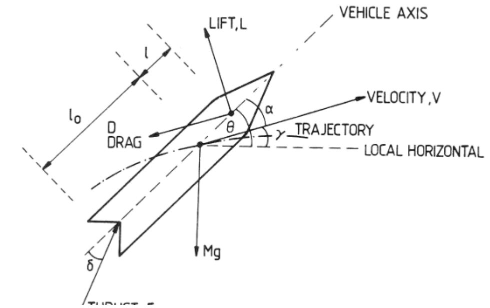
Real single-stage launcher (cnt'd)

Culmination altitudes of single-stage launchers, for I_{sp} = 200 s (left) and 400 s (right). Maximum acceleration = 10g.





Real single-stage launcher (cnt'd)



Gravity loss: minimize by shifting to horizontal flight a.s.a.p.

Drag loss: minimize by reducing trajectory through atmosphere

CONFLICT !!

Solution 1: start in vertical directory, then turn to (more) horizontal direction.

Solution 2: use air-launched vehicle.

Example: Pegasus

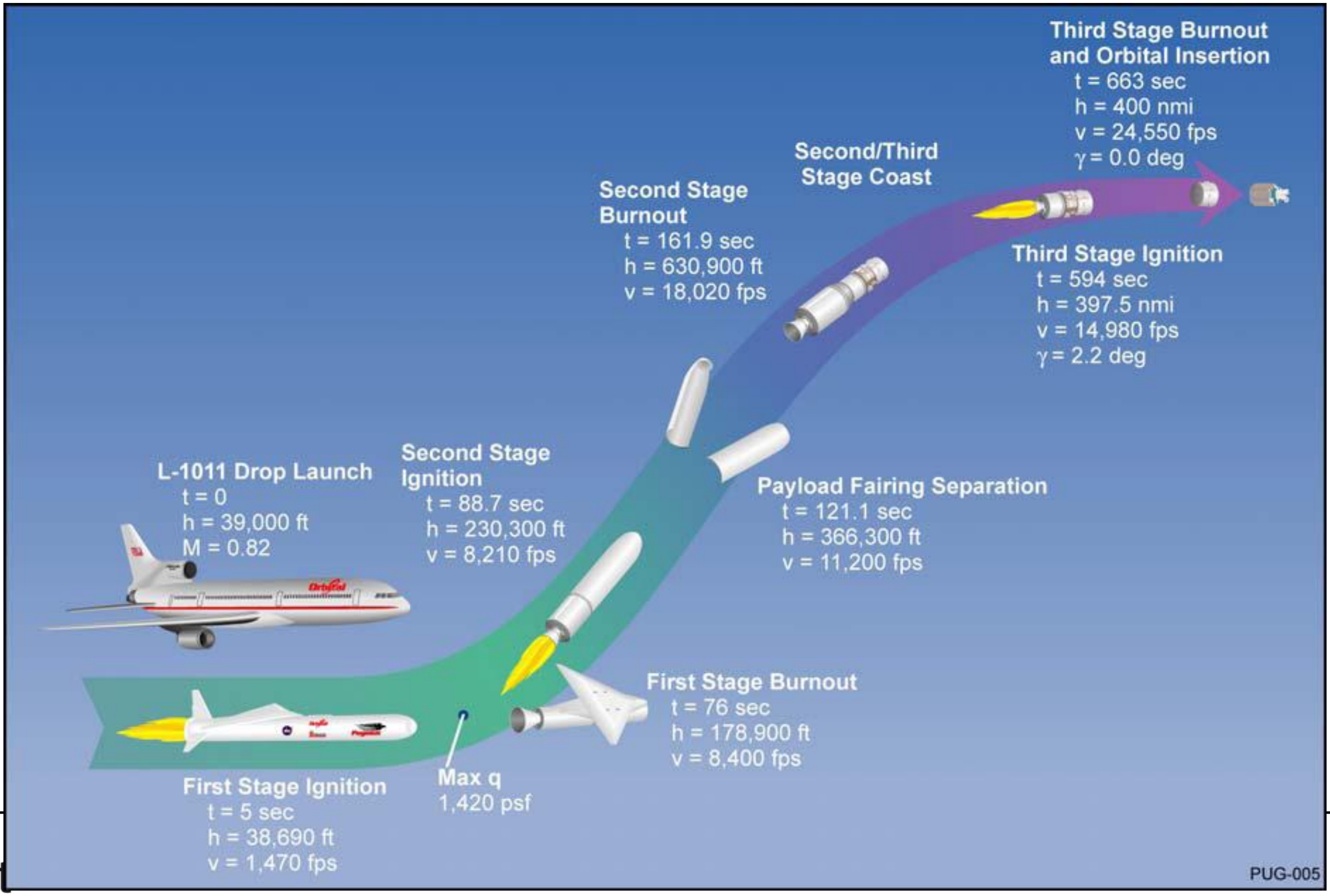
Requirements [OSC, 2003]:

- maximum payload 455 kg into LEO
- cost-effective
- reliable
- flexible
- minimum ground support
- multiple payload capability
- short lead time
- (released at 12 km altitude)

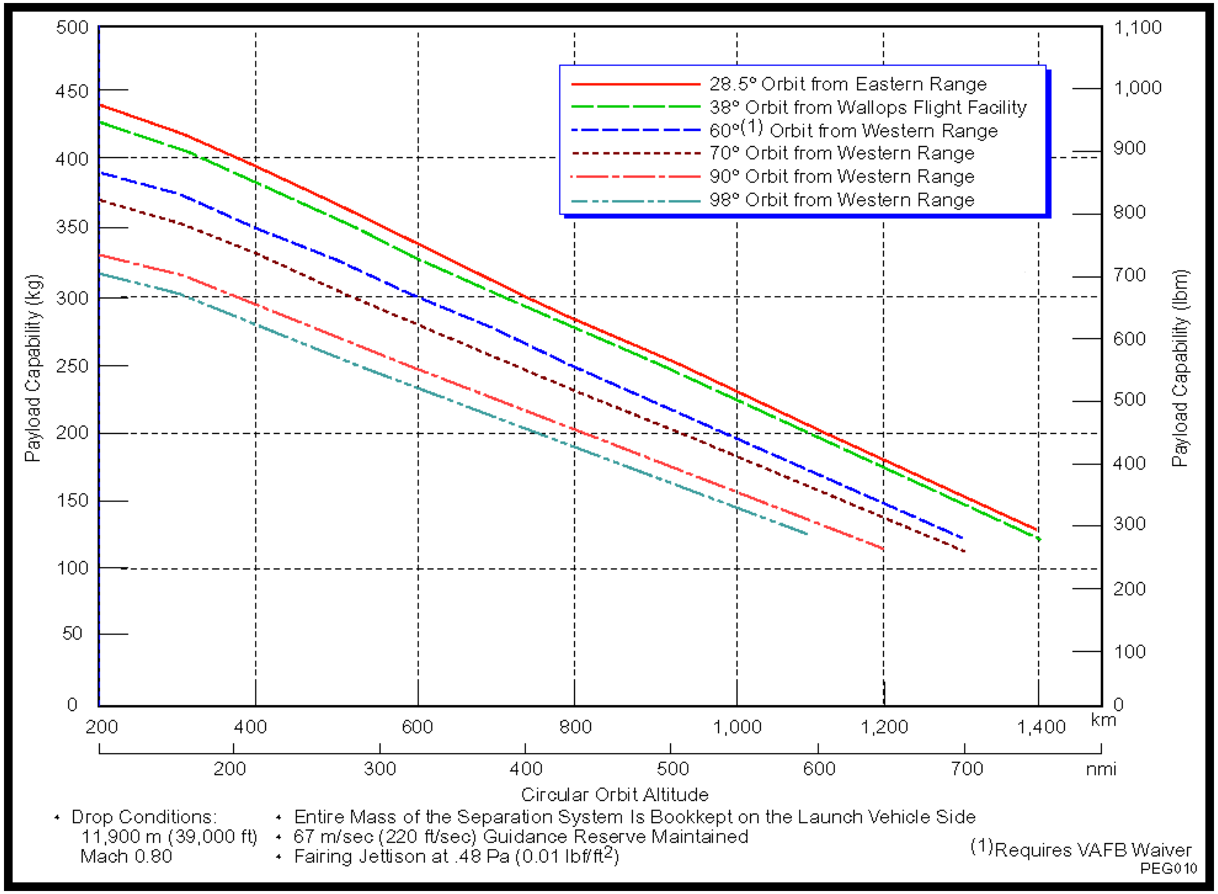
[OSC, 2010]

Example: Pegasus (cnt'd)

Pegasus XL mission profile [OSC, 2007]



Overall performance



[OSC, 2000]

Can we (easily) reproduce these numbers?

Overall performance (cnt'd)

Specific energy (*i.e.*, energy per unit of mass):

$$E_{orbit} = E_{pot,begin} + E_{kin,eff} - \Delta E_{pot}$$

- E_{orbit} = total energy in orbit (sum of kinetic+potential)
- $E_{pot,begin}$ = potential energy at launch
- $E_{kin,eff}$ = effective kinetic energy
- ΔE_{pot} = gain in potential energy

Overall performance (cnt'd)

Substitution:

$$-\frac{\mu}{2a} = -\frac{\mu}{R_e + h_{launch}} + \frac{1}{2}\left(V_0 + \Delta V_1 + \Delta V_2 + \Delta V_3 - \Delta V_{d+g}\right)^2 - \left(-\frac{\mu}{a} + \frac{\mu}{R_e + h_{launch}}\right)$$

- μ = gravitational parameter Earth
- a = semi-major axis of orbit
- h_{launch} = altitude of launch platform
- V_0 = velocity of launch platform
- $\Delta V_{1,2,3}$ = velocity increment delivered by stage 1,2,3
- ΔV_{d+g} velocity loss due to atmosphere and gravity

Overall performance (cnt'd)

Pegasus carrier:

velocity Earth

velocity L1011

$$V_0 = 0.463\cos(\delta_{launch})\frac{\cos(i)}{\cos(\delta_{launch})} + 0.222$$

Pegasus vehicle:

stage	I_{sp} [s]	M_{prop} [kg]	M_{constr} [kg]	M_{begin} [kg]
3	289.3	770	126	$M_{payload}+M_{prop,3}+M_{constr,3}$
2	291.3	3925	416	$M_{begin,3}+M_{prop,2}+M_{constr,2}$
1	295.9	15014	1369	$M_{begin,2}+M_{prop,1}+M_{constr,1}$

➔ a = f(i, δ_{launch}, h_{launch}, payload mass)

Overall performance (cnt'd)

[Wertz&Larson, 1991]:

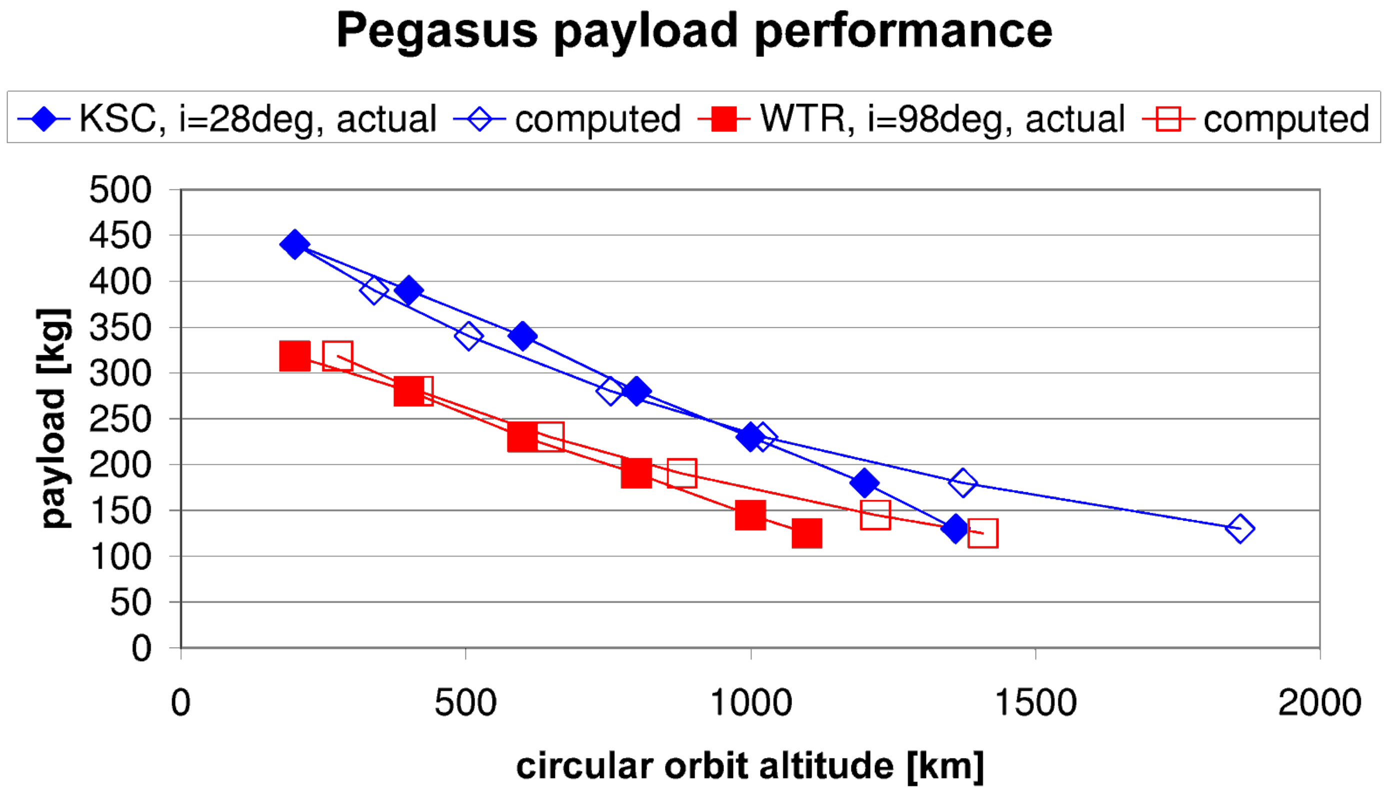
- Drag+gravity losses 1.5-2.0 km/s
- Drag loss: 0.3 km/s

Pegasus: small launcher ➔

- Drag+gravity losses 1.5 km/s
- Drag loss 0.3 km/s
- Gravity loss 1.5 – 0.3 = 1.2 km/s

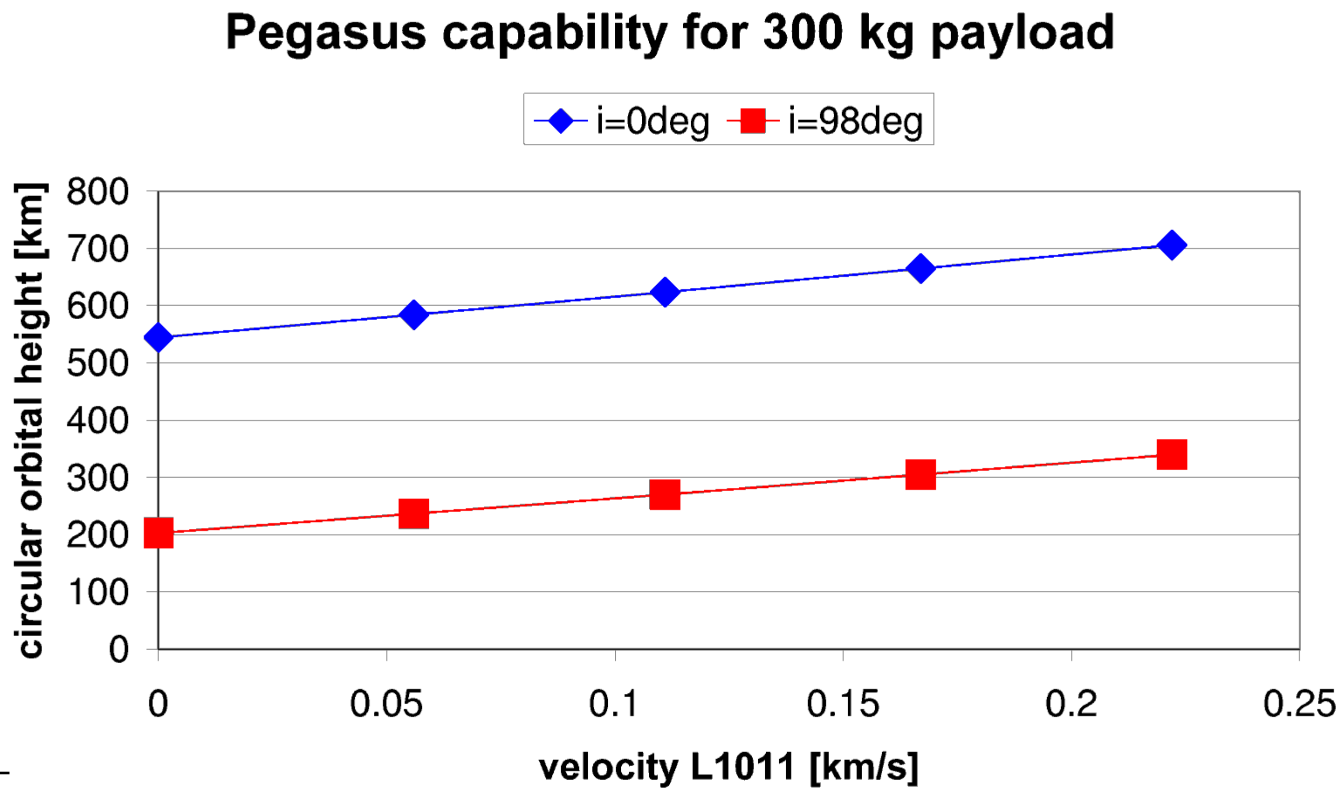
Overall performance (cnt'd)

Results for launches due East from KSC (δ=28.5°) and WTR (δ=34.6°):



Overall performance (cnt'd)

Orbit altitude as a function of carrier velocity ($M_{payload}$ = 300 kg, launch at equator):



Design

Can we (easily) reproduce the overall layout of a launcher?

Example: Pegasus

Design (cnt'd)

Some data and assumptions:

- 3 stages
- I_{sp} identical for all stages (290 s)
- M_{constr}/M_{total} identical for all stages (0.08)
- V_c = 7.784 km/s at h=200 km
- V_{earth} = 0.464 km/s at equator
- $V_{carrier}$ = 0.222 km/s w.r.t. Earth
- → $V_{pegasus,initial}$ = 0.686 km/s
- → ΔV_{ideal} = 7.784 – 0.686 = 7.098 km/s

Design (cnt'd)

- Drag loss 0.3 km/s
- Gravity loss 1.2 km/s

1st order approach:

- ΔV_{ideal} equally distributed over 3 stages
- Drag loss on account of 1st stage
- Gravity loss equally distributed over 3 stages

➔

- Stage 1: $\Delta V = 2.366 + 0.3 + 0.4 = 3.066$ km/s
- Stage 2 and 3: $\Delta V = 2.366 + 0.4 = 2.766$ km/s (each)

Design (cnt'd)

Tsiolkovsky's rocket equation:

$$\Delta V = g_0 \, I_{sp} \ln\left(\frac{M_{total}}{M_{total} - M_{prop}} \right)$$

$$\Delta V = g_0 \, I_{sp} \ln\left(\frac{M_{total}}{M_{constr} + M_{payload}} \right)$$

$$\frac{M_{constr}}{M_{total}} + \frac{M_{payload}}{M_{total}} = \exp\left(\frac{-\Delta V}{I_{sp} \, g_0} \right)$$

Design (cnt'd)

Stage 3:

$M_{payload}$ = 455 kg, I_{sp} = 290 s, M_{constr} / M_{total} ~ 0.08:

so:

- M_{total} = 1526 kg
- M_{constr} = 122 kg
- $M_{payload}$ = 455 kg
- M_{prop} = 949 kg

Next: total mass of stage 3 is equal to payload mass of stage 2.

Design (cnt'd)

	stage 3			stage 2			stage 1		
	re-eng [kg]	real [kg]	Δ [%]	re-eng [kg]	real [kg]	Δ [%]	re-eng [kg]	real [kg]	Δ [%]
payload	455	455	0.0	1526	1351	12.9	5116	5692	-10.1
constr.	122	126	-3.1	409	416	-1.6	1572	1369	14.8
prop.	949	770	23.2	3181	3925	-19.0	12961	15014	-13.7
total	1526	1351	12.9	5116	5692	-10.1	19649	22075	-11.0

Further reading

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