SPACE ELEVATOR CLIMBER DYNAMICS ANALYSIS AND CLIMB FREQUENCY OPTIMISATION

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Why is Dynamics Analysis Important ?

- **The Tether should be loaded to some safe stress limit to maximise capacity**
- **The peak tether stress depends on three parameters**

- Tether weight and mass distribution

Material Specific Strength, Density, Taper Ratio ***FIXED***

\- Tension at Earth Port

Another paper

\- Climber Masses and Positioning (if more than one on the tether)

Distribution of multiple climbers depends on dynamic behaviour :

Mass, departure frequency, power, maximum velocity, power source, …

Tether Taper and Stress Distribution

Conventionally : Tether Stress is constant

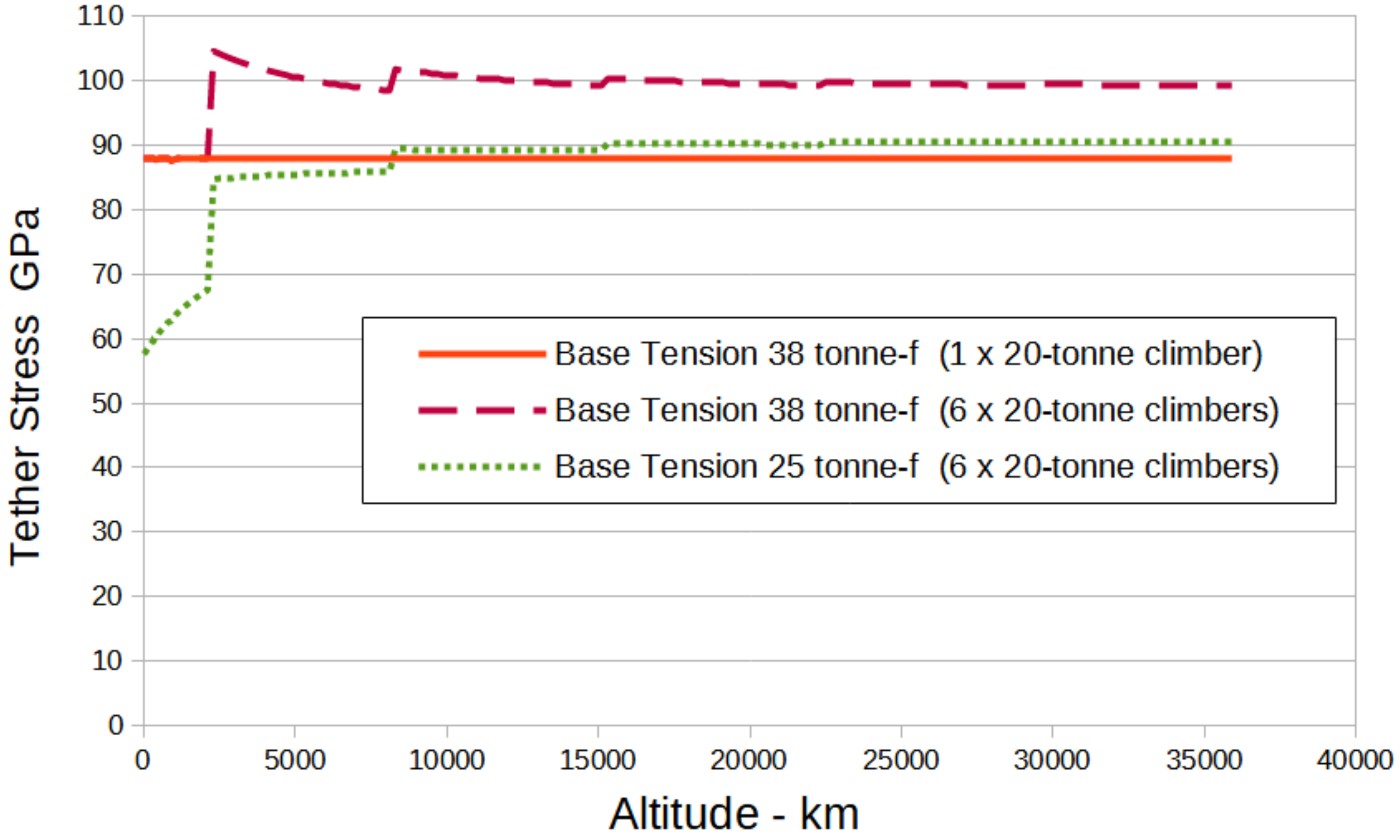
- Single Climber at Earth Port + Retention Force

BUT : Multiple Climbers increase stress

Lower base tension does not resolve problem

HENCE: a far heavier tether would be necessary

OPTIMISATION NEEDED



Spreadsheet Built to Study Climber / Tether Loading

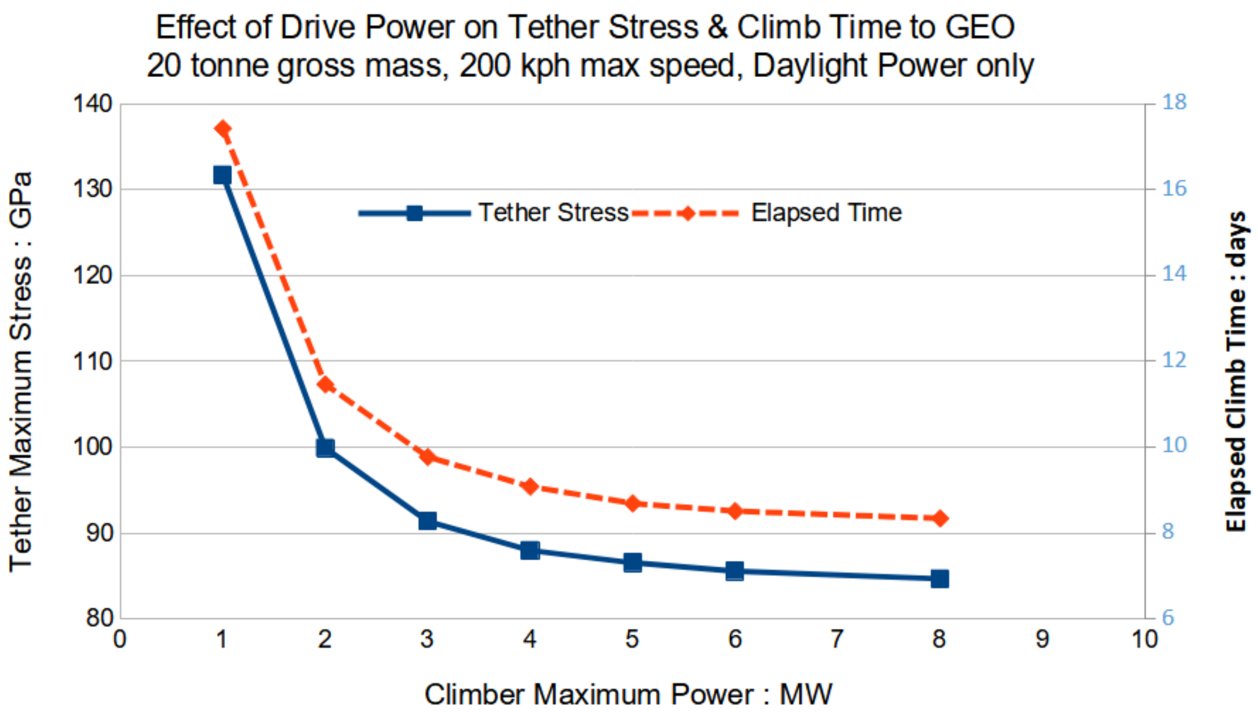
- **Based on finite-element tether model**
- **Climber velocity calculated for each element**
  - Based on power, mass, altitude
  - Time to ascend each element then derived ...
  - … and hence climb time to GEO
- **Climber weight added to tether based on Earth Port departure interval**
  - Peak tether stress found (+ *'suspended weight' for reference)*

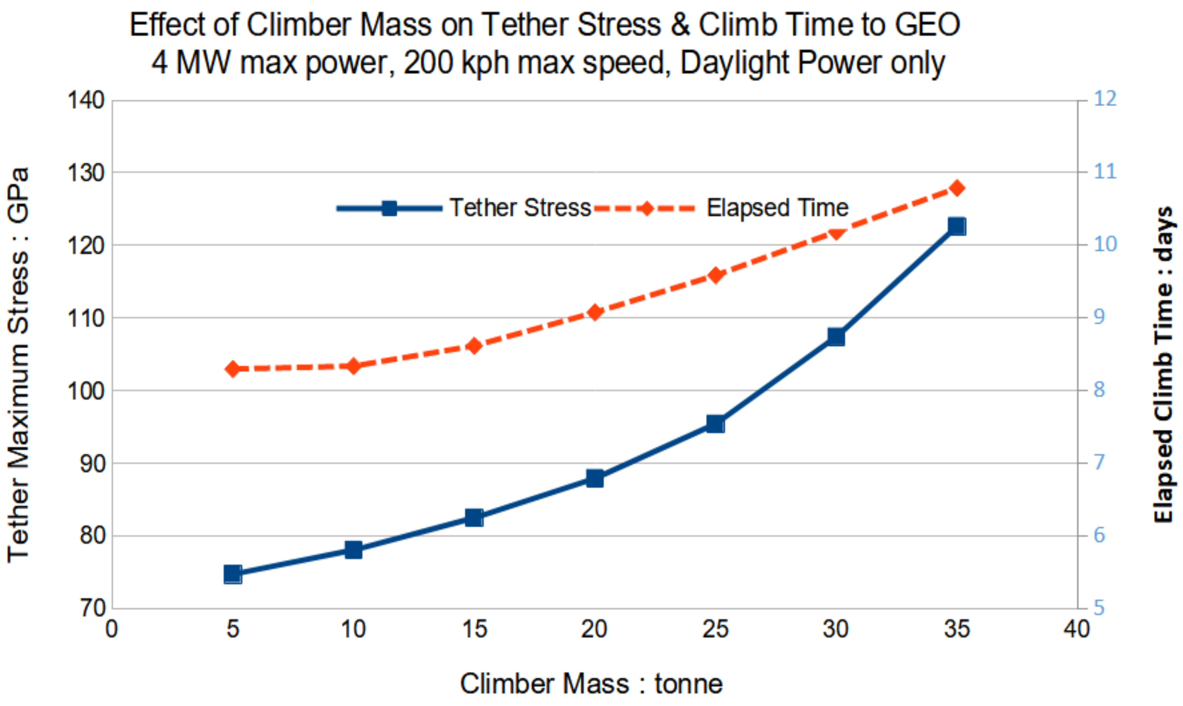
SUMMARY 'DASHBOARD

	Q	R	S	T	U	V	W	X	Y	
31	Dashboard	Climber Max Power	4.00	MW	Seasonal Axis Tilt			0 deg		
32		Maximum Speed	200.0	km/hr						
33		Climber Mass	20000	kg	*(Set Axis Tilt to zero for equinox, 23.5 deg for solstice)*					
34		Tether Stress	87.97	GPa						
35		Suspended Weight	46763	kgf at GEO						
36		Start Speed (60km)	75.1	km/hr						
37		Climbing Time	8.00	days	Climb Interval (hrs) 0=daylight only			0	Per Day	1
38		Elapsed Time	9.08	days	Climb Logic (0 or 1)		0	24		
39		*Yellow = INPUT*	*Blue = OUTPUT*							

Spreadsheet Built to Study Climber / Tether Loading

- **Manual Variation of Input Data yields results of parameter changes**
- EXAMPLES : effect of climber maximum power & mass on stress & climb time





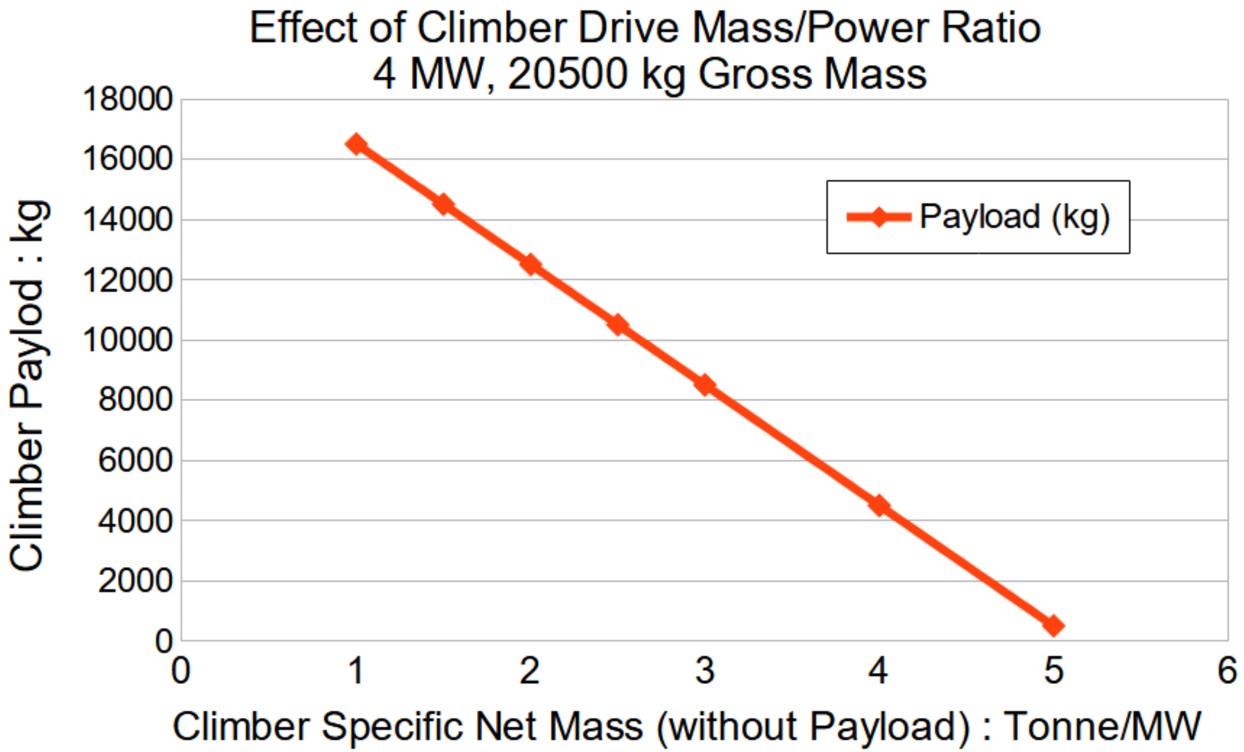
BUT : Tether Working Stress is effectively FIXED
and parameters can be varied independently

Spreadsheet Analysis : Payload

- **Payload** is a valuable parameter for Climber Performance analysis
  Payload = Gross Mass – Net Mass **CALCULATED IN POST-PROCESSING**
  Net Mass (tonnes) = Climber Specific Mass (tonne/MW) x Power (MW)

E21 f_x Σ = =E$15-E$13*$B21*1000

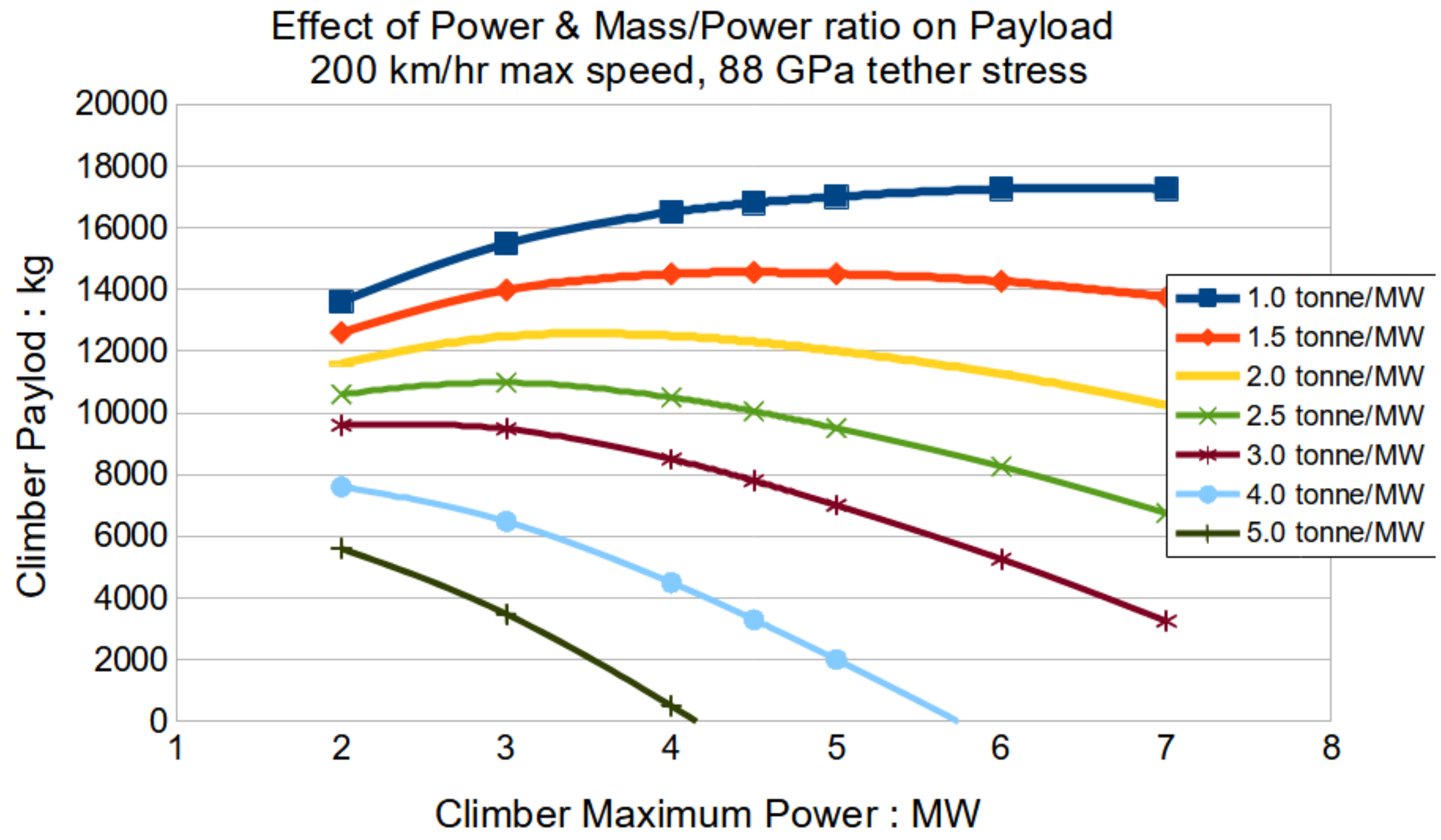
	A	B	E
13	**Climber Power**	MW	4.0
14	**Max Speed**	kph	200
15	**Climber Mass**	kg	20500
16	**Tether Stress**	GPa	88.0
17	**Climbing Time**	days	8.03
18	**Elapsed Time**	days	9.09
19		tonne/MW	
20	Payload (kg)	1.0	16500
21	Payload (kg)	1.5	14500
22	Payload (kg)	2.0	12500
23	Payload (kg)	2.5	10500



Payload has complex relationship with other parameters

Spreadsheet Analysis : Payload

Payload has complex dependency on **Specific Mass, Power** and **Maximum Climb Speed**



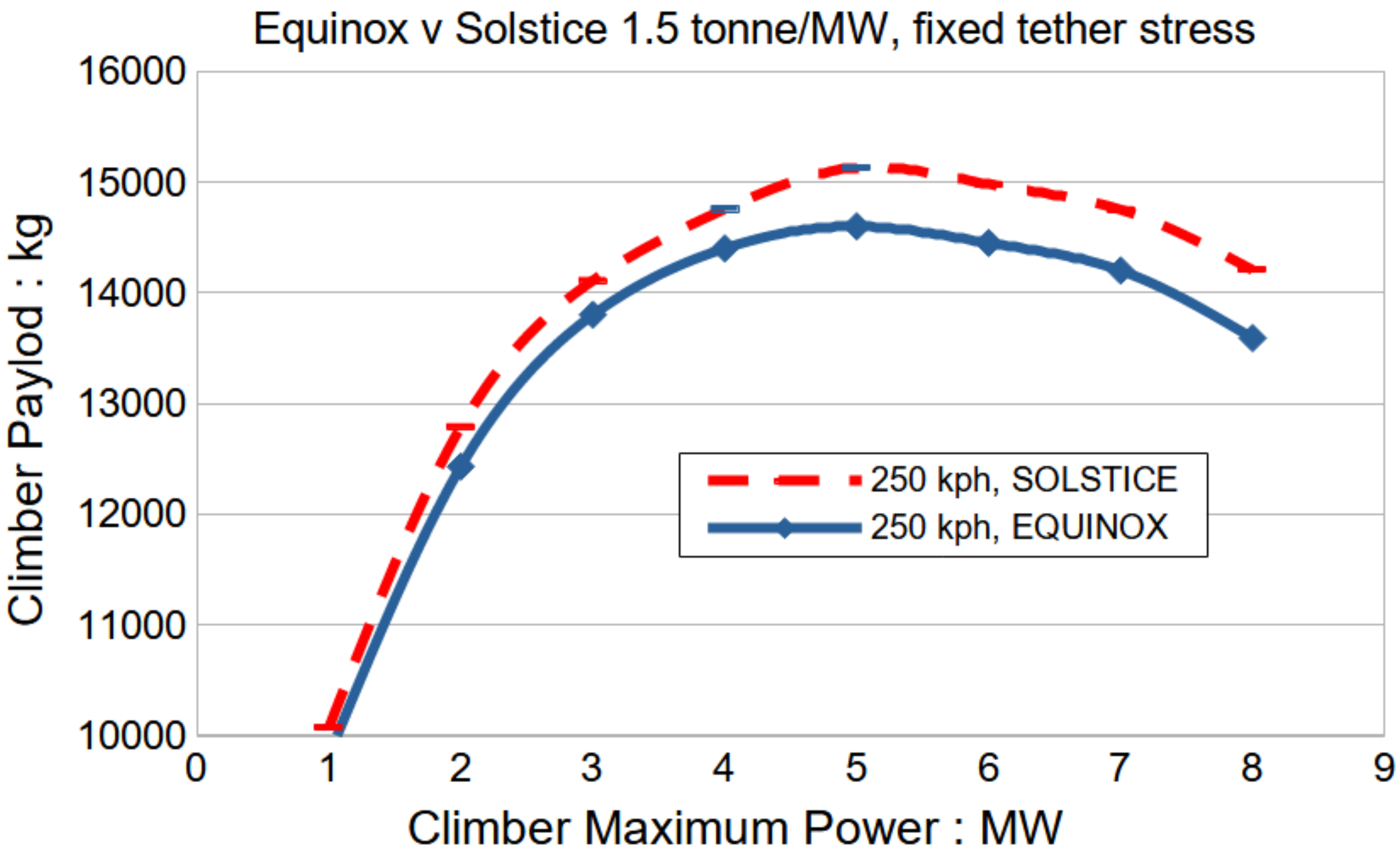
Note : a Net Mass of 6 tonnes is near optimum for many Specific Masses for 200 kph max speed

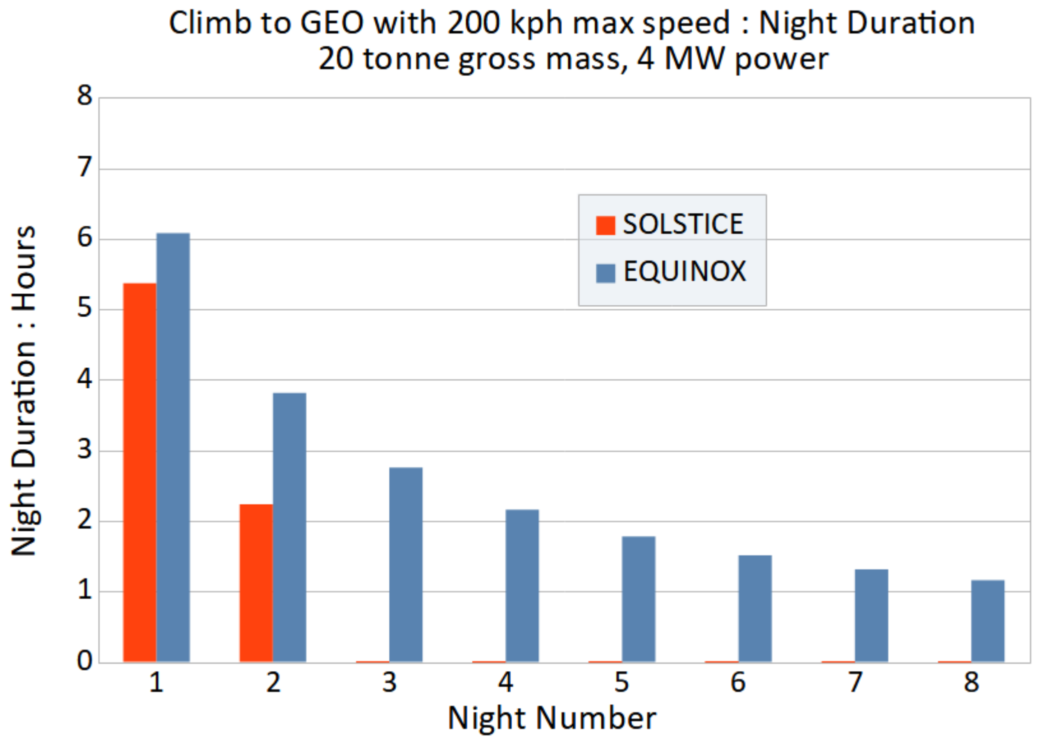
Spreadsheet Analysis : Payload

Potential Payload also depends on time of year for solar-powered climbers

Equinox : 'night' at all altitudes to GEO

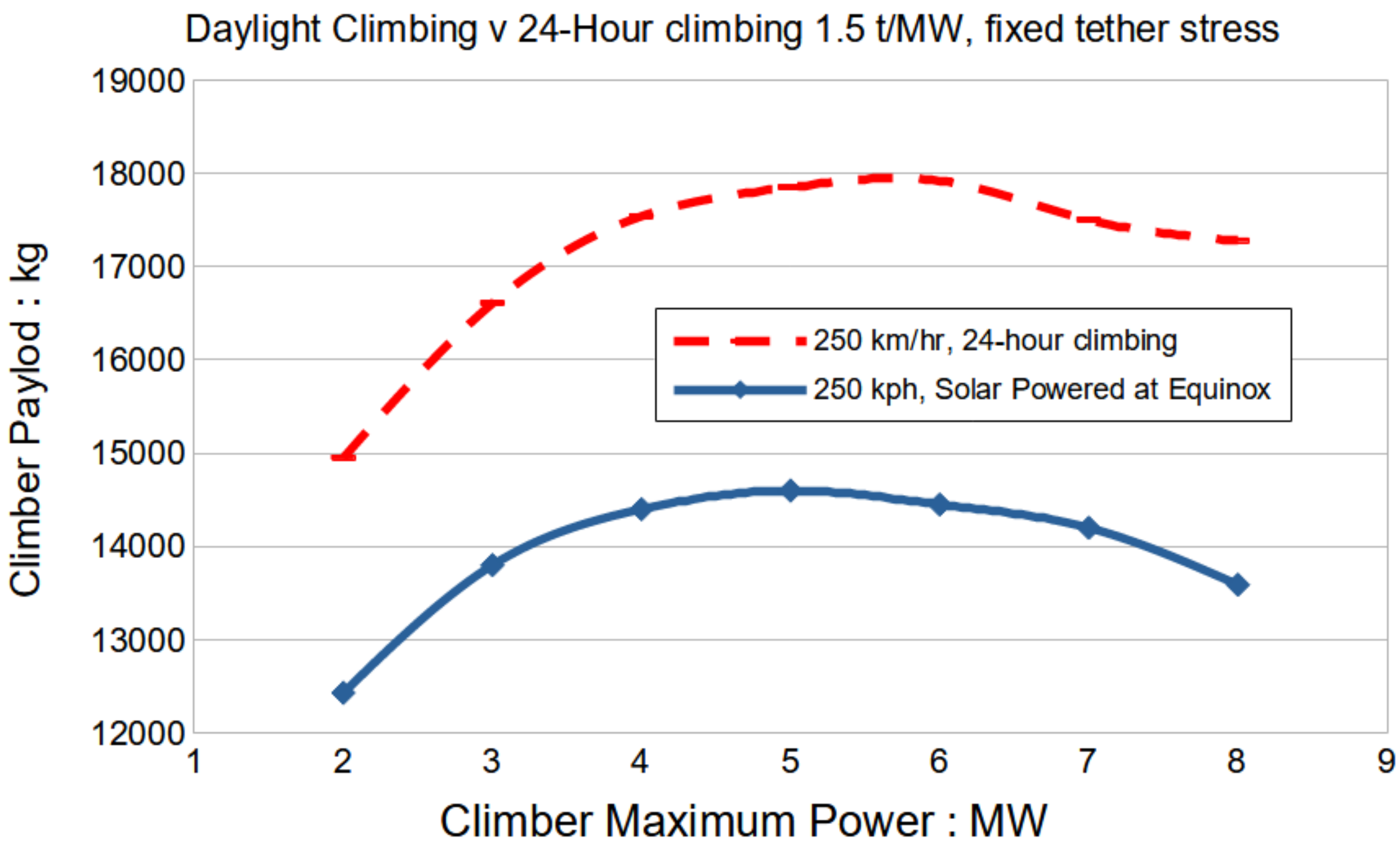
Solstices : no night above 10,000 km





Spreadsheet Analysis : Payload

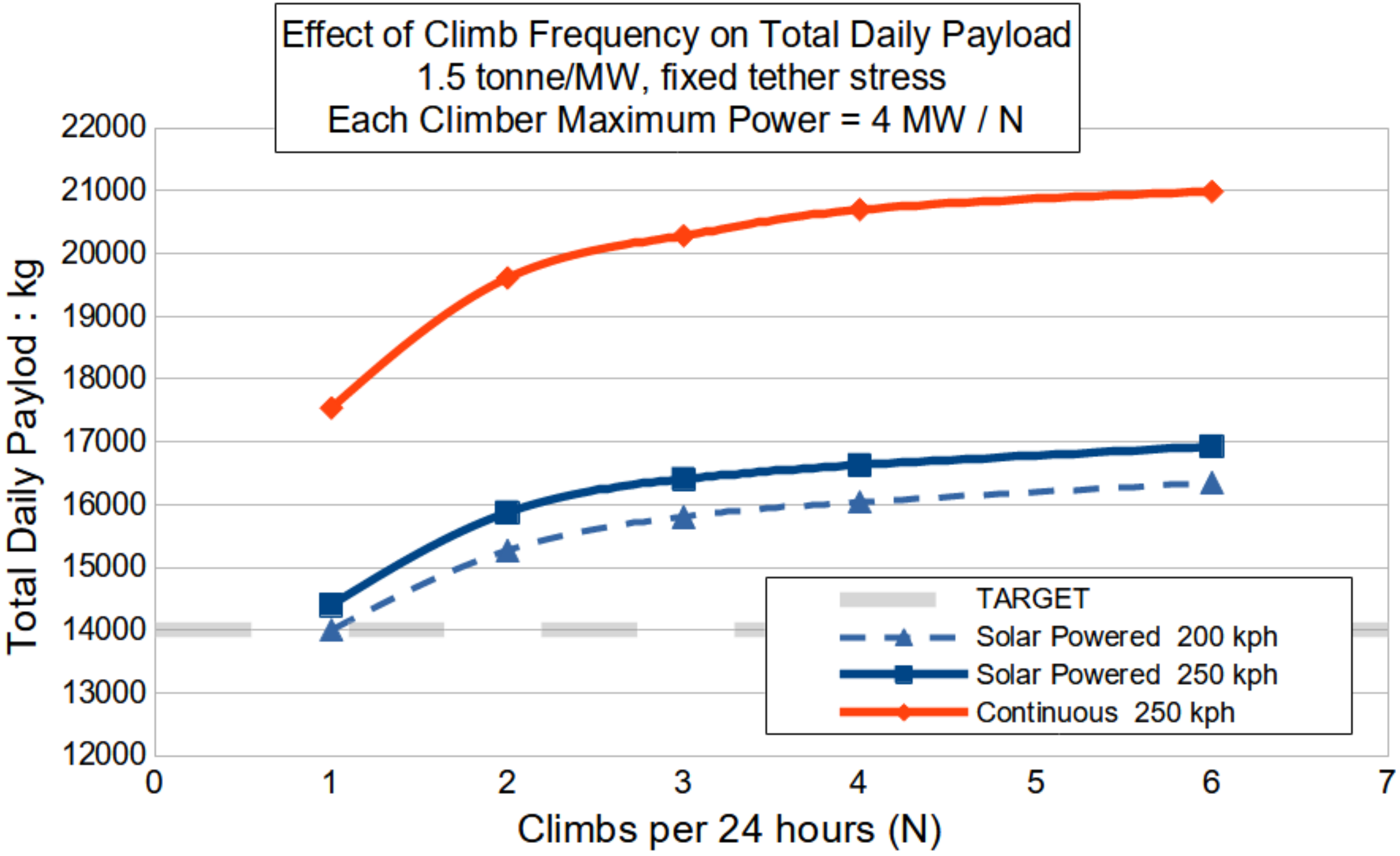
Potential Payload is strongly dependent on Power Source
24-hour climbing greatly reduces tether load, enabling greater payload



Spreadsheet Analysis : Payload

Potential DAILY Payload can be increased by Multiple Departures daily

with climber specific mass unchanged and same total MW/day



CONCLUSIONS

- A Spreadsheet method can be used to automatically position multiple climbers on a tether model to forecast peak tether stress

- Climber Payload can be optimised for any given tether working stress
  - Complex dependencies on climber mass, power, maximum speed

- Major Payload benefit from 24-hour climbing with multiple climbers
  - Overnight stops with solar power lead to reduced spacing

- Major Payload benefit from multiple smaller climbers each day
  - Single daily ascent means all payload is subject to 1g gravity

EARLIER WORK

Ben Shelef (Spaceward Foundation) paper published 2012 :

“Space Elevator Power System Analysis and Optimization”

yielded similar conclusions using analytic approach

“The trend continues to the limiting case of a continuous (variable speed) belt of cargo, though we see no practical way of implementing this case”

$$v_e = \beta \cdot \rho_P / g$$
$$r_T = r_e (v_T/v_e)^{0.5} = r_e \cdot Q_T$$
$$a_T = r_T - r_e$$
$$t_T = (r_e/r_T)(r_T - r_e)/v_e = (r_e/v_e)(Q_T - 1)/Q_T$$
$$r_H = r_e/k_H^{0.5}$$
$$a_H = r_H - r_e$$
$$t_H = t_T + (r_H - r_T)/v_T = (r_e/v_e)(Q_T - 1)/Q_T + (r_e k^{-0.5} - r_e Q_T)/v_T =$$
$$(r_e/v_T) \cdot [Q_T(Q_T - 1) - Q_T + k_H^{-0.5}] = (r_e/v_T)[Q_T(Q_T - 2) + k_H^{-0.5}]$$
$$k_H = [(t_H v_T/r_e) - Q_T(Q_T - 2)]^{-2}$$

$$v_e = \beta \cdot \rho_P / g$$
$$r_H = r_e (v_H/v_e)^{0.5} = r_e \cdot Q_H = r_e \cdot (k_H)^{-0.5}$$
$$a_H = r_H - r_e$$
$$v_H = v_e Q_H^2$$
$$t_H = (r_e/r_H)(r_H - r_e)/v_e = (r_e/v_e)(Q_H - 1)/Q_H = (r_e/v_H) Q_H (Q_H - 1)$$
$$\beta = g \cdot v_e/\rho_P = (g/\rho_P) \cdot (r_e/t_H) \cdot (Q_H - 1)/Q_H$$
$$c_H = (g/\rho_P) \cdot (r_e/t_H)$$
$$k_H = Q_H^{-2} = [c_H / (c_H - \beta)]^{-2}$$

QUESTIONS ?