# Problem sletanja na južnu hemisferu Marsa

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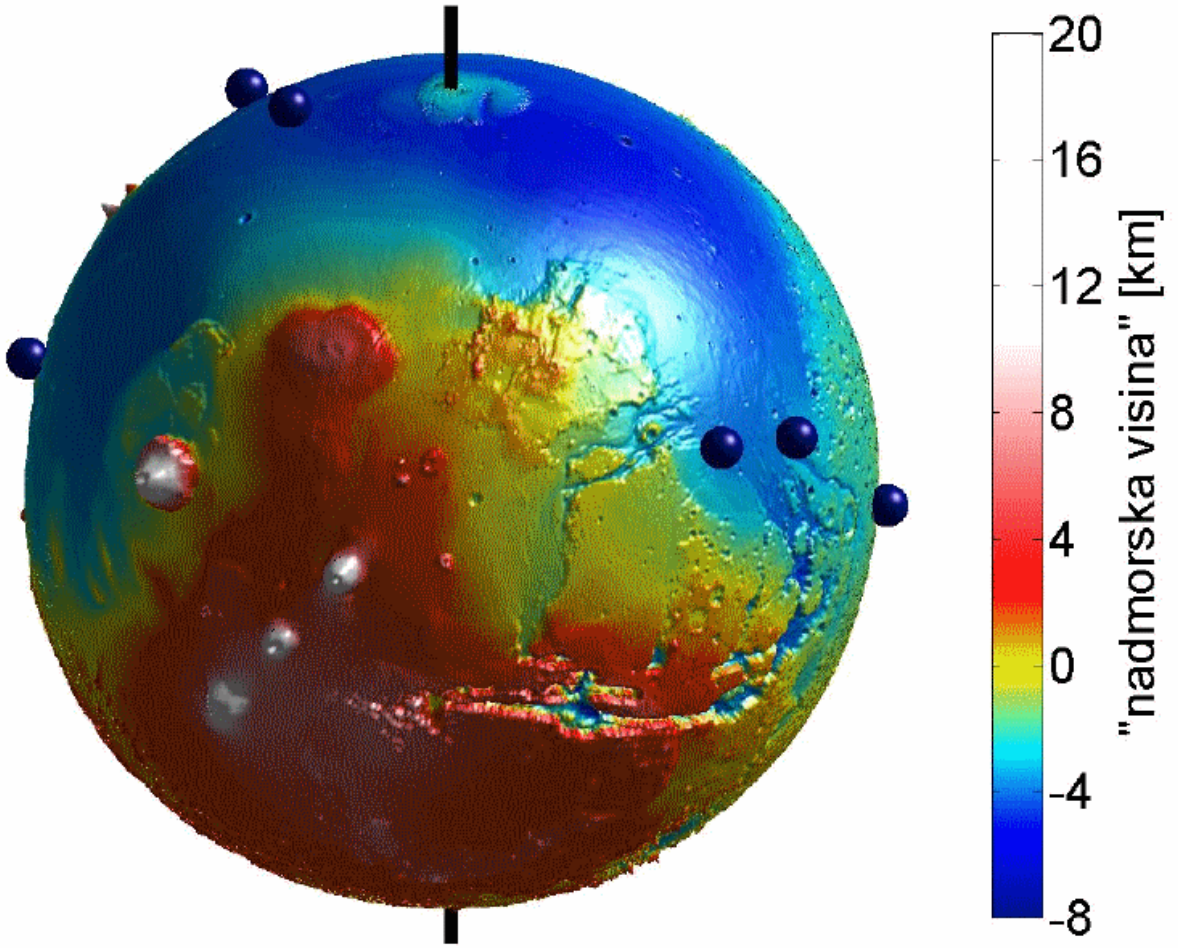
# CILJEVI ISTRAŽIVANJA

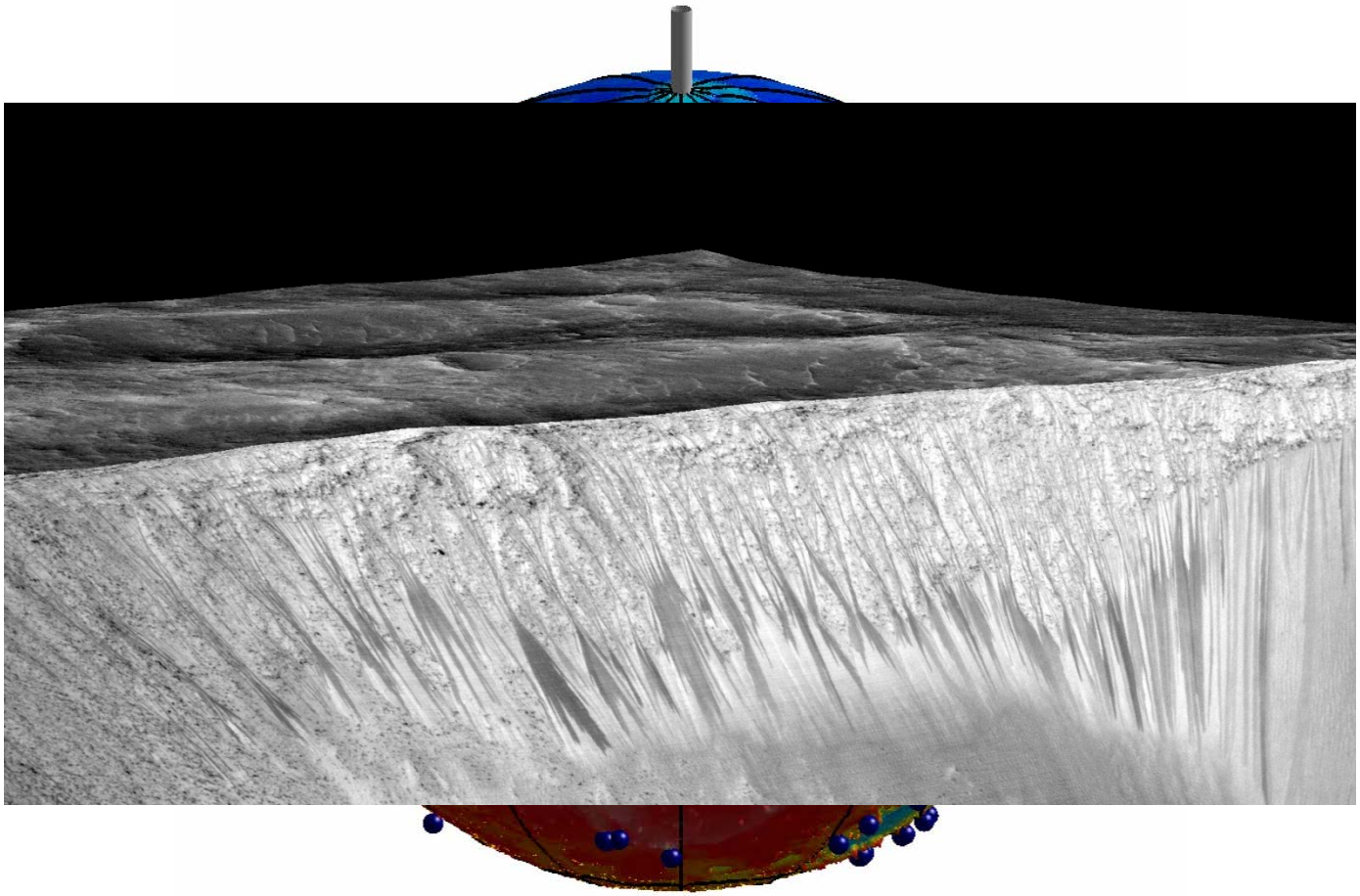
- Razvoj algoritma za određivanje balističke putanje objekta kroz planetsku atmosferu
- Istraživanje mogućnosti za sletanje na južne visoravni, bez unapređivanja postojeće tehnologije
- Određivanje optimalnih parametra za sletanje (*Ls, LPSV, v, γ*)

# MOTIVACIJA



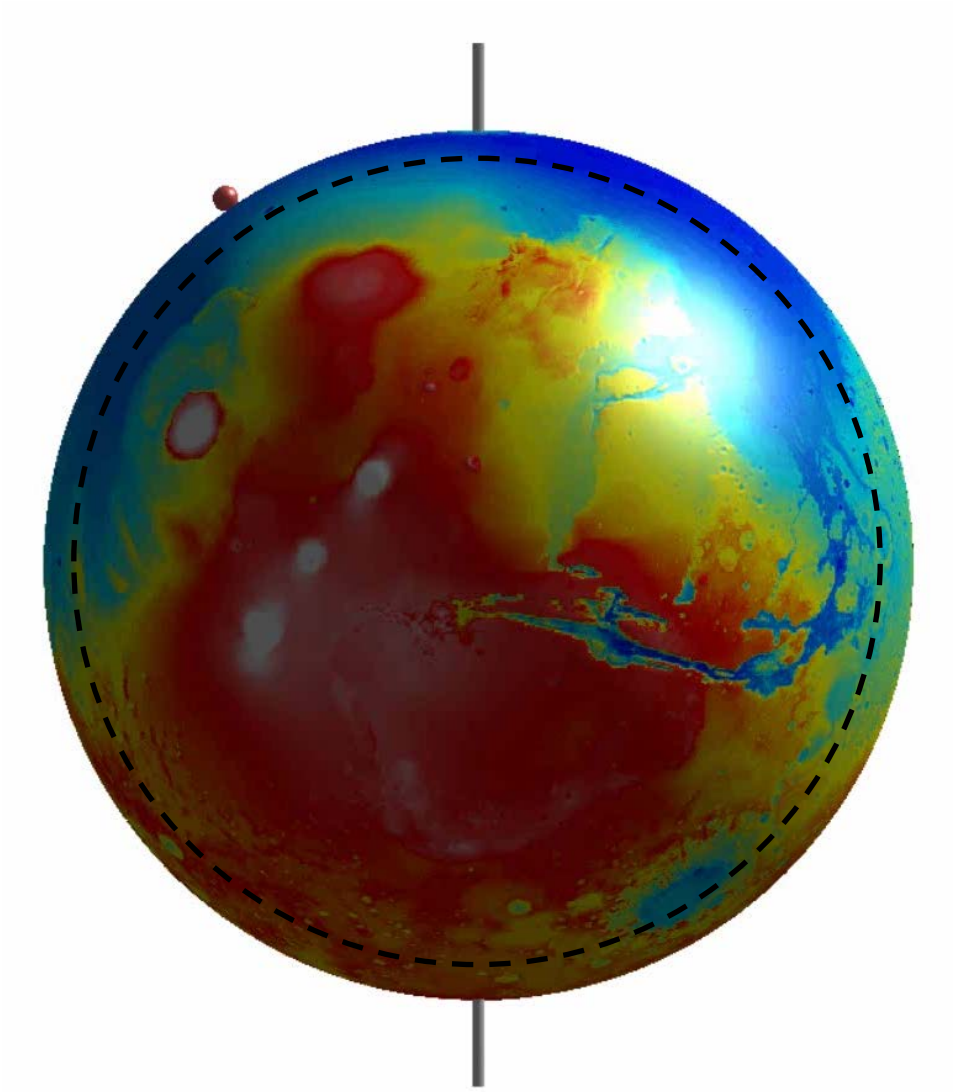

Smith et al., *Science, 1999.*

# MOTIVACIJA



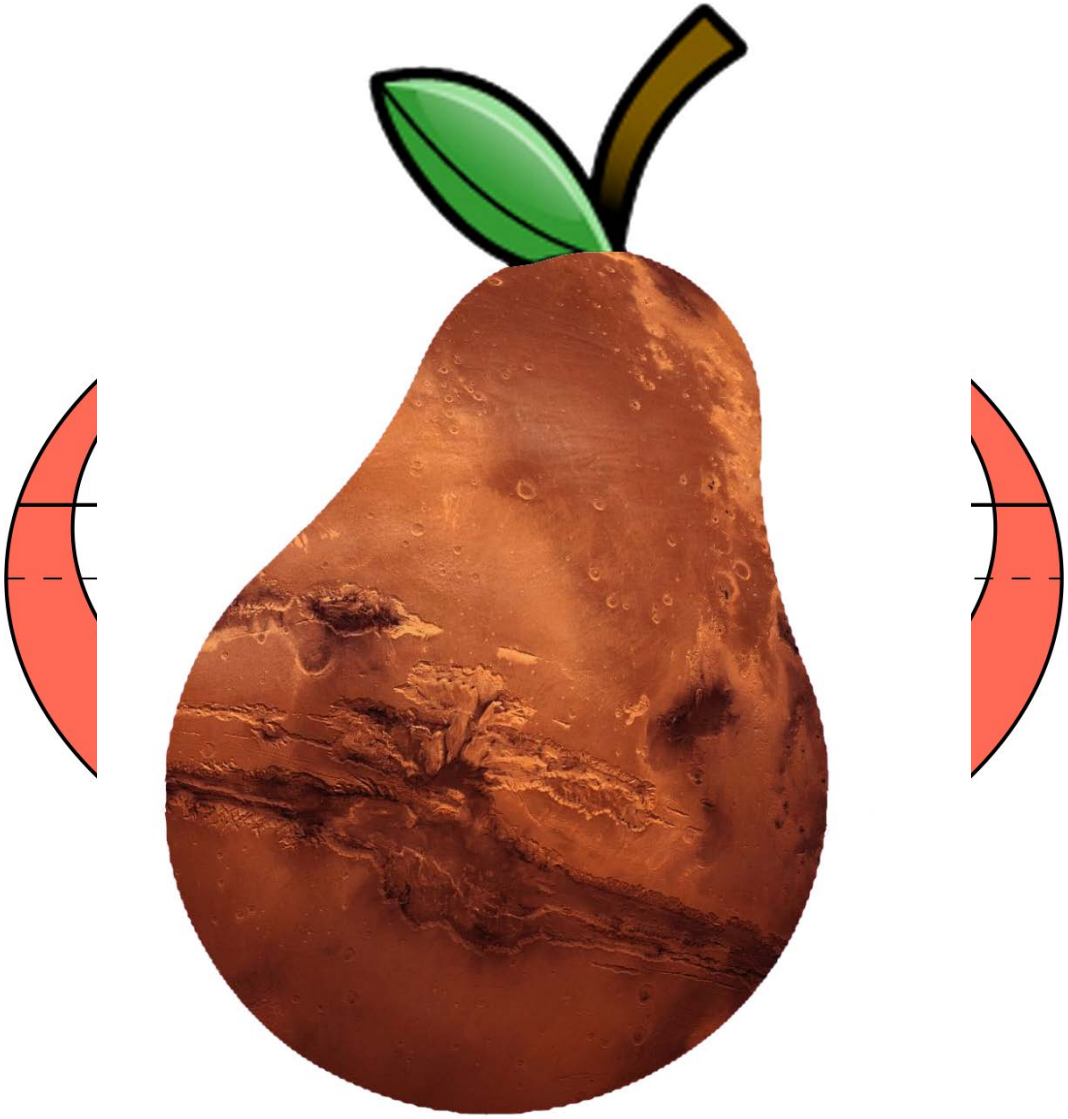
Fassett & Head, *Icarus, 2008.*

# POREKLO GLOBALNE DIHOTOMIJE



Wilhelms & Squyres, *Nature, 1984.*

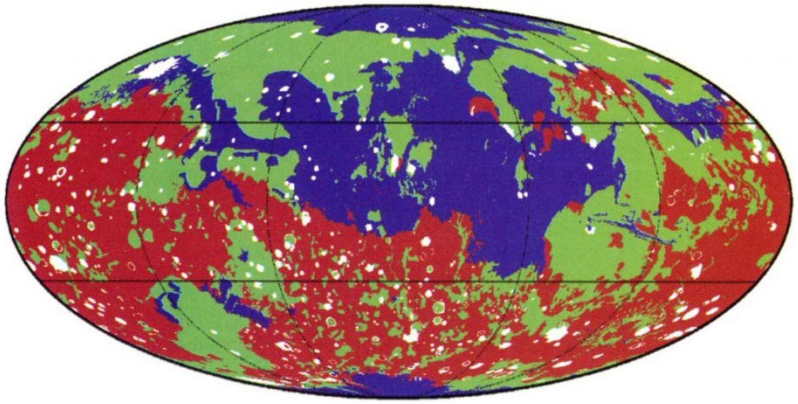
# UNUTRAŠNJA STRUKTURA MARSA



Smith et al., *Science, 1999.*

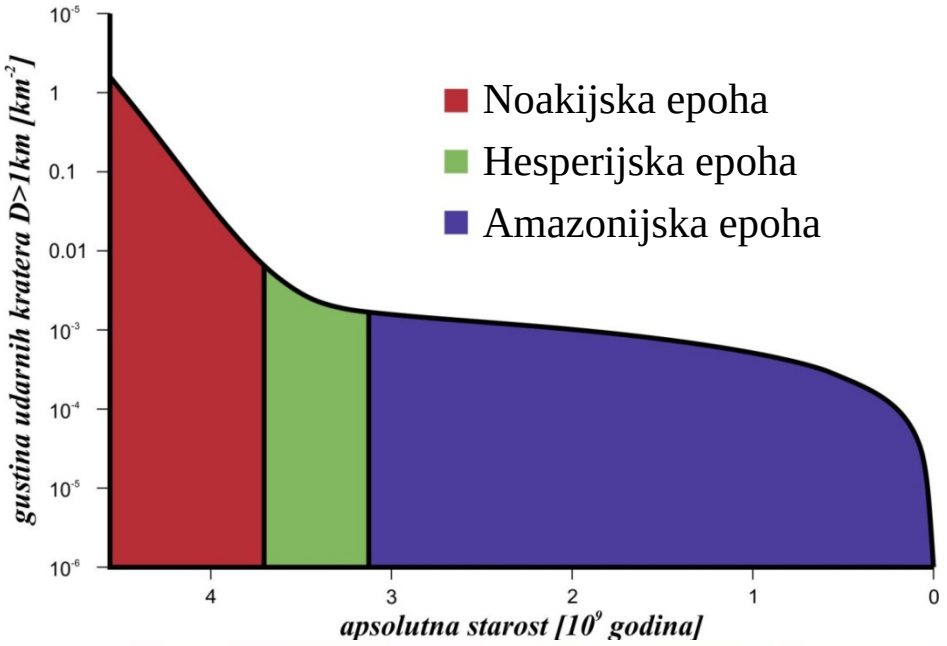
# STRATIGRAFIJSKA PODELA POVRŠINE MARSA

Solomon et al., *Science, 2005.*

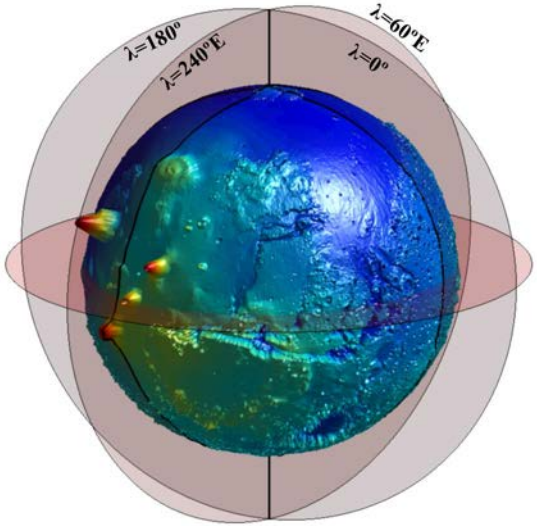


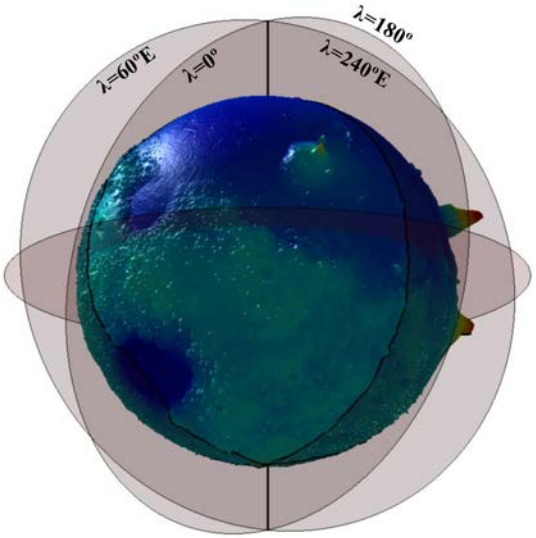
$$N(1km) = 2.68 \cdot 10^{-14}(e^{6.93t} - 1) + 4.131 \cdot 10^{-4}t$$

Neukum, *Lunar and Planetary Science Conference, 2008*

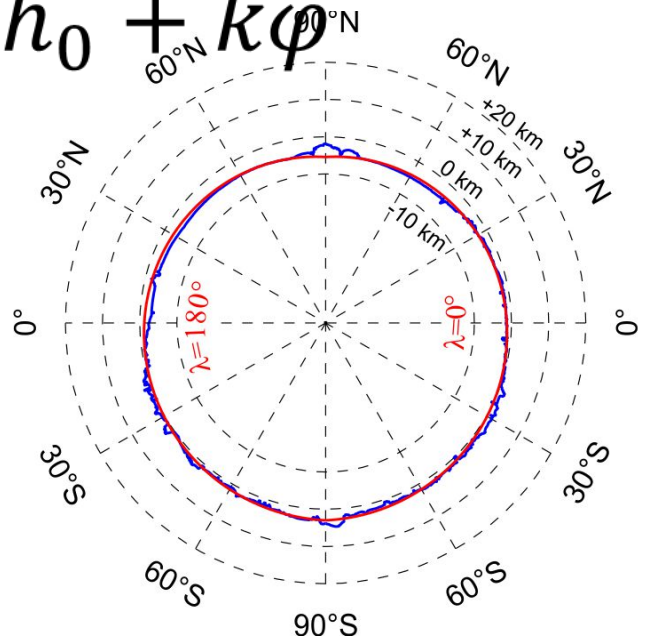


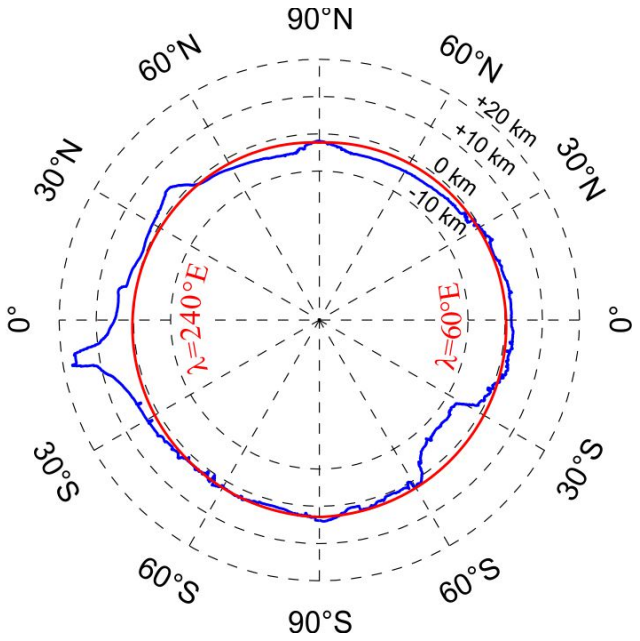
# TOPOGRAFIJA MARSOVE POVRŠINE



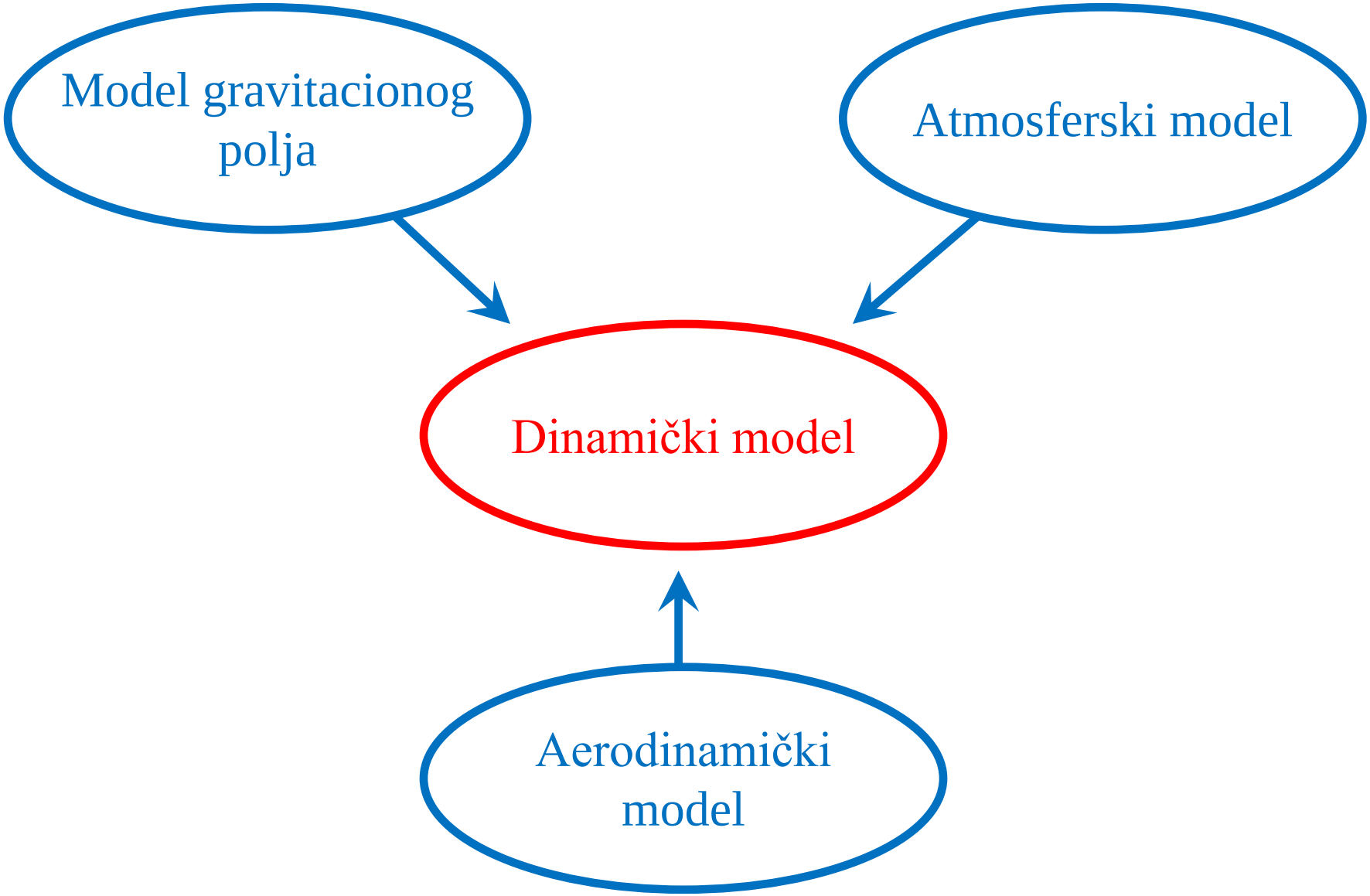

$$h = h_0 + k\varphi$$



# Mars vs Zemlja

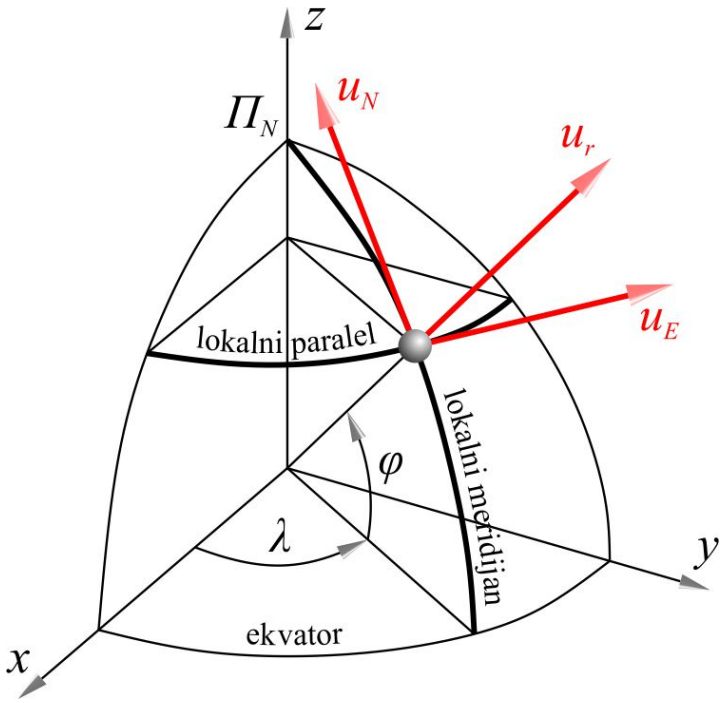
# ATMOSFERSKA PUTANJA



# GRAVITACIONO POLJE MARSA

$$U = \frac{GM}{r}\left\{1 + \sum_{l=2}^{\infty}\left(\frac{r_0}{r}\right)^l \sum_{m=0}^{l} P_{lm}(\sin\delta)[C_{lm}\cos m\lambda + S_{lm}\sin m\lambda]\right\}$$

$$\vec{a} = \frac{\partial U}{\partial r}\vec{u}_r + \frac{1}{r}\frac{\partial U}{\partial \delta}\vec{u}_N + \frac{1}{r\cos\delta}\frac{\partial U}{\partial \lambda}\vec{u}_E$$



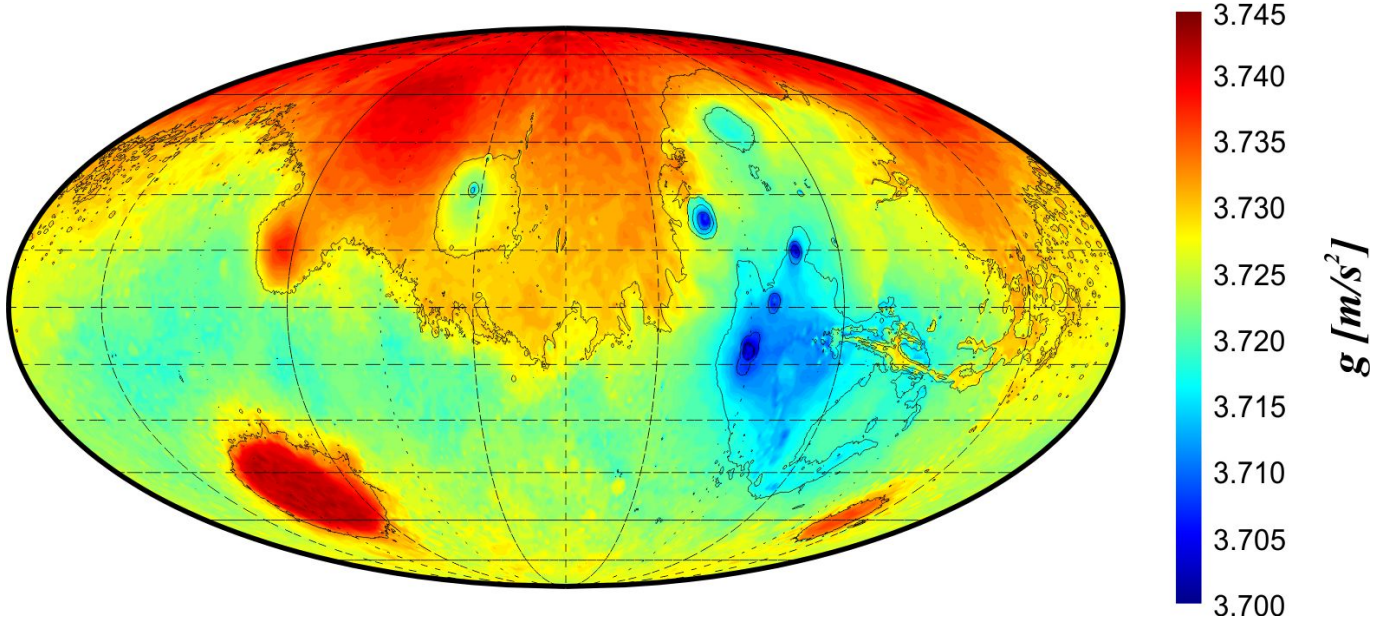
# UBRZANJA GRAVITACIONOG POLJA

$$a_r = -\frac{GM}{r^2}\left(1 + \sum_{l=2}^{\infty}(l+1)\left(\frac{r_0}{r}\right)^l \sum_{m=0}^{l} P_{lm}(\sin\delta)[C_{lm}\cos m\lambda + S_{lm}\sin m\lambda]\right)$$

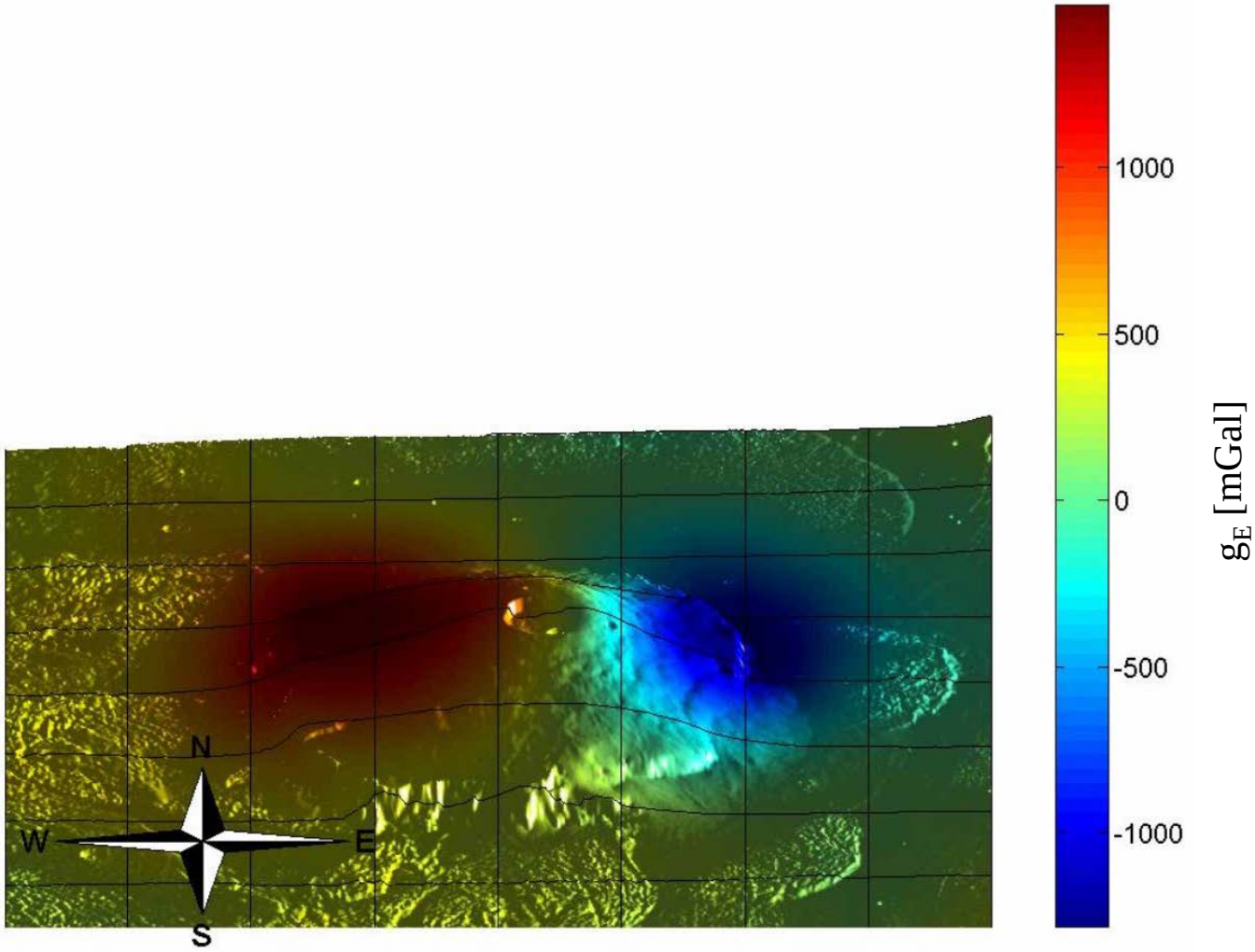
$$a_N = \frac{GM}{r^2}\sum_{l=2}^{\infty}\left(\frac{r_0}{r}\right)^l \sum_{m=0}^{l}\{P_{l,m+1}(\sin\delta) - m\tan\phi\, P_{lm}(\sin\delta)\}[C_{lm}\cos m\lambda + S_{lm}\sin m\lambda]$$

$$a_E = \frac{GM}{r^2\cos\delta}\sum_{l=2}^{\infty}\left(\frac{r_0}{r}\right)^l \sum_{m=0}^{l} P_{lm}(\sin\delta)m[-C_{lm}\sin m\lambda + S_{lm}\sin m\lambda]$$

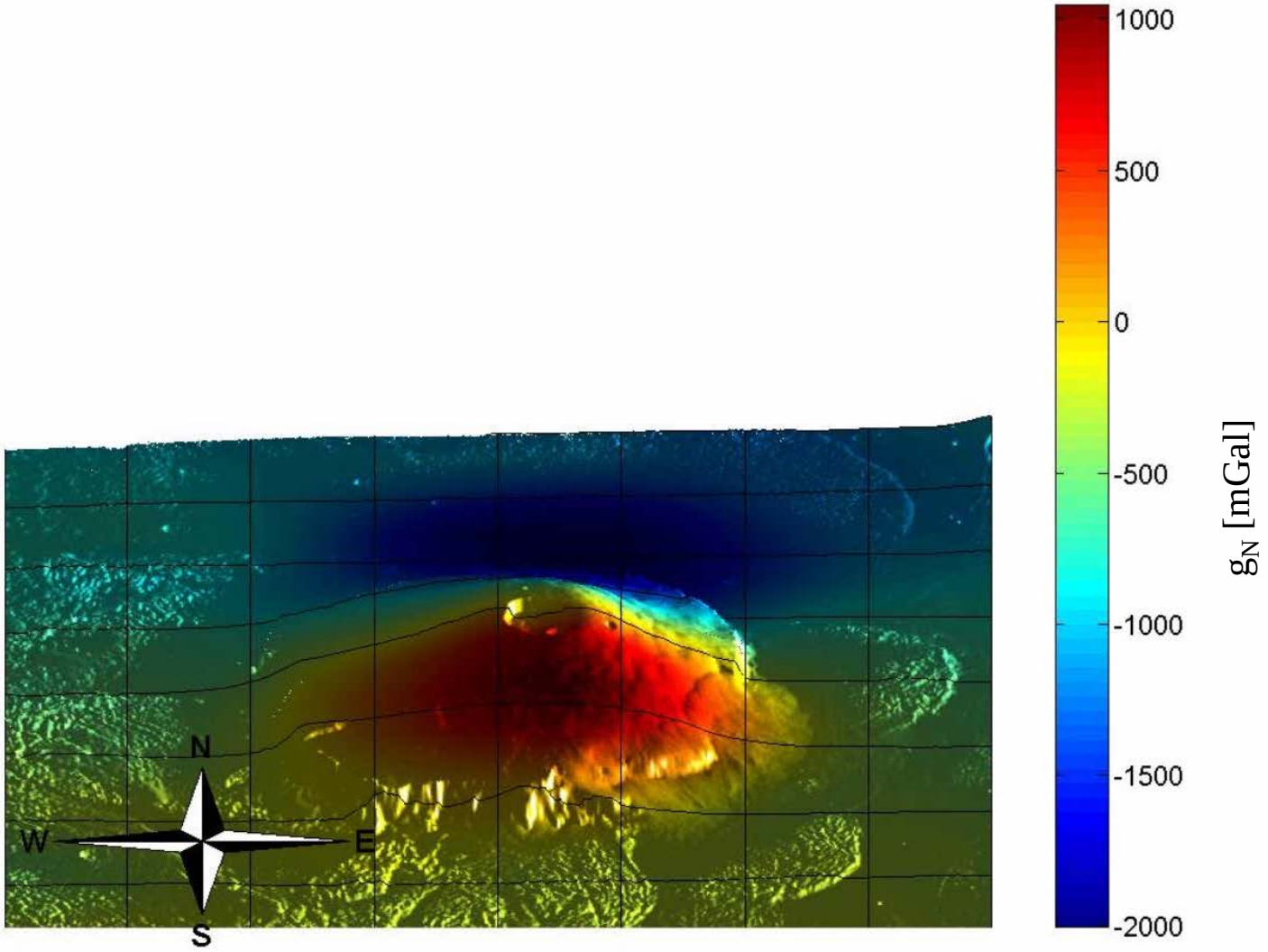
# UBRZANJA GRAVITACIONOG POLJA



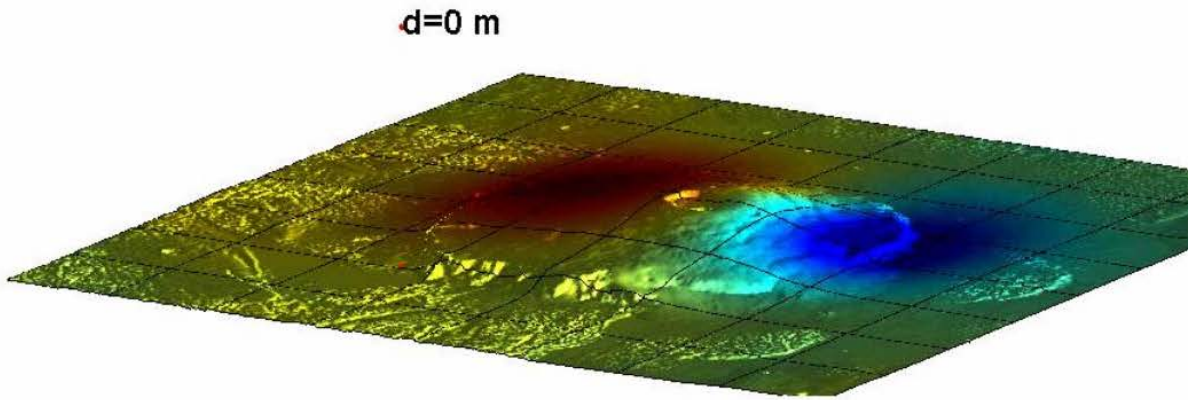
# OLIMPUS MONS



# OLIMPUS MONS



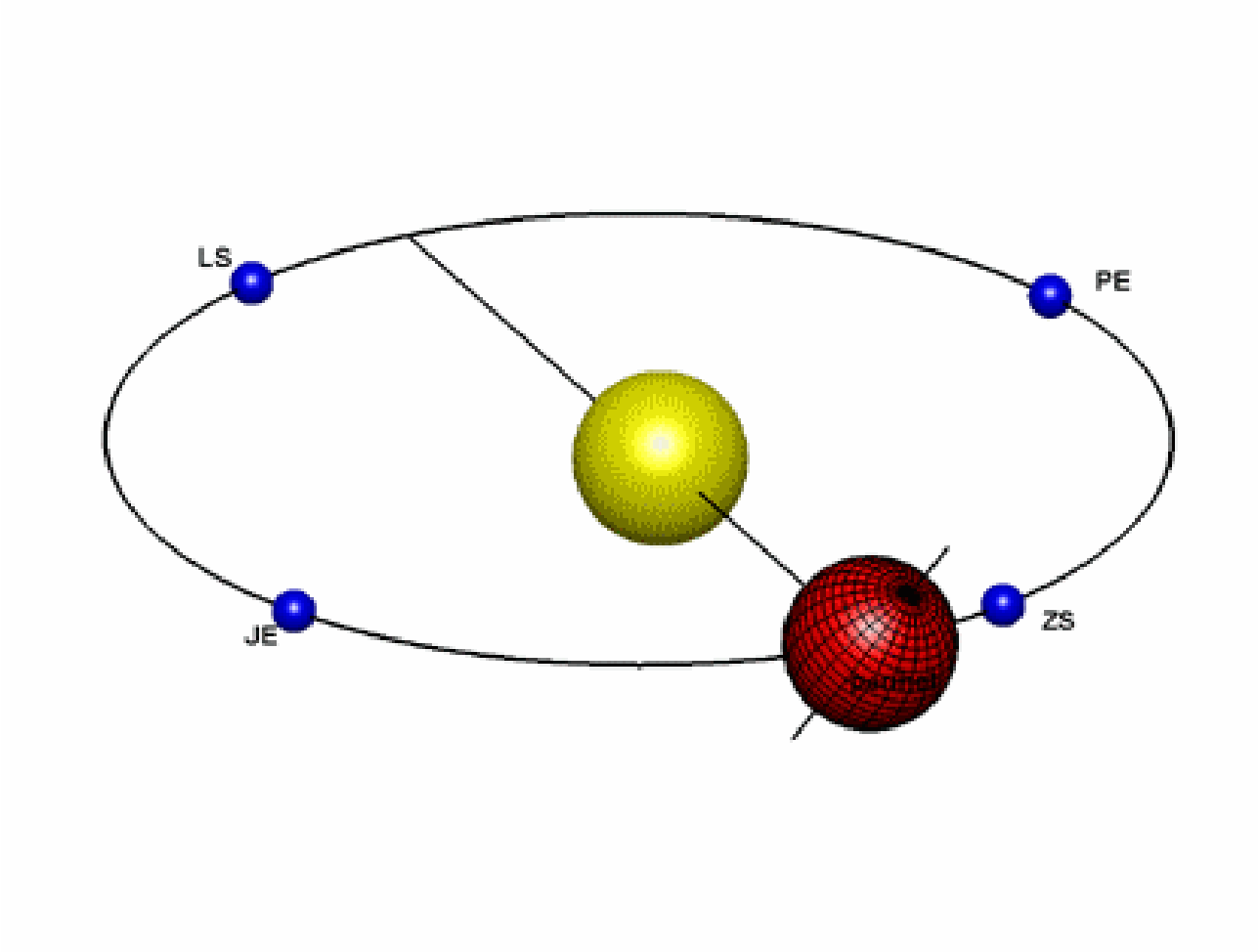
# UTICAJ GRAVITACIONIH ANOMALIJA NA PUTANJU



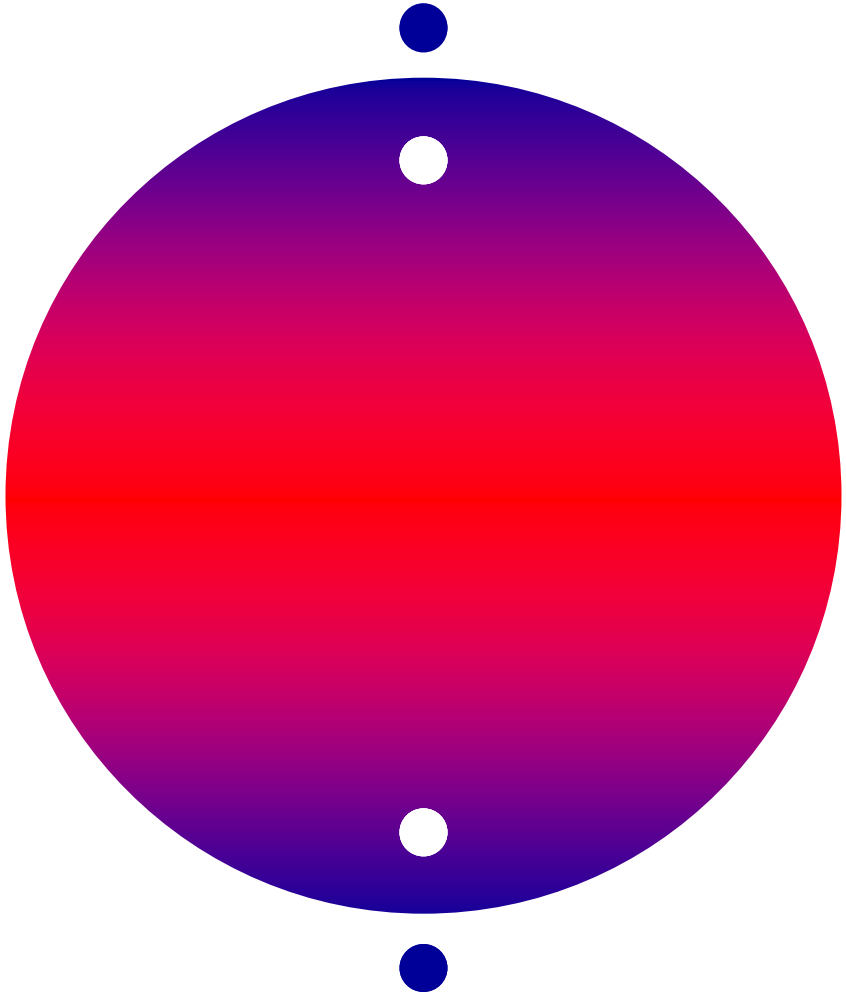
# DANAŠNJA ATMOSFERA MARSA

| | Zemlja | Mars | Odnos |
|---|---|---|---|
| $p_0$ [Pa] | 101400 | 636 | 159 |
| $\rho_0$ [kg/m$^3$] | 1.217 | 0.02 | 60.8 |
| H [km] | 8.5 | 11.1 | 0.77 |

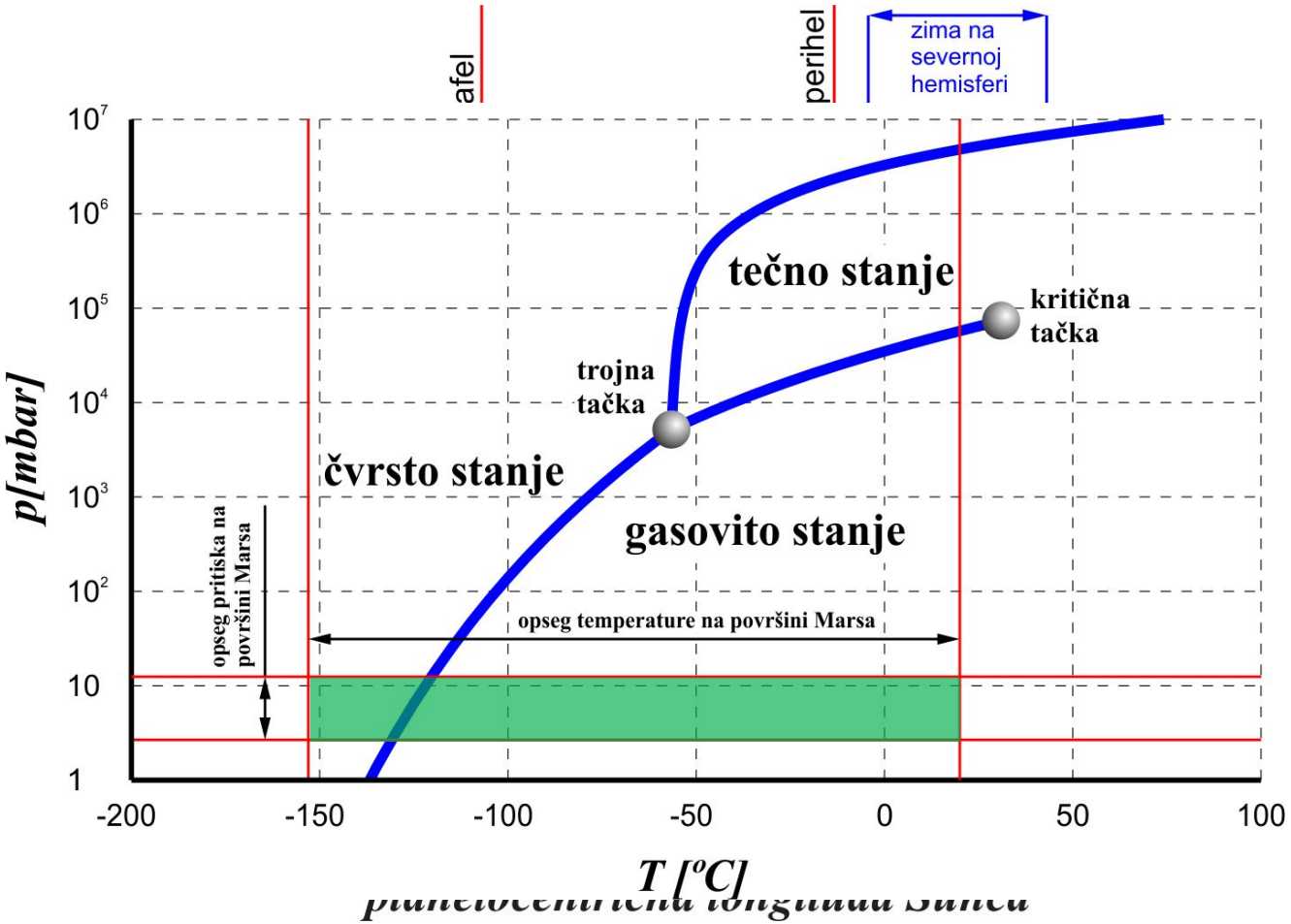
# CIRKULACIJA ATMOSFERE



# CIRKULACIJA ATMOSFERE

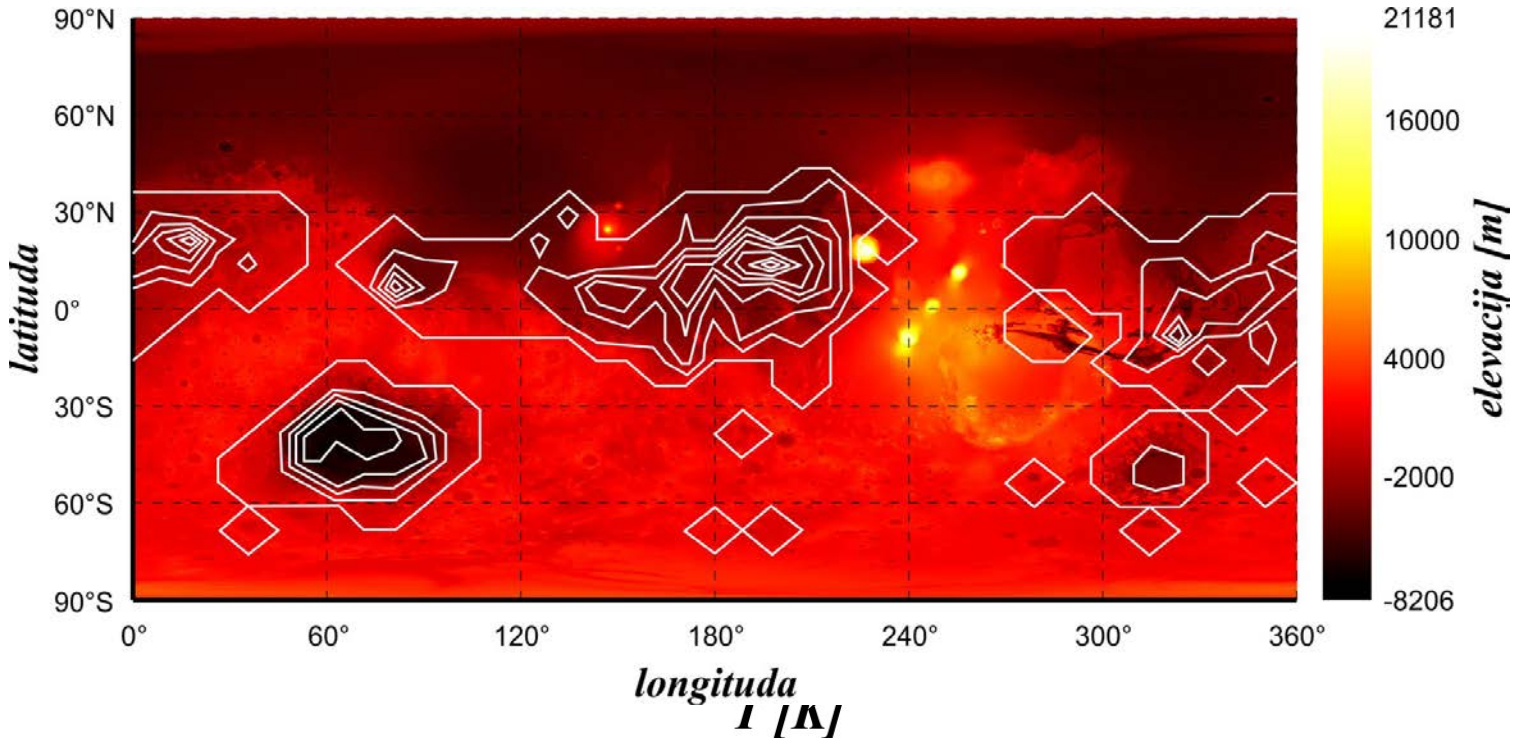


# $CO_2$ CIKLUS




Haberle, *Encyclopedia of Atmospheric Sciences,* 2003.

# $H_2O$ CIKLUS




Haberle et al., *Journal of Geophysical Research*, 2001.

# MODELI CIRKULACIJE MARSOVE ATMOSFERE

$p = \rho R_s T$ Jednačina stanja

Globalni Regionalni Lokalni

$\frac{D\rho}{Dt} + \rho \nabla \vec{v} = 0$ Jednačina kontinuiteta

$\frac{D\theta}{dt} = Q$ Jednačina energije

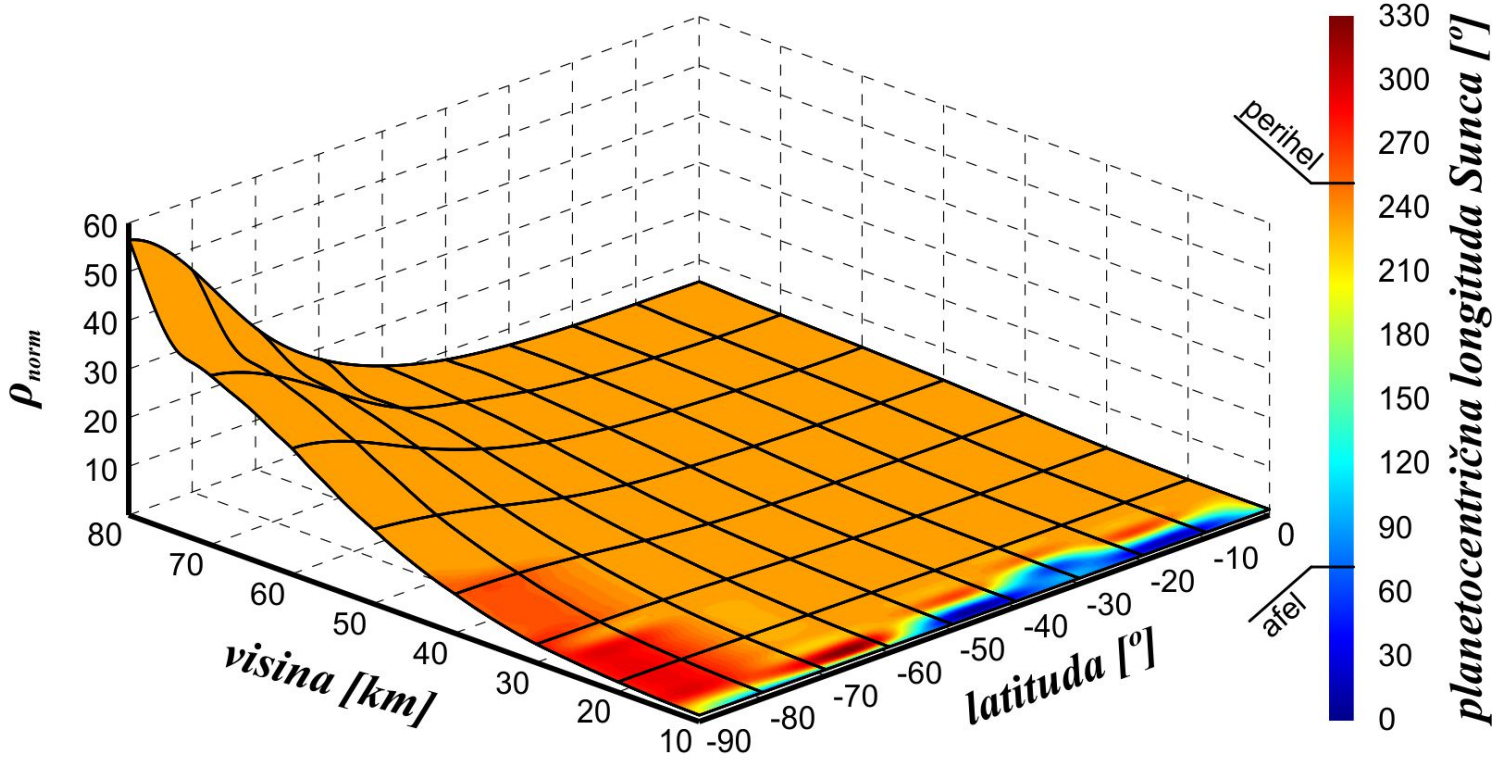
Atmosferske baze podataka

$\frac{D\vec{v}}{Dt} = -2\Omega \times \vec{v} - \Omega \times (\Omega \times r) - \vec{g} - \frac{1}{\rho}\nabla p + \frac{\eta_d}{\rho}\nabla^2 \vec{v}$ N-S jednačina

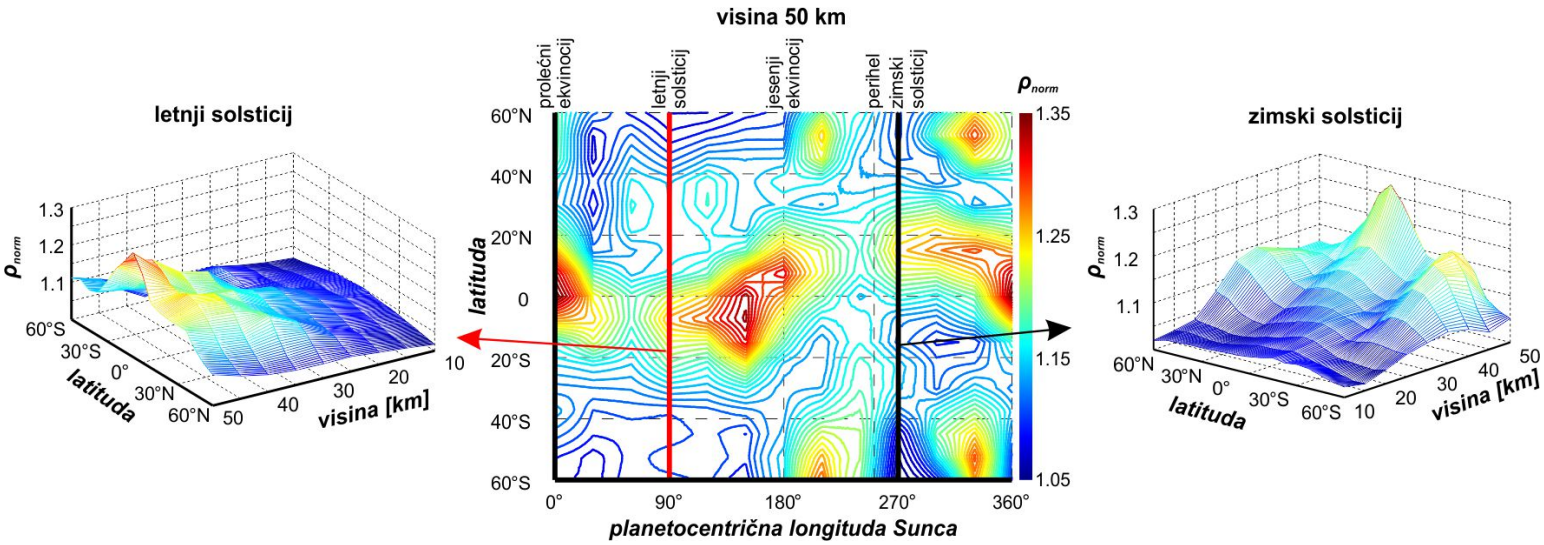
# SEZONSKI CIKLUS

Severna hemisfera

Južna hemisfera



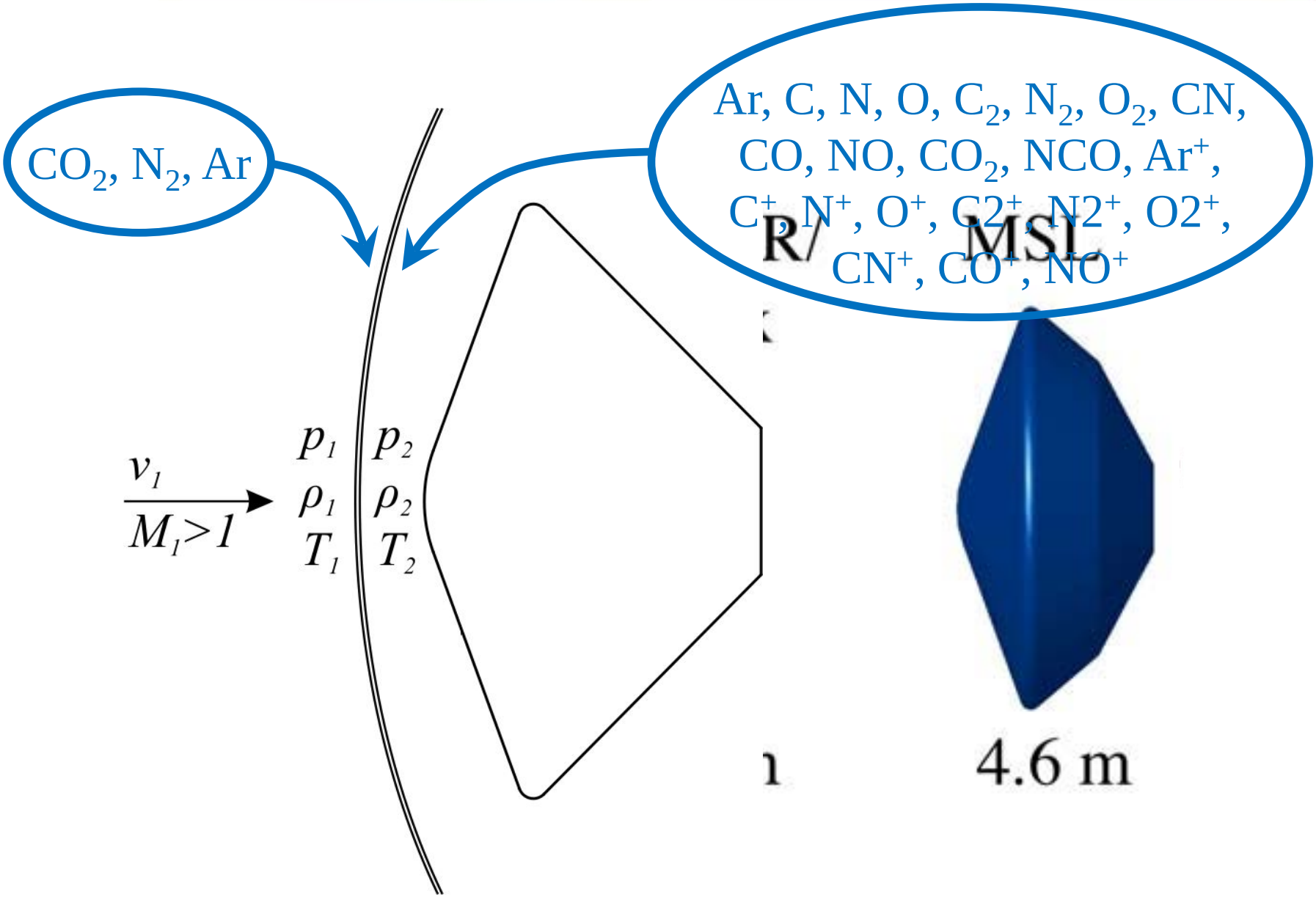
# DNEVNI CIKLUS



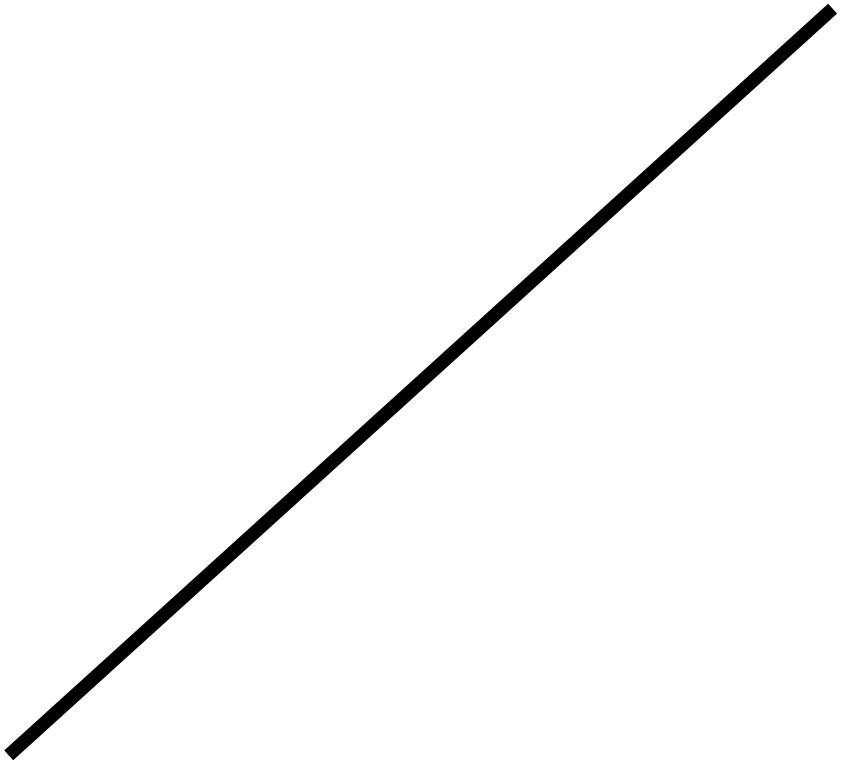
# AERODINAMIKA

$$F_x = \frac{1}{2}\rho v^2 S C_x$$

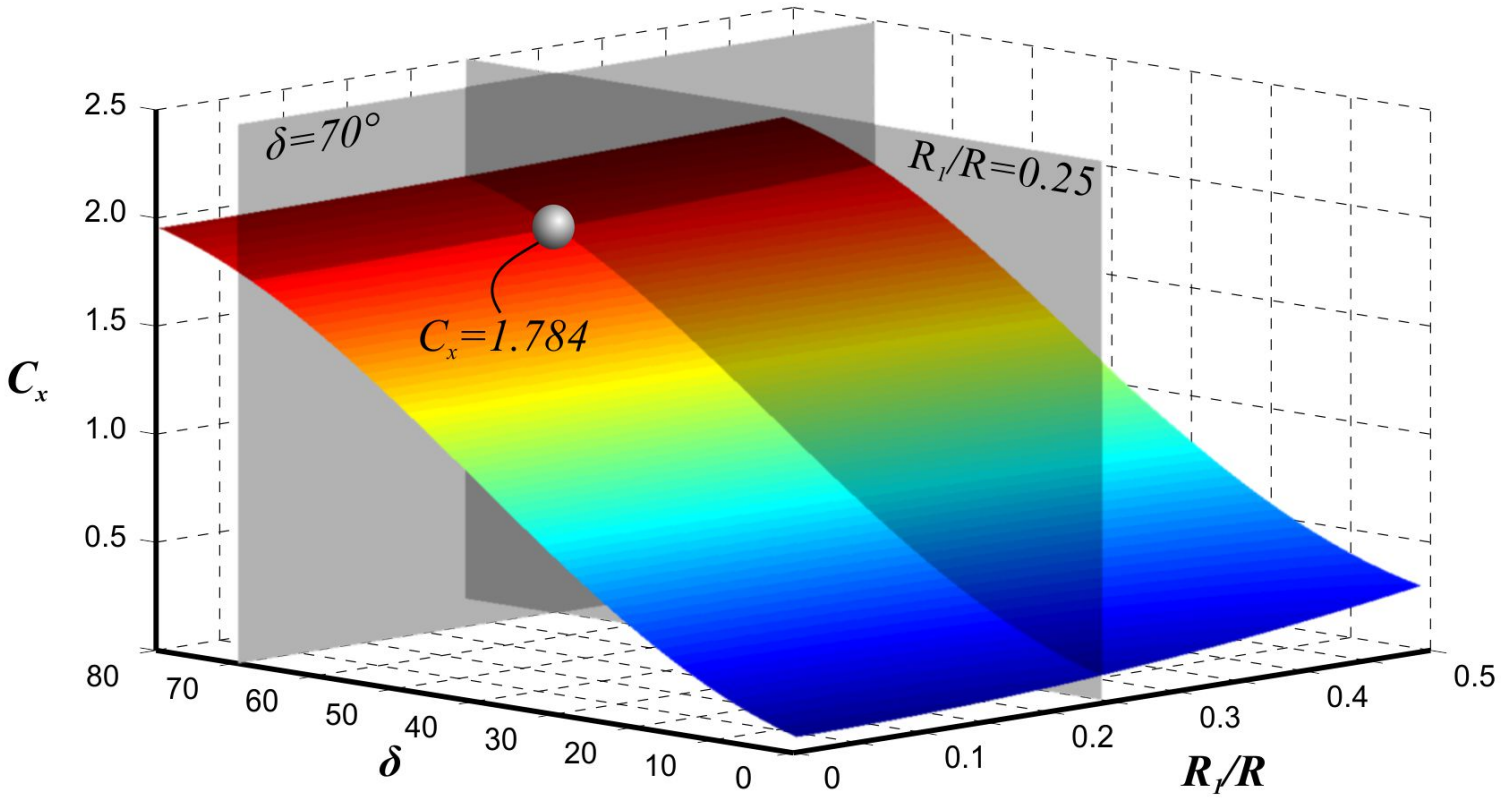
# PARADOKS TUPOG TELA



# NJUTNOVA TEORIJA

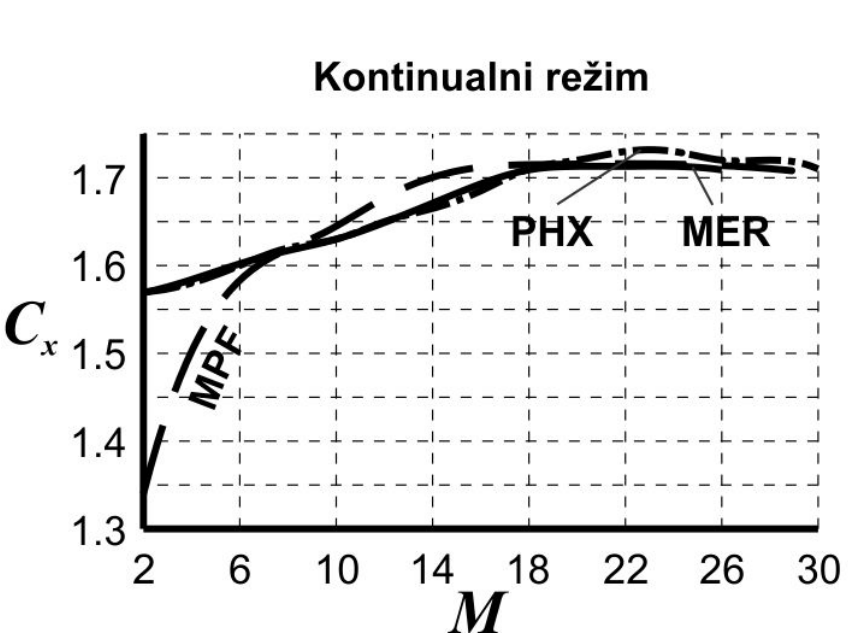


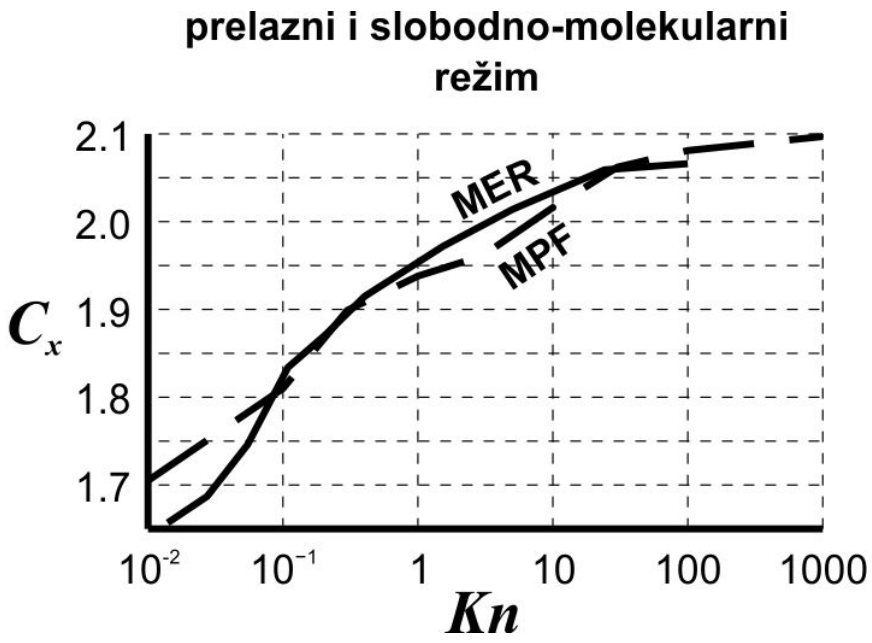
# NJUTNOVA TEORIJA




$$C_x = \frac{1}{S}\iint_A C_p dA = \frac{2}{R^2\pi}\iint_A \sin^2\theta dA$$

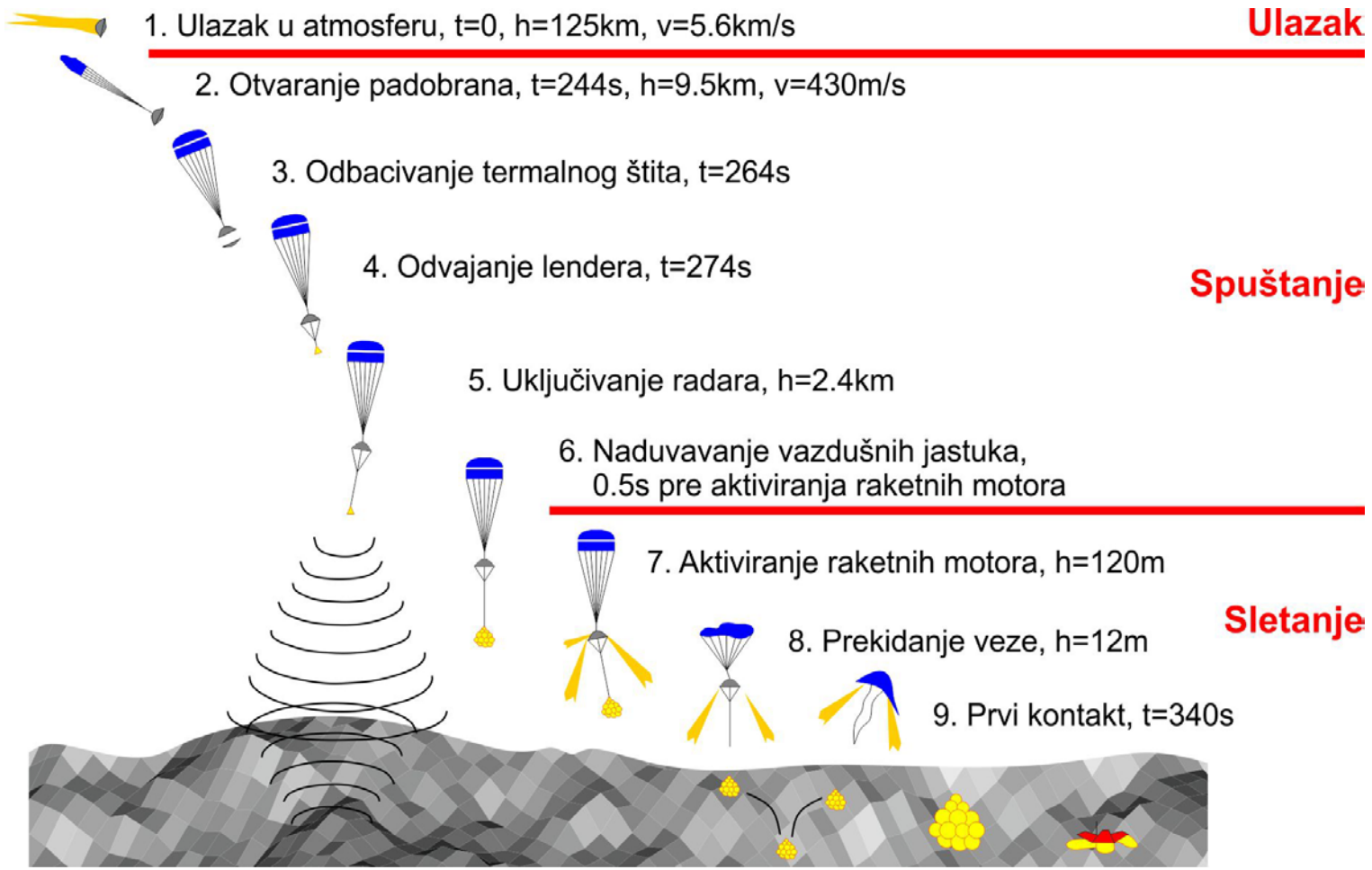
# AERODINAMIČKI MODEL



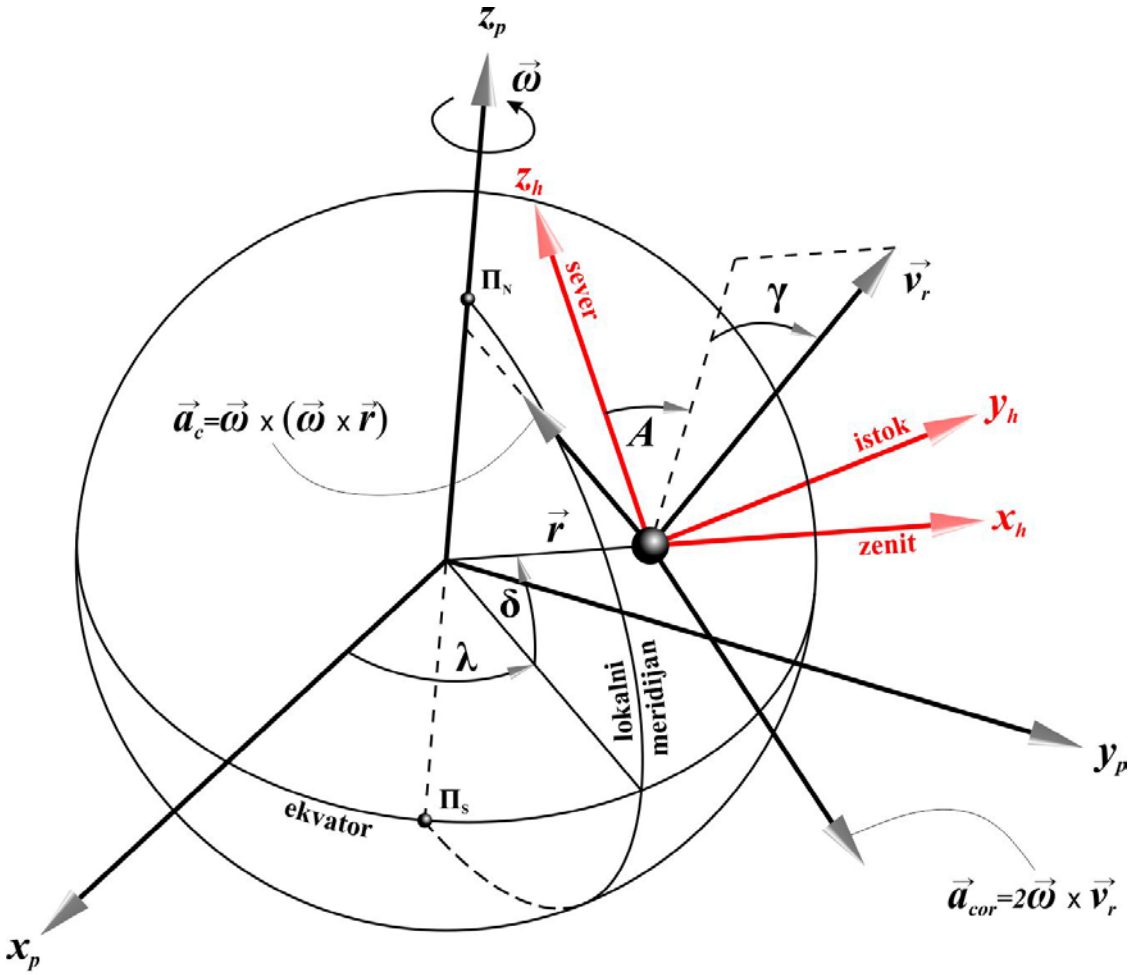

Gnoffo et al., *Journal of Spacecraft and Rockets,* 1996.
Moss et al., *AIAA paper 98-0298*, 1998.
Edquist & Desai, *Journal of Spacecraft and Rockets,* 2011.
Schoenenberger & Cheatwood, *AIAA paper 2005-0056*, 2005.

# DINAMIKA ULASKA U ATMOSFERU, SPUŠTANJA I SLETANJA NA POVRŠINU MARSA



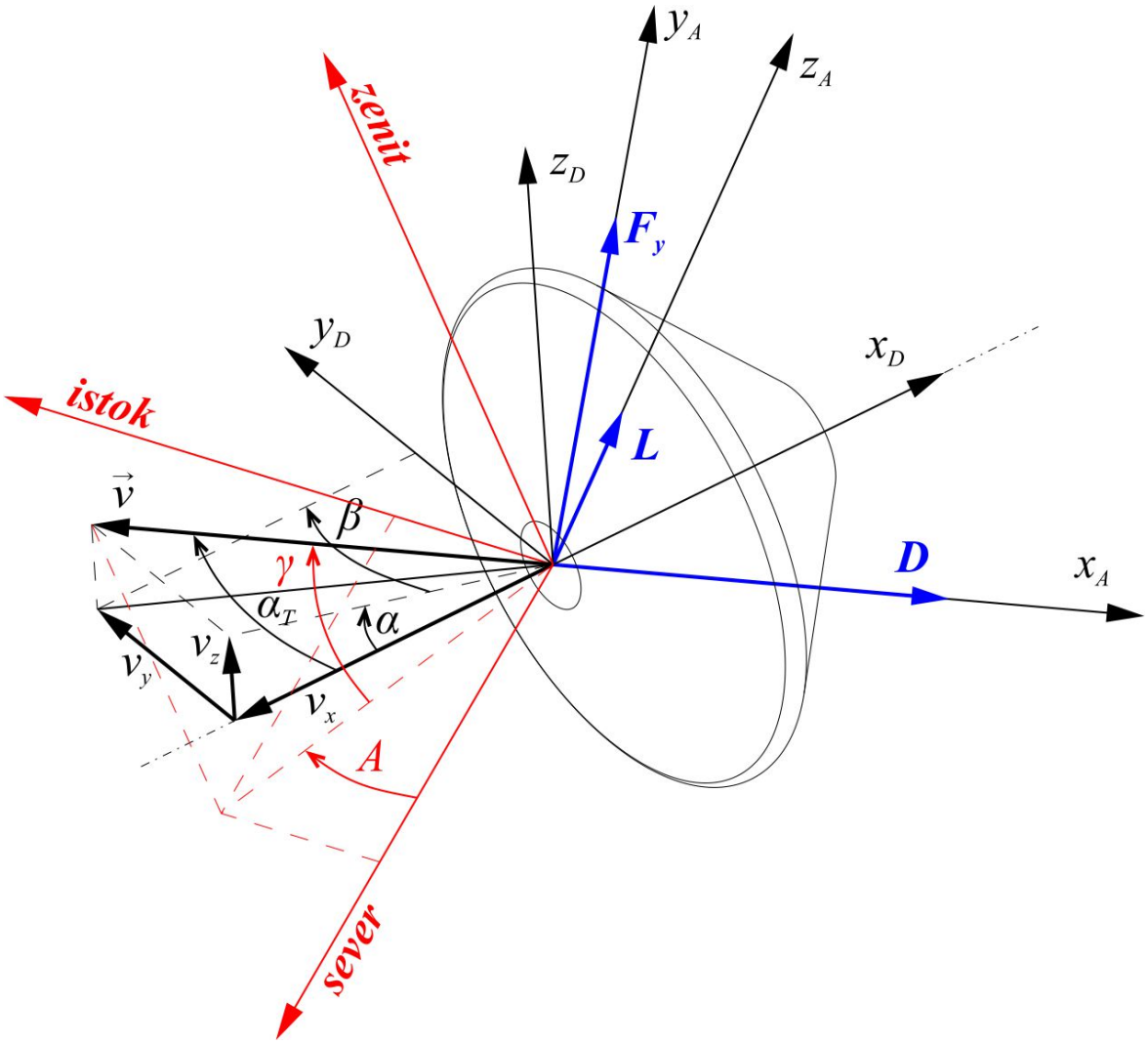

Desai & Knocke, *The Journal of the Astronautical Sciences,* 2007.

# KOORDINATNI SISTEMI




$$\vec{a} = \vec{a}_r + 2\vec{\omega} \times \vec{v}_r + \vec{\omega} \times (\vec{\omega} \times \vec{r})$$

# KOORDINATNI SISTEMI



# JEDNAČINE KRETANJA

$$\dot{v} = -\frac{1}{m}F_x - g_C \sin\gamma + g_N \cos\gamma \cos A$$

$$g_E \cos\gamma \sin A - \omega^2 r \cos\delta(\cos\gamma \cos A \sin\delta - \sin\gamma \cos\delta)$$

$$\dot{v} = -\frac{1}{2m}\rho v^2 C_x - g \sin\gamma$$

$$\dot{A} = \frac{v}{r}\cos\gamma \sin A \tan\delta + \frac{1}{v\cos\gamma}(\omega^2 r \sin A \sin\delta \cos\delta - g_N \sin A + g_E \cos A)$$

$$-2\omega(\tan\gamma \cos A \sin\delta + \cos\delta)$$

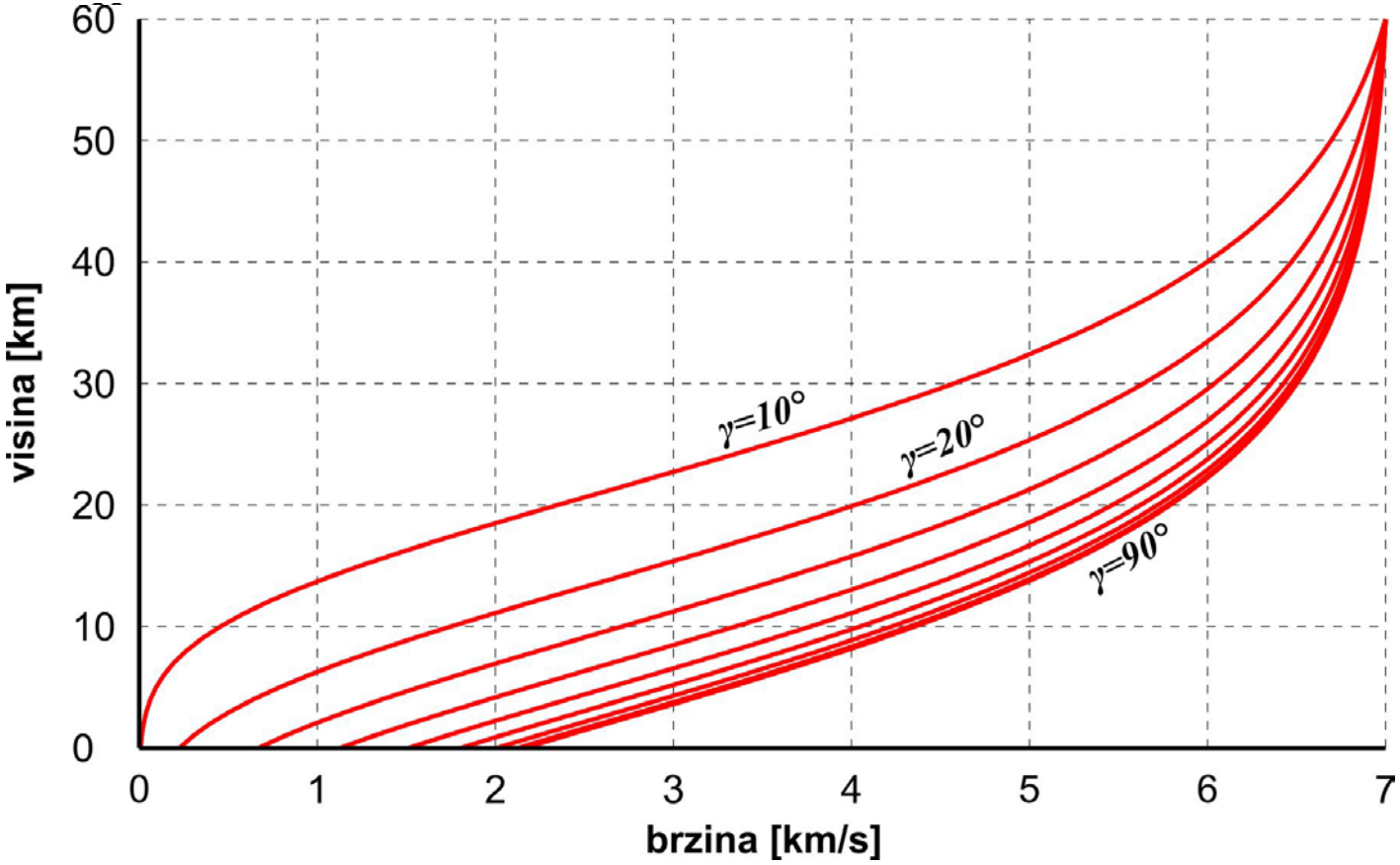
$$\dot{\gamma} = \cos\gamma\left(\frac{v}{r} - \frac{g}{v}\right)$$

$$\dot{\gamma} = \frac{v}{r}\cos\gamma$$

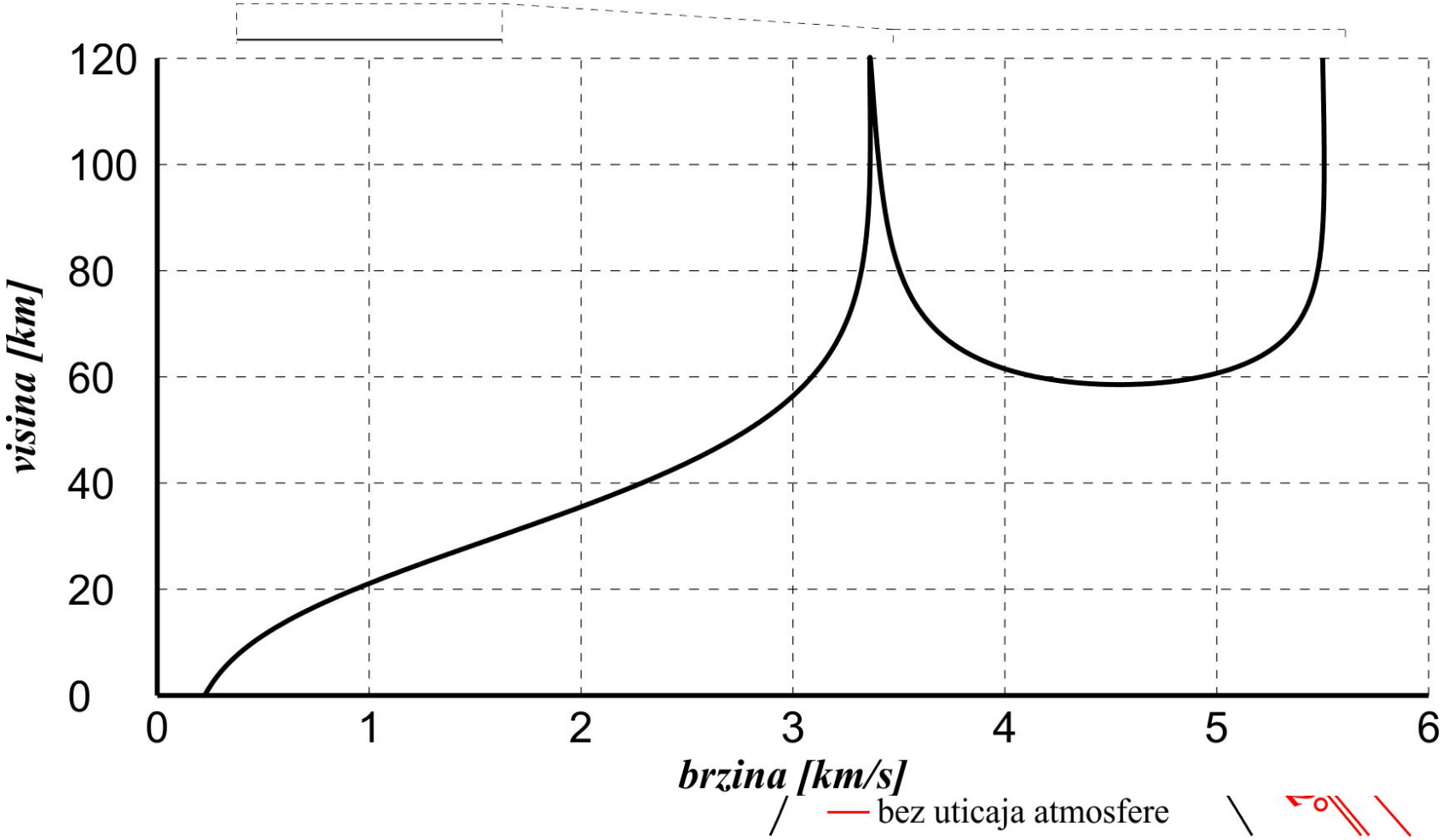
$$-\frac{1}{v}[g_C \cos\gamma + g_N \sin\gamma \cos A + g_E \sin\gamma \sin A - \omega^2 r \cos\delta(\sin\gamma \cos A \sin\delta + \cos\gamma \cos\delta)]$$

$$+2\omega \sin A \cos\delta$$

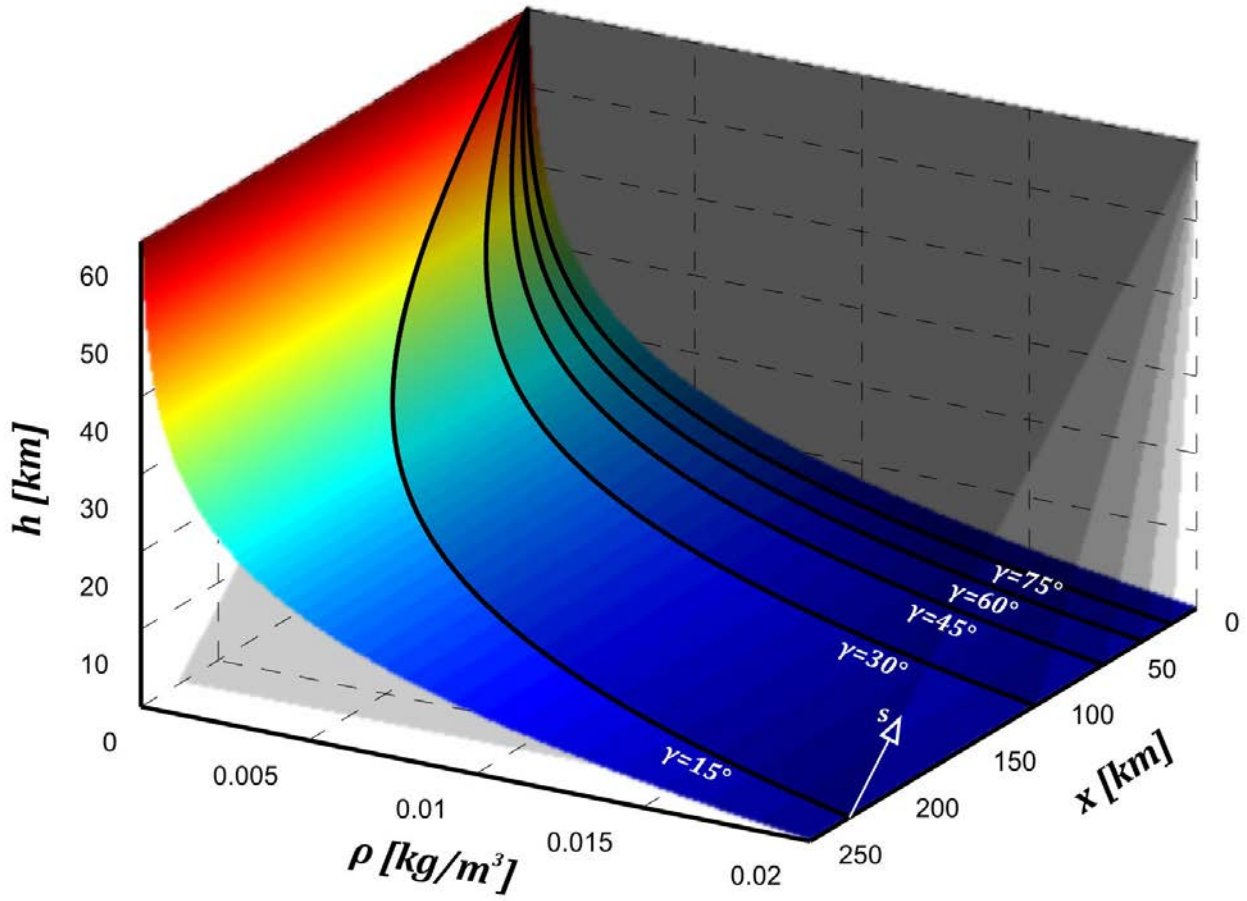
# ANALITIČKO REŠENJE



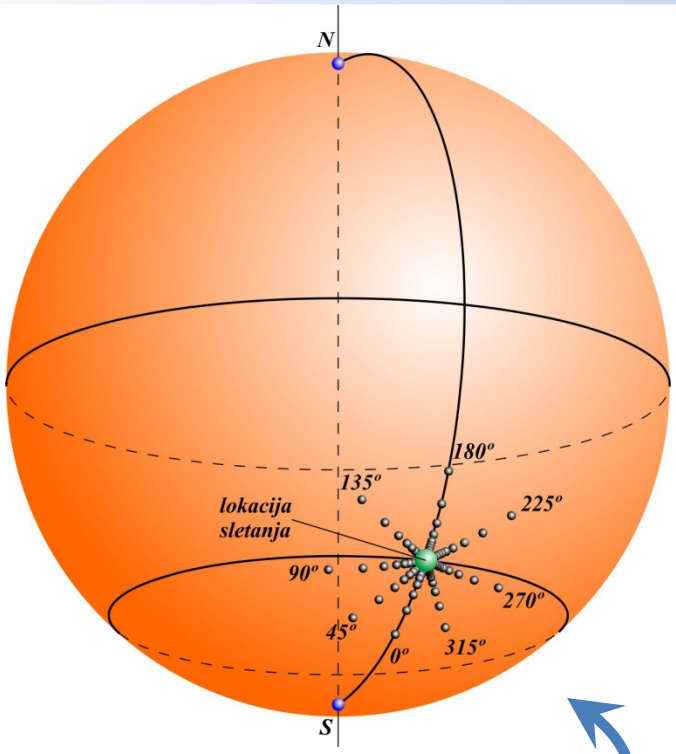
# GRANIČNA PUTANJA

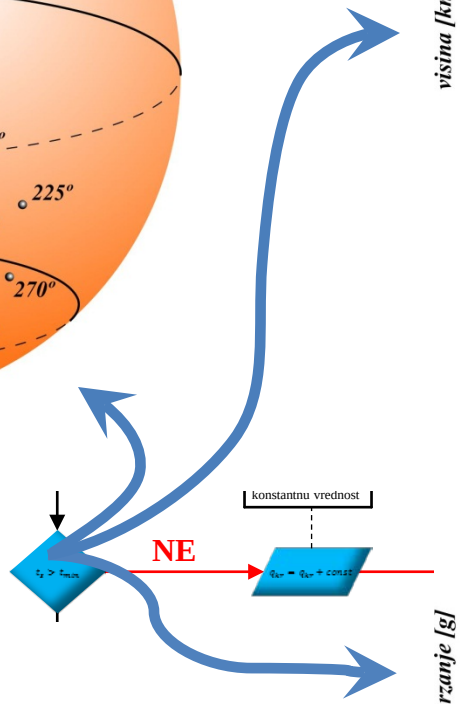


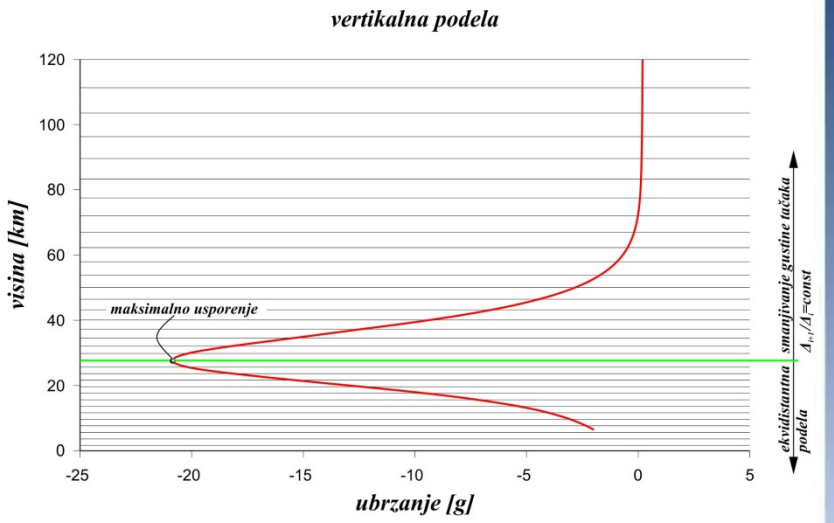
# „PRIVIDNA“ ATMOSFERA

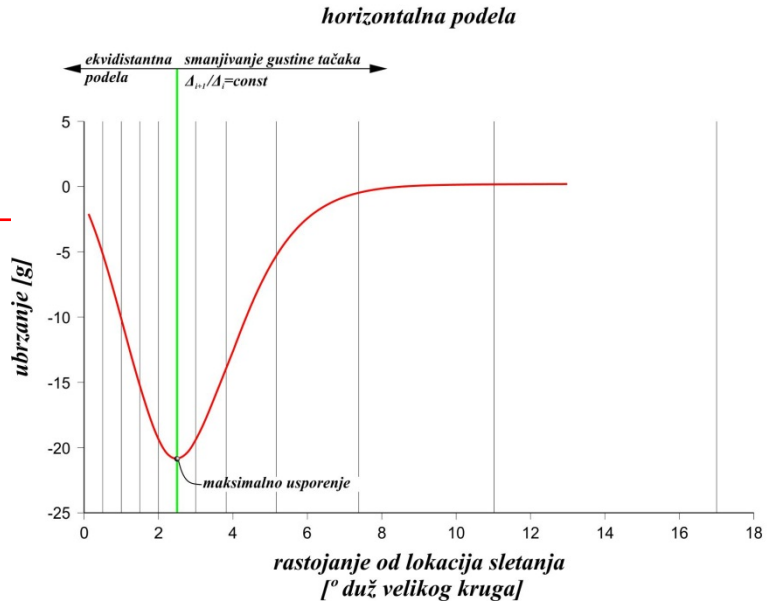


# ODREĐIVANJE OPTIMALNE PUTANJE

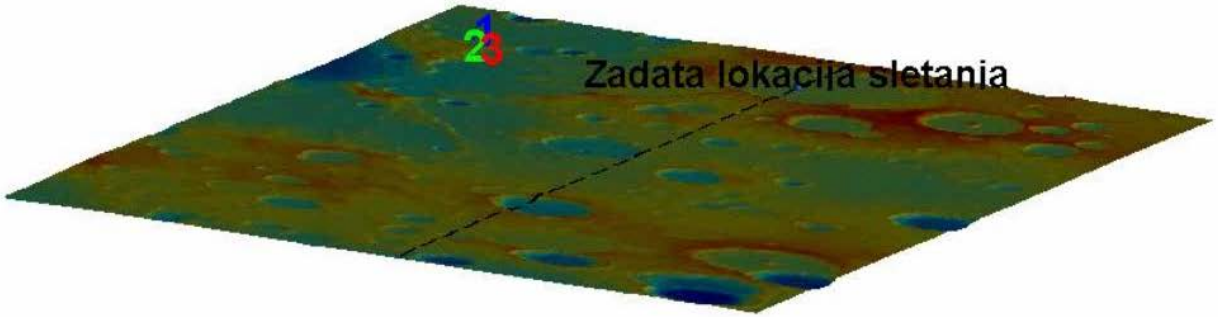


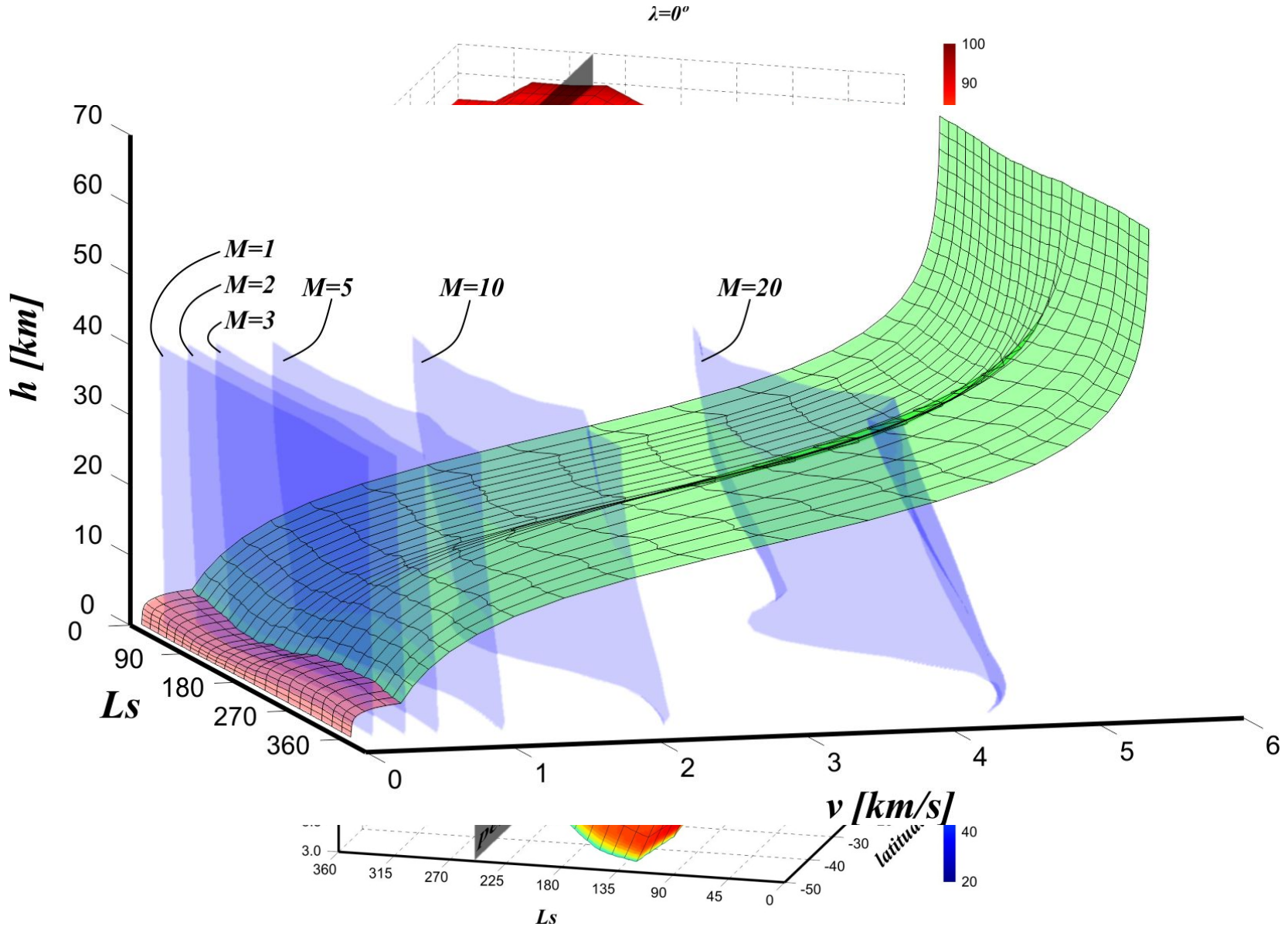



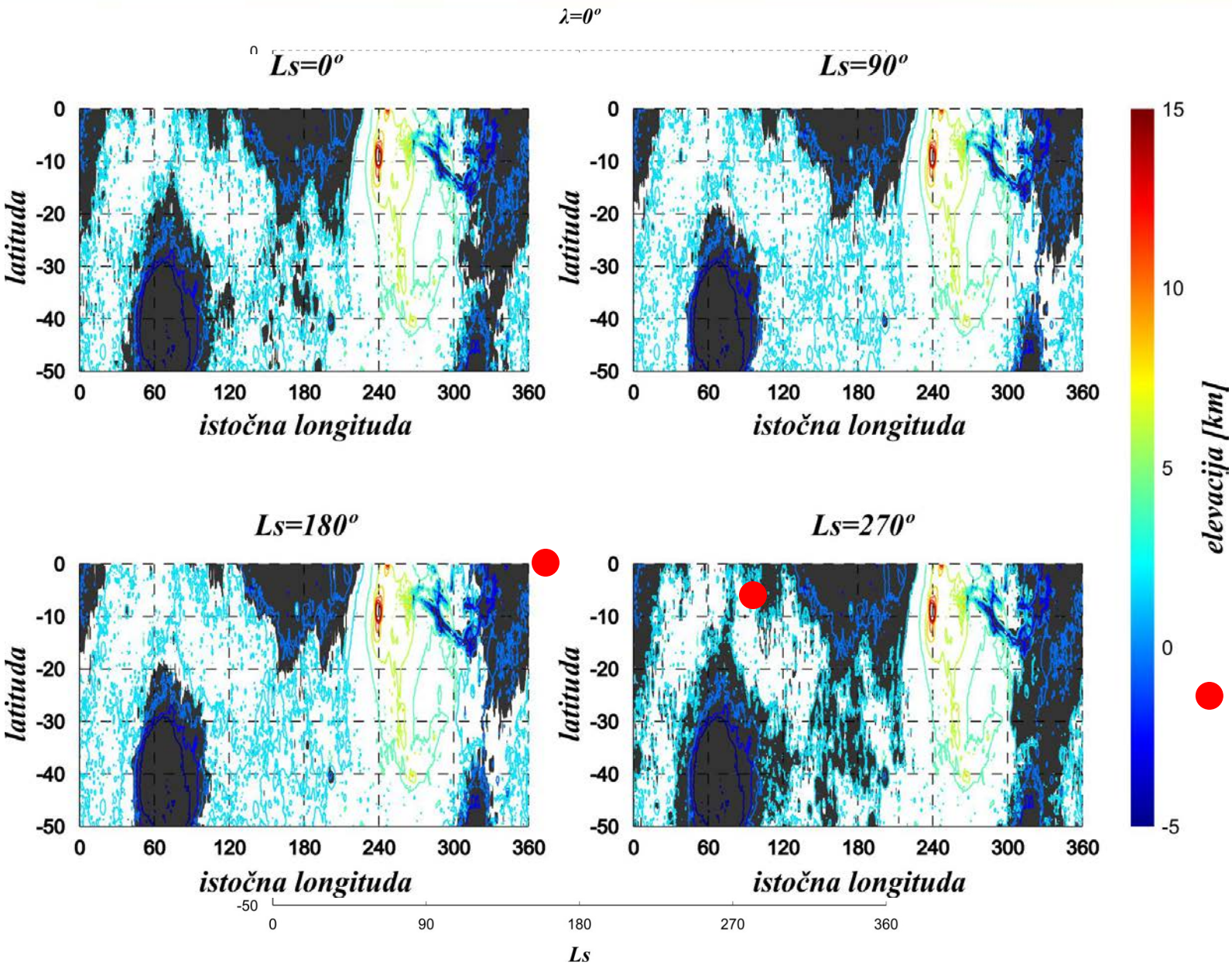
# KONVERGENCIJA PUTANJE



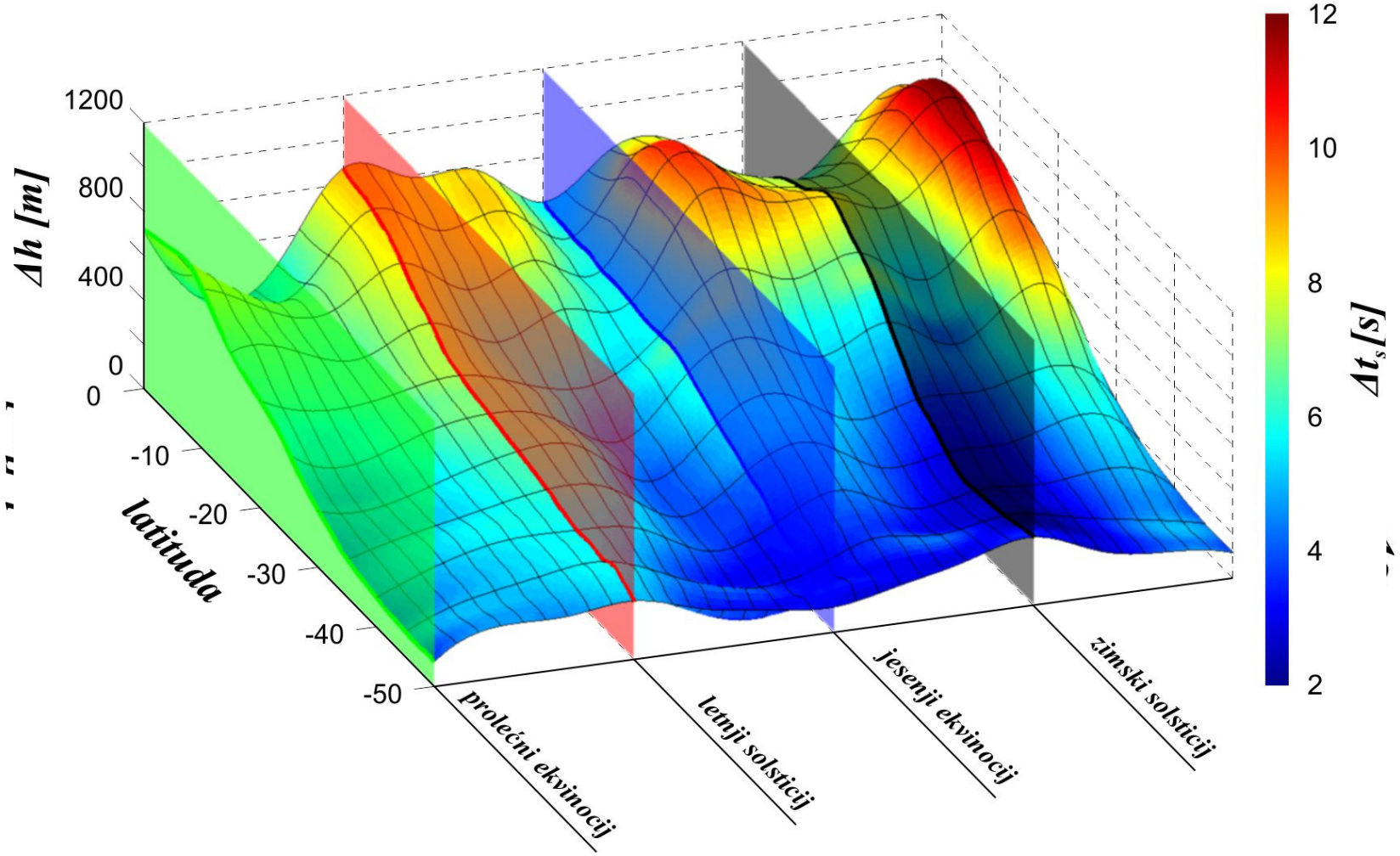
# UTICAJ SEZONSKOG CIKLUSA



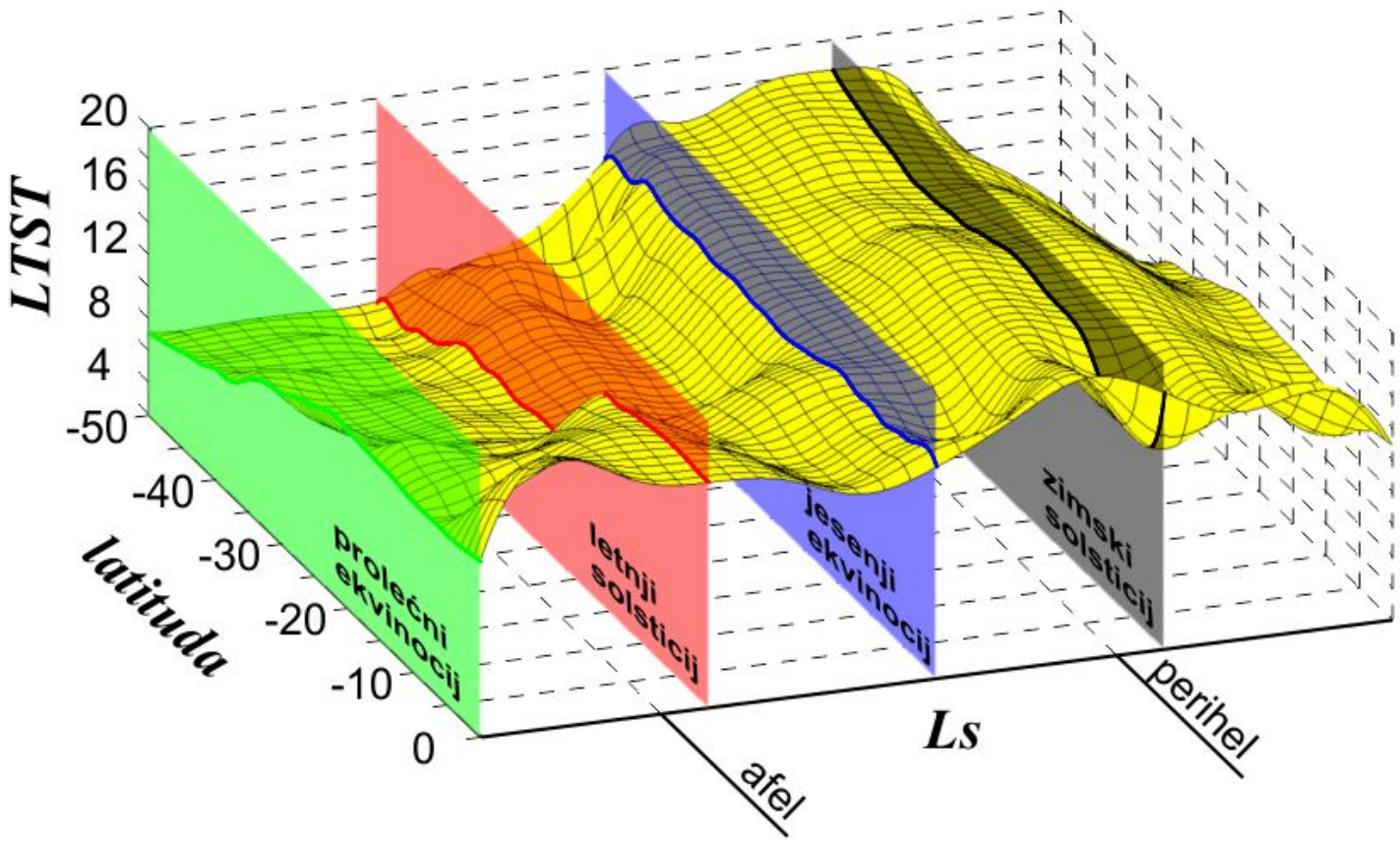
# PRISTUPAČNE LOKACIJE



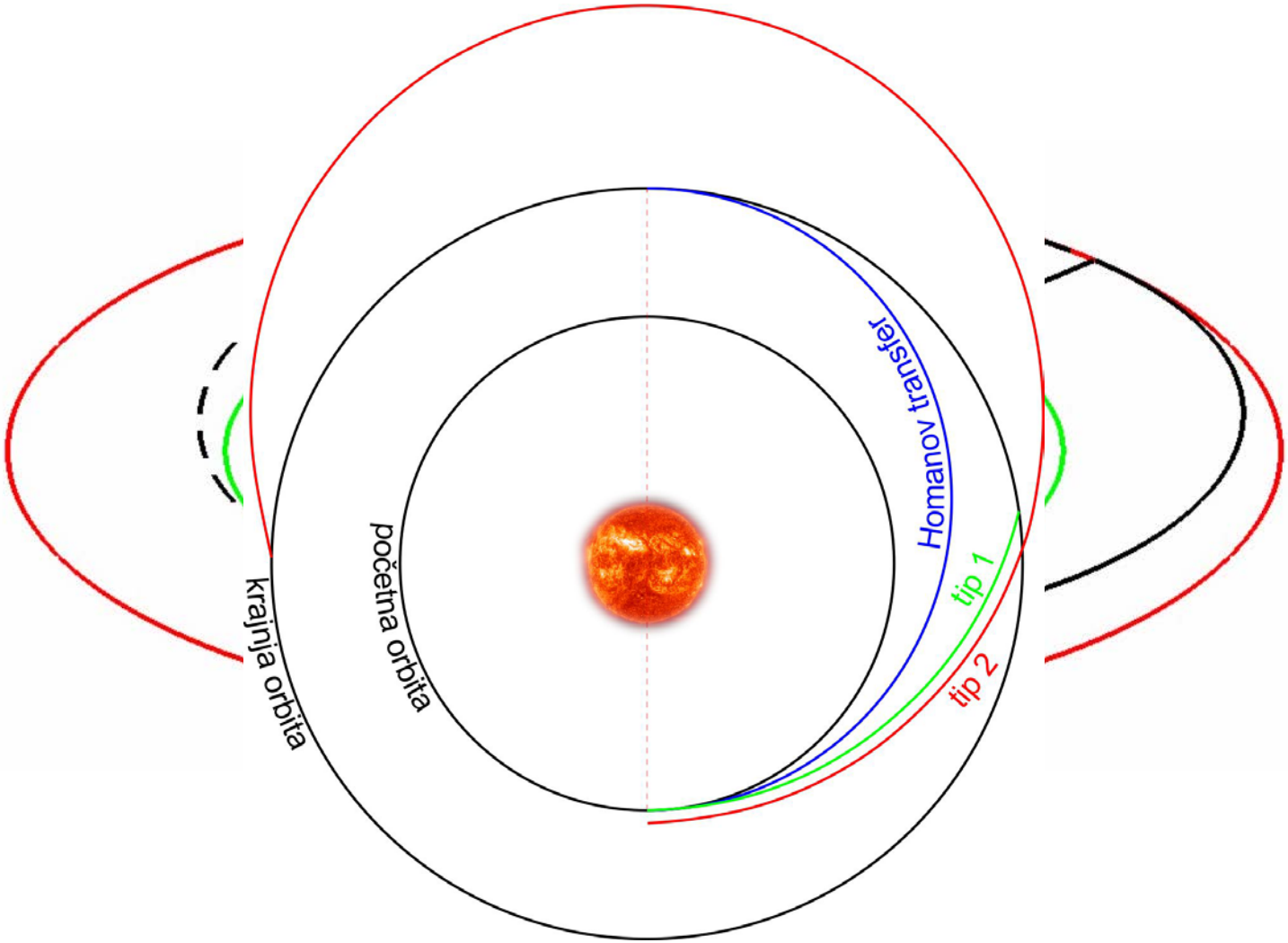
# UTICAJ DNEVNOG CIKLUSA



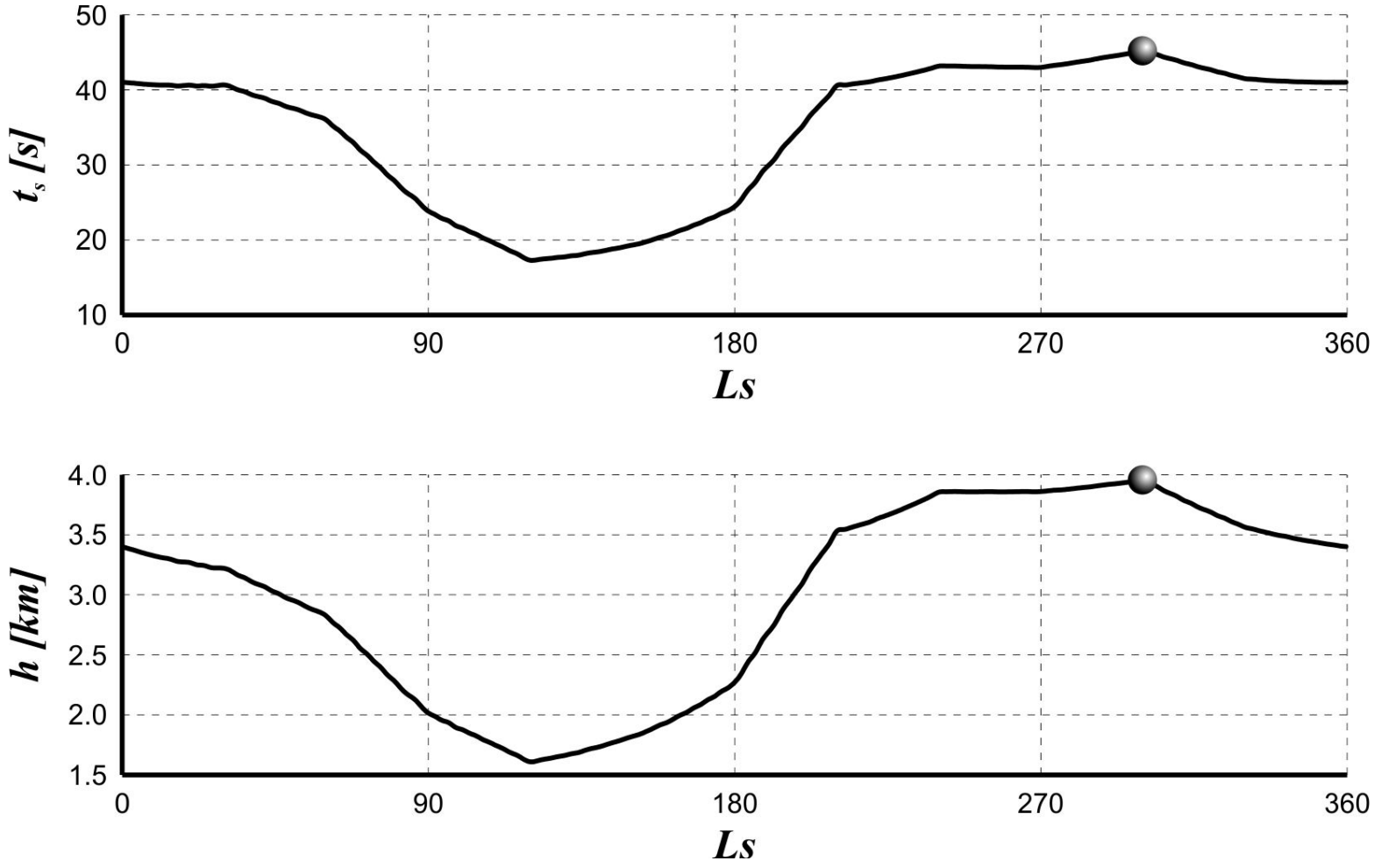
# OPTIMALNO LPSV



# MEĐUPLANETARNI TRANSFER



# OPTIMIZACIJA POČETNIH USLOVA



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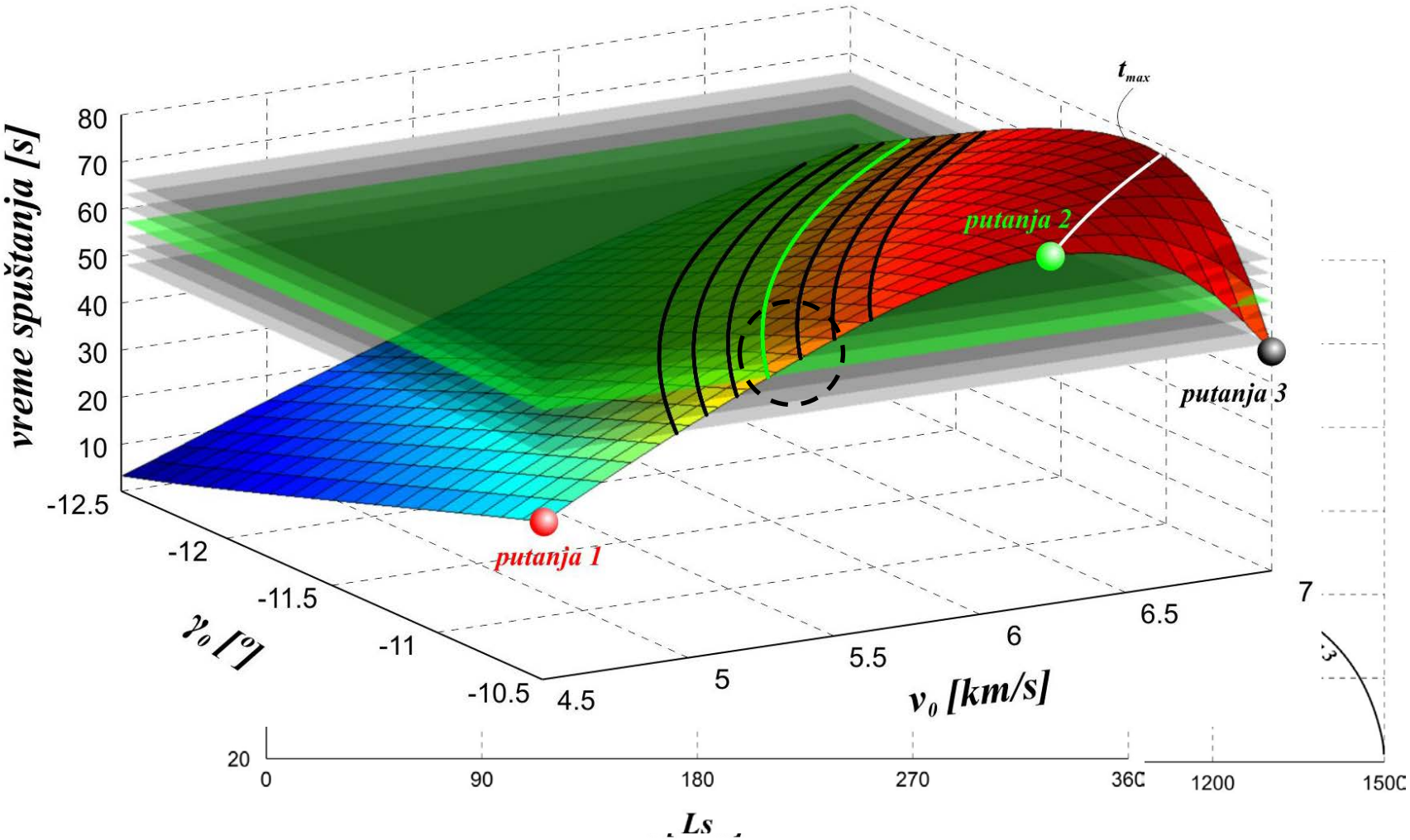

# SAŽETAK

- Zbog sezonskih varijacija atmosferskih parametara, pre svega gustine, koje su dominantno uzrokovane $CO_2$ ciklusom u Marsovoj atmosferi, pristupačne elevacije sletanja se menjaju za oko 2.5 *km* u toku godine.

- Optimalna sezona za sletanje na južne visoravni je u okolni perihela orbite, od kasnog proleća do rane jeseni.

- Uticaj sezonskih varijacija atmosferskih parametara raste sa udaljavanjem od ekvatora.

- Pristupačne lokacije sletanja pojavljuju se u visokim oblastima, na visoravnima Sirenum, Simeria i Noakis, kada je Mars u okolini perihela.

- Optimizacijom početnih uslova ($v_0$, $\gamma_0$) može se postići sletanje na lokacije sa velikom elevacijom bez unapređenja postojeće tehnologije.

- Početni uslovi ($v_0$, $\gamma_0$) imaju paraboličku zavisnost na izohronama spuštanja.

- Uticaj dnevnih varijacija atmosferskih parametara je višestruko manji od sezonskih i, suprotno od njih, opada sa udaljavanjem od ekvatora.

- Optimalno vreme sletanja je uvek tokom obdanice.

# HVALA NA PAŽNJI