gravitational signatures of atmospheric mass transport by thermal tides on Venus

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Sun raises two types of tides on Venus

- gravitational tide
  - larger amplitude
  - attracts mass
  - yields positive anomaly near sub-solar point
- thermal tide
  - smaller amplitude
  - heats sub-solar point
  - gas expands and moves away
  - yields negative anomaly near sub-solar point

An important, but currently unanswered, question concerning Venus atmospheric dynamics, is the following:

what is the depth profile of ***radiative energy absorption*** within the atmosphere?

We believe that future orbital missions, which enable gravitational monitoring of mass transport by the thermal tide, will resolve this issue

Venus has a slow, retrograde rotation.

The spin period is $-2\pi/\Omega = 243.025\ days$
The orbit period is $2\pi/n\ = 224.701\ days$

The mean solar day represents the beat between these input periods

$\omega = n - \Omega = 3.083\ deg/day$ so that

The sub-solar point moves East, at that rate, and circulates with a period of

$$2\pi/\omega\ = 116.752\ days$$

Present study examines gravitational signature of thermal tide

Approach

- use GCM to simulate atmospheric dynamics
- examine surface pressure variations over one solar day
- remove Venus-fixed average (mainly due to topography)
- back-rotate and average Sun-fixed pattern (mean thermal tide)
- examine residuals
- compute gravitational signature of thermal tide

Conclusions

- thermal tide gravitational signature is
  - too small to have been seen previously (Magellan)
  - large enough to be easily seen by likely future missions

Future Work

- constraints on key atmospheric dynamics parameters
- plausible mission designs

Examine surface pressure field

- compute time average (in Venus-fixed frame)
- remove average → anomaly
- compute time average (in Sun-fixed frame)
- examine spatial pattern of thermal tide
- remove (back-rotated) thermal tide → residual

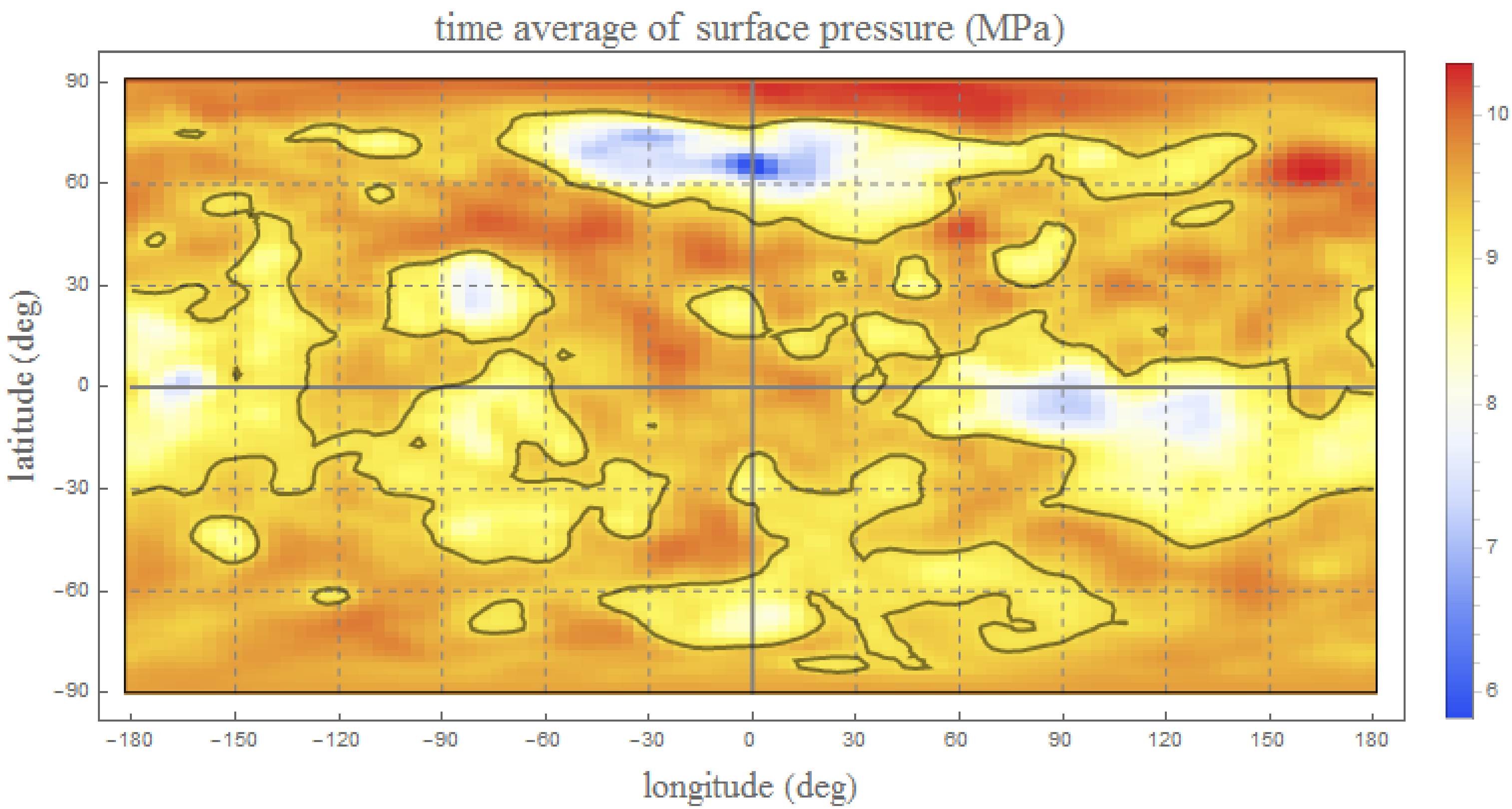
components of the surface pressure field

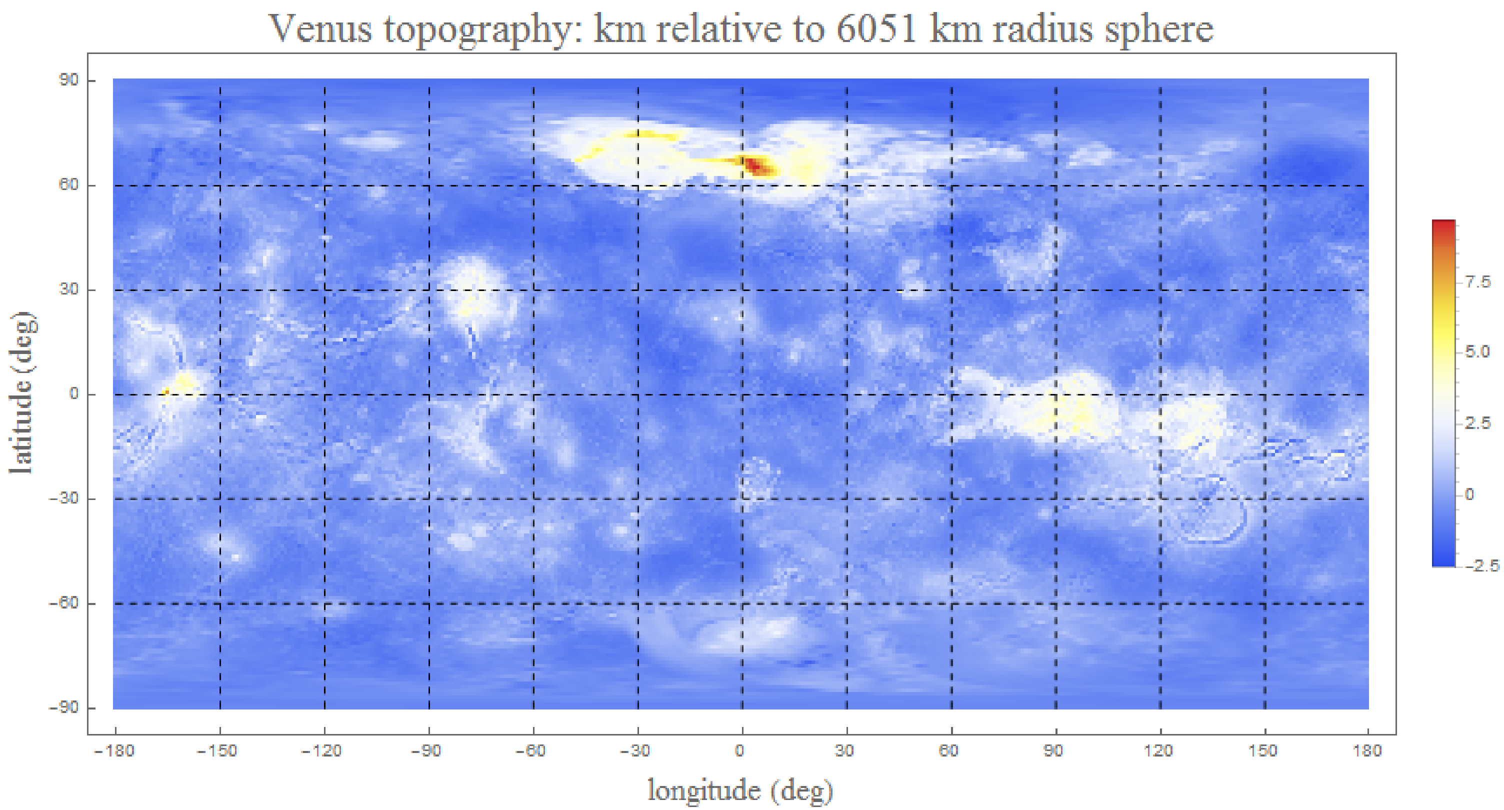
$$P[\theta, \varphi; t] \; = \; Q[\theta, \varphi] \quad + \quad \Delta P[\theta, \varphi; t]$$

full value   time average   anomaly

$$\Delta P[\theta, \varphi; t] = F[\theta, \varphi + \omega t] \quad + \quad \delta P[\theta, \varphi; t]$$

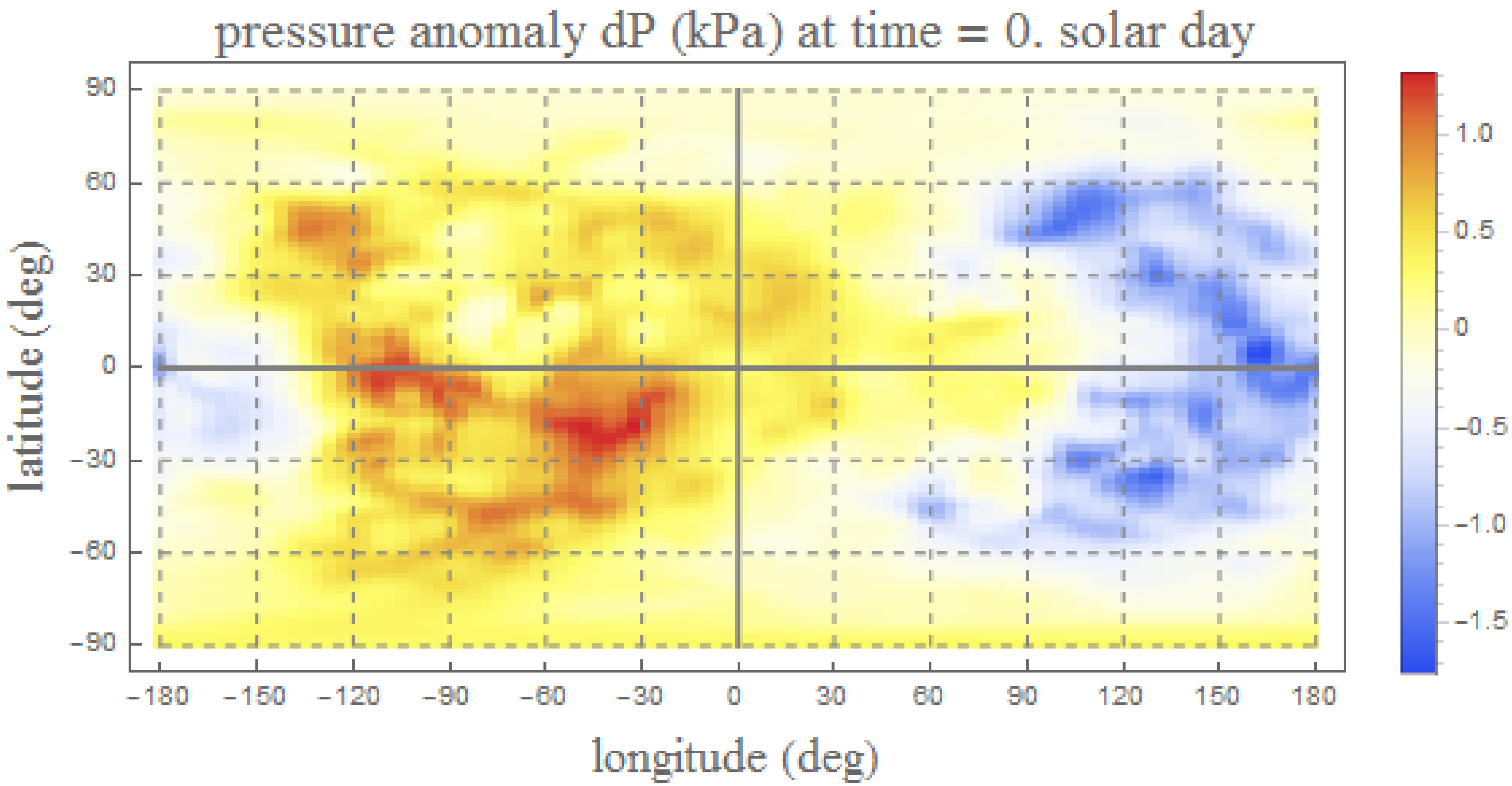
anomaly   thermal tide   residual

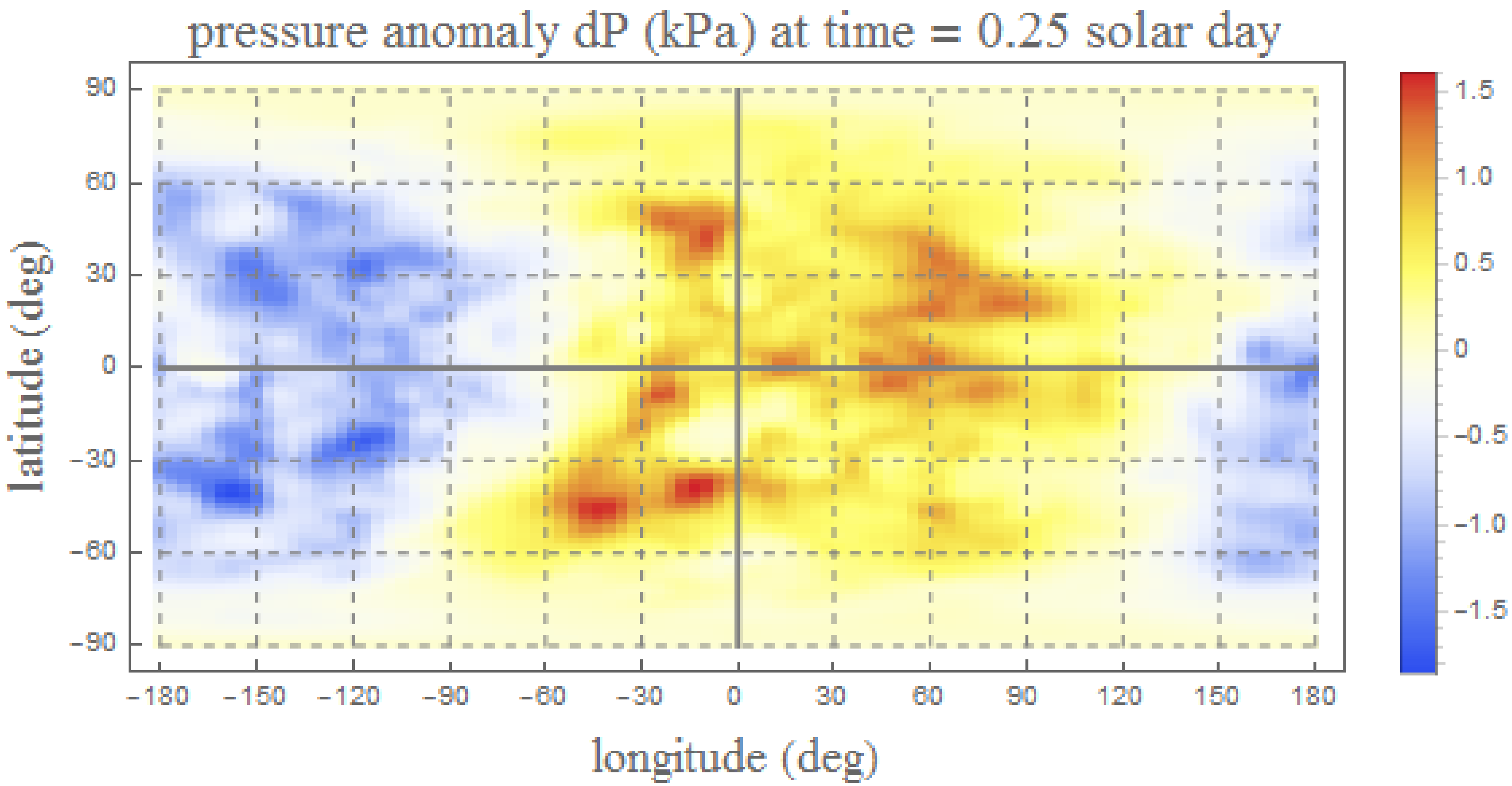

time average of surface pressure (MPa)
latitude (deg)
longitude (deg)
90
60
30
0
−30
−60
−90
−180
−150
−120
−90
−60
−30
0
30
60
90
120
150
180
10
9
8
7
6

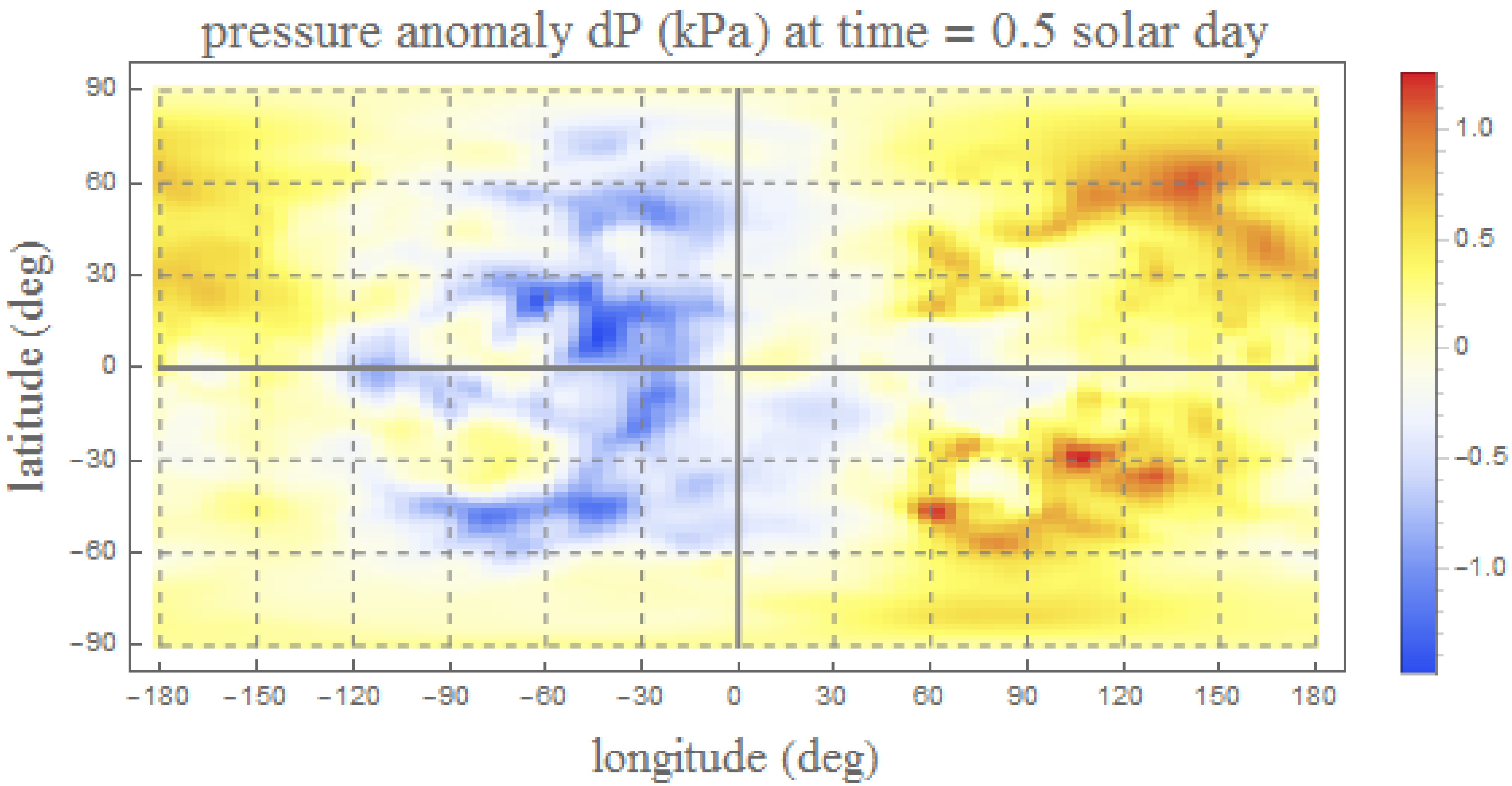

Venus topography: km relative to 6051 km radius sphere
latitude (deg)
longitude (deg)
90
60
30
0
−30
−60
−90
−180
−150
−120
−90
−60
−30
0
30
60
90
120
150
180
7.5
5.0
2.5
0
−2.5

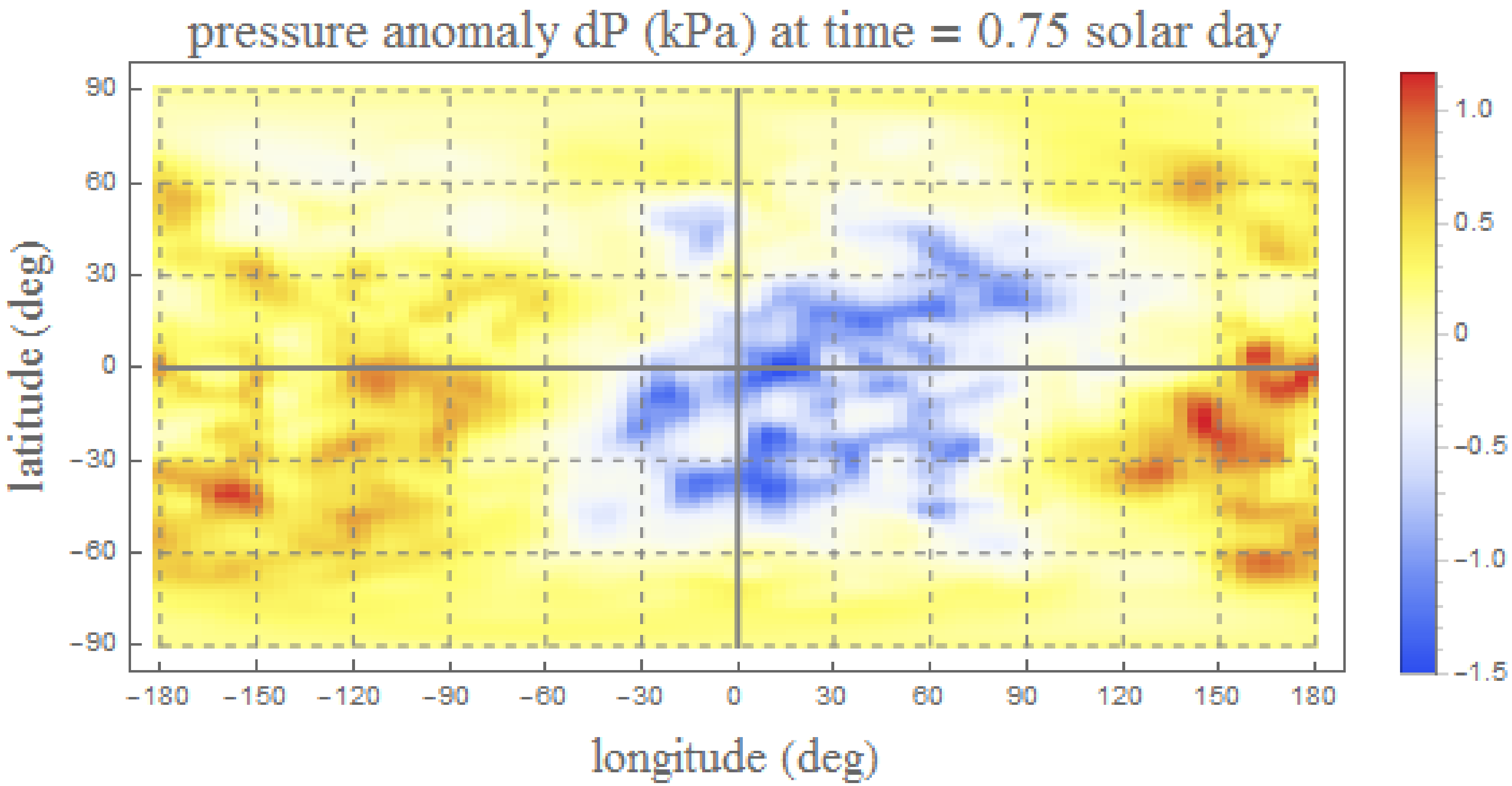
The next 4 figures show motions of the anomaly field, with time steps of ¼ solar day.

The pattern moves east, following the sub-solar point


pressure anomaly dP (kPa) at time = 0. solar day
latitude (deg)
longitude (deg)
90
60
30
0
−30
−60
−90
−180
−150
−120
−90
−60
−30
0
30
60
90
120
150
180
1.0
0.5
0
−0.5
−1.0
−1.5

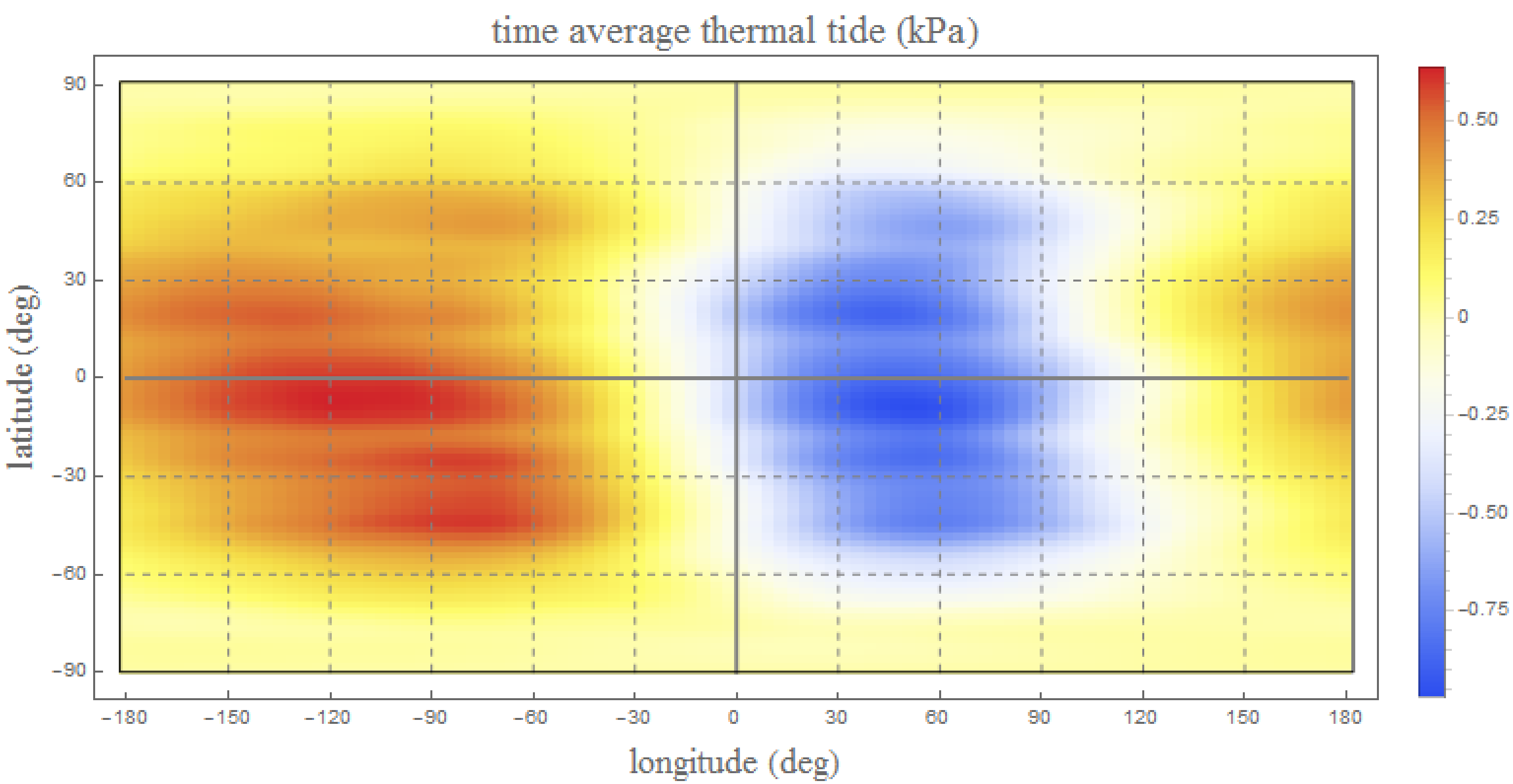

pressure anomaly dP (kPa) at time = 0.25 solar day
latitude (deg)
longitude (deg)
90
60
30
0
−30
−60
−90
−180
−150
−120
−90
−60
−30
0
30
60
90
120
150
180
1.5
1.0
0.5
0
−0.5
−1.0
−1.5


pressure anomaly dP (kPa) at time = 0.5 solar day
latitude (deg)
longitude (deg)
90
60
30
0
−30
−60
−90
−180
−150
−120
−90
−60
−30
0
30
60
90
120
150
180
1.0
0.5
0
−0.5
−1.0


pressure anomaly dP (kPa) at time = 0.75 solar day
latitude (deg)
longitude (deg)
90
60
30
0
−30
−60
−90
−180
−150
−120
−90
−60
−30
0
30
60
90
120
150
180
1.0
0.5
0
−0.5
−1.0
−1.5

compute average thermal tide

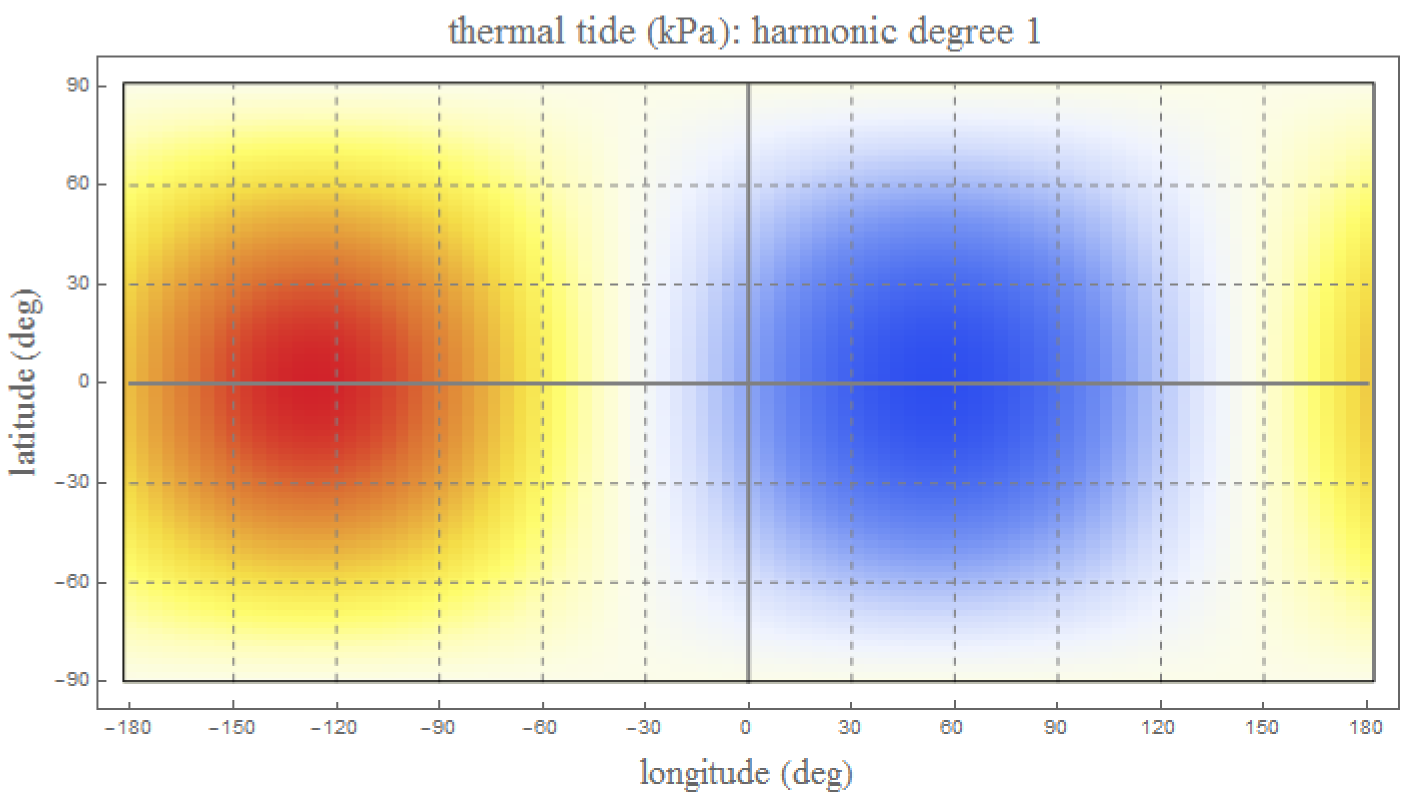
- sub-solar point moves east by 360 deg/solar day
- rotate each time-slice back to reference position
- average back-rotated values

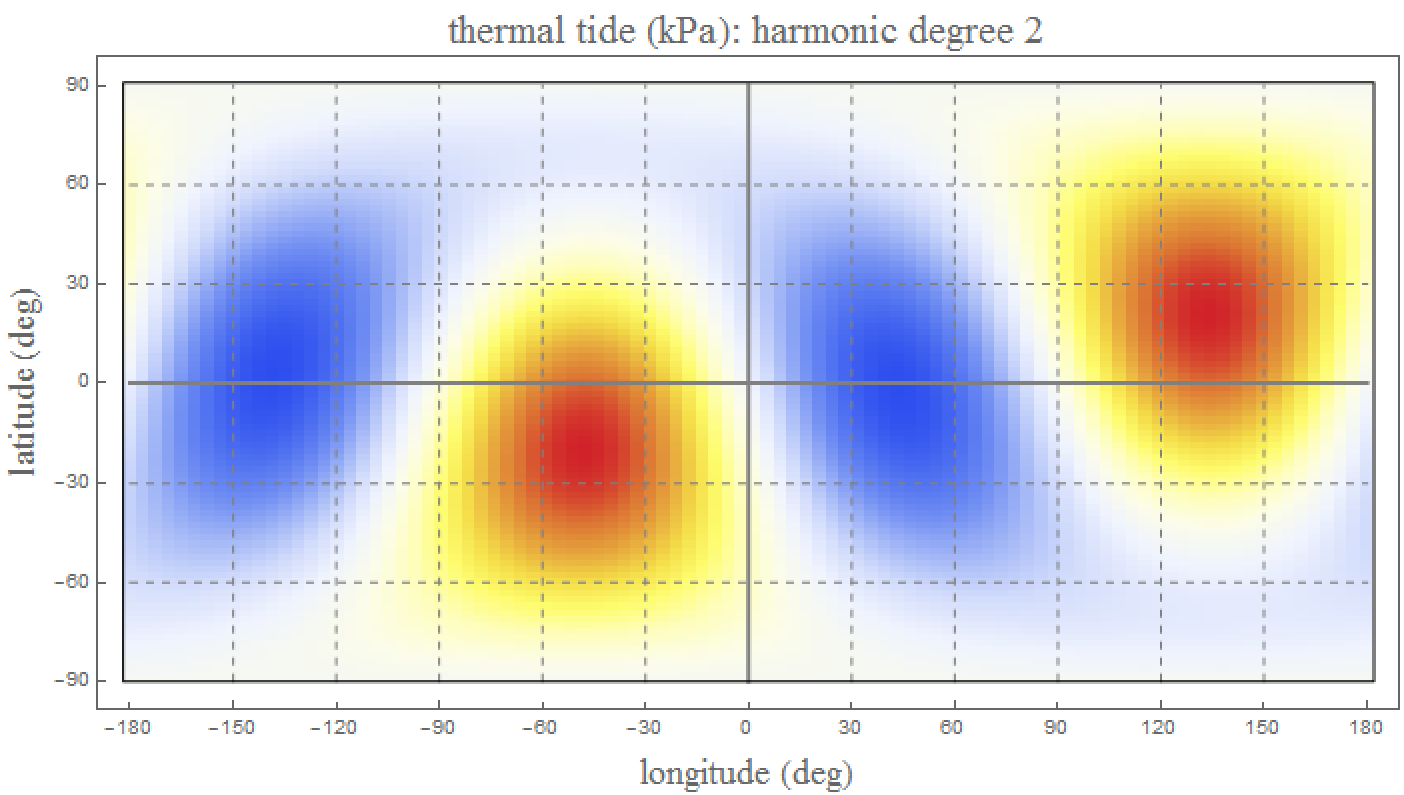

time average thermal tide (kPa)
latitude (deg)
longitude (deg)
90
60
30
0
-30
-60
-90
-180
-150
-120
-90
-60
-30
0
30
60
90
120
150
180
0.50
0.25
0
-0.25
-0.50
-0.75

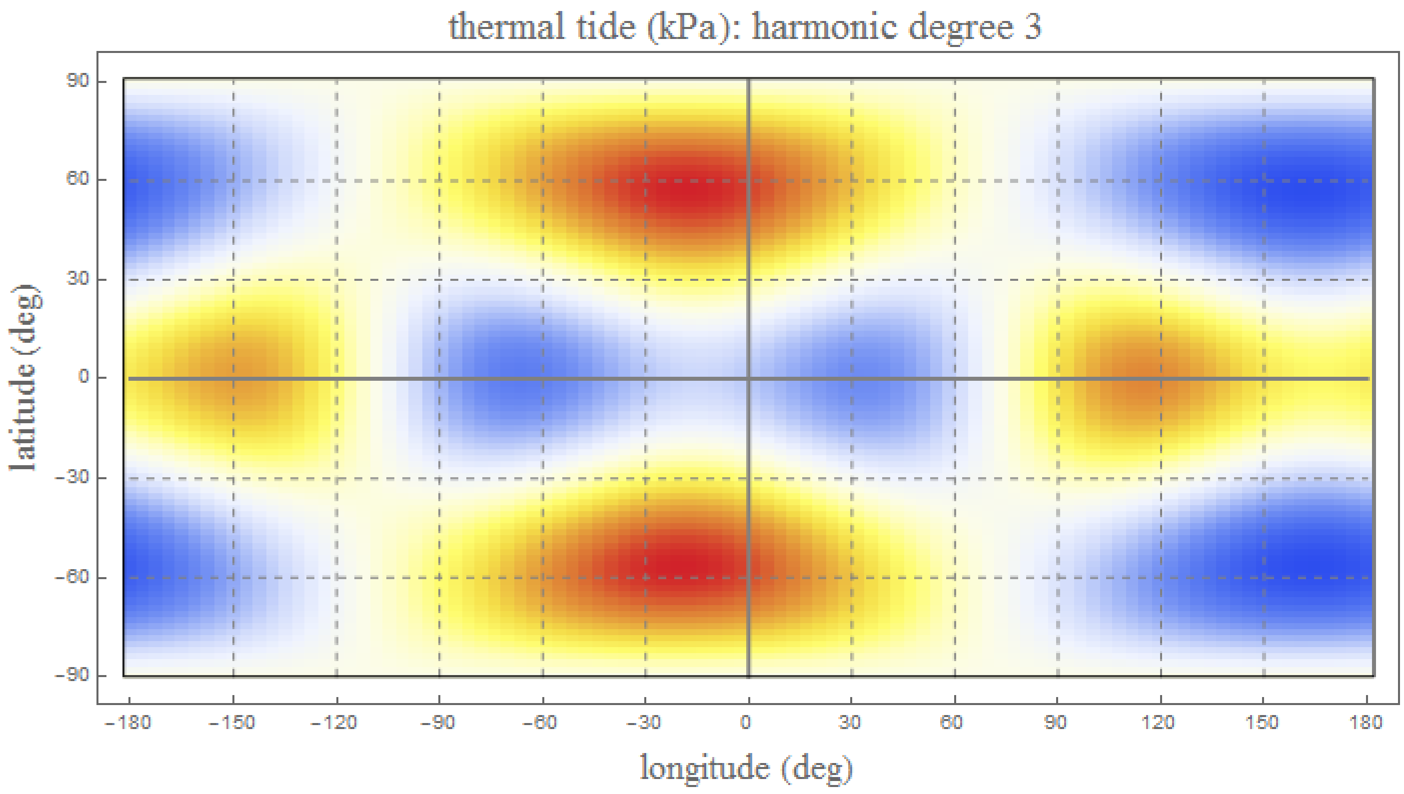
This pattern is, of course, equal to a sum of contributions from spherical harmonic functions.

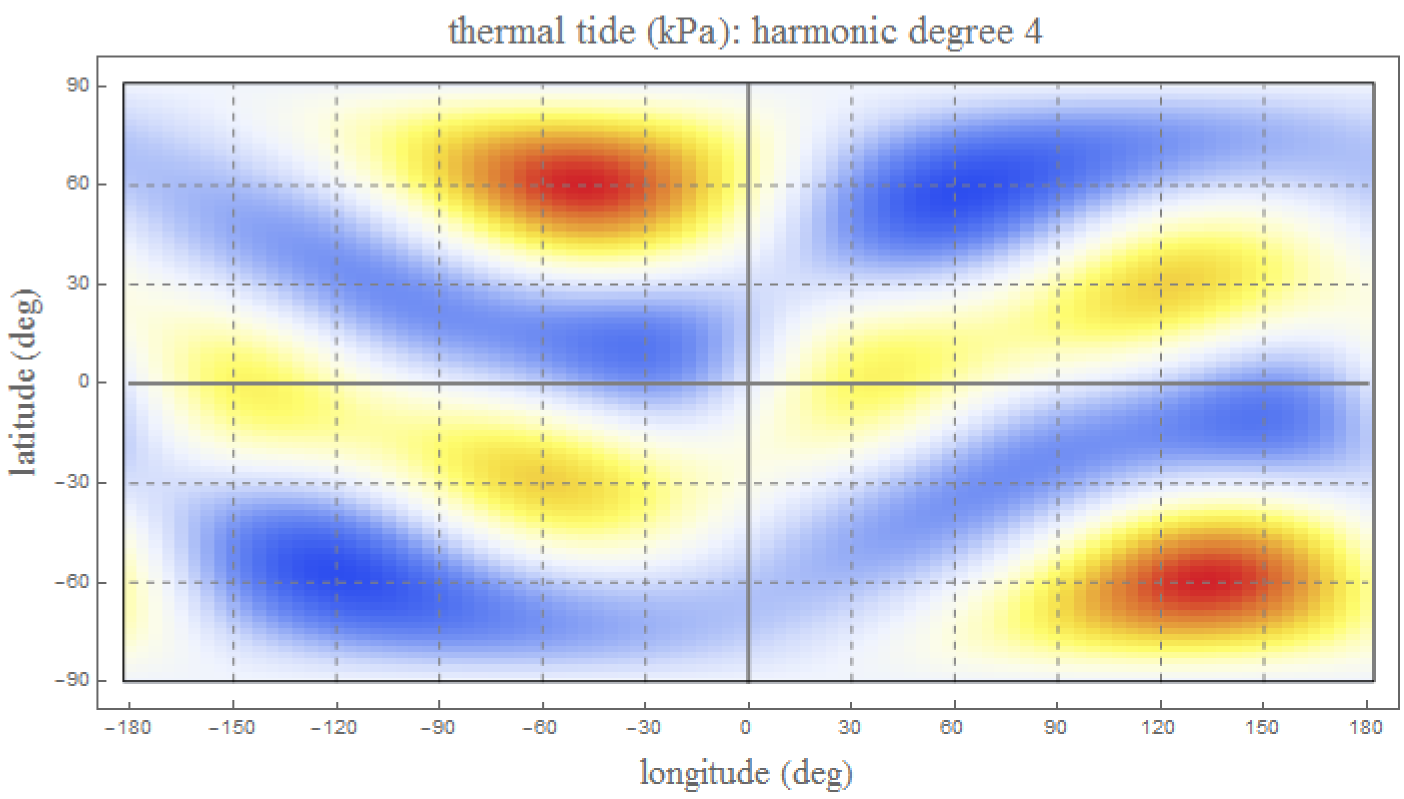
This harmonic decomposition:

- helps understand the spatial pattern, and
- is a first step in the gravity analysis

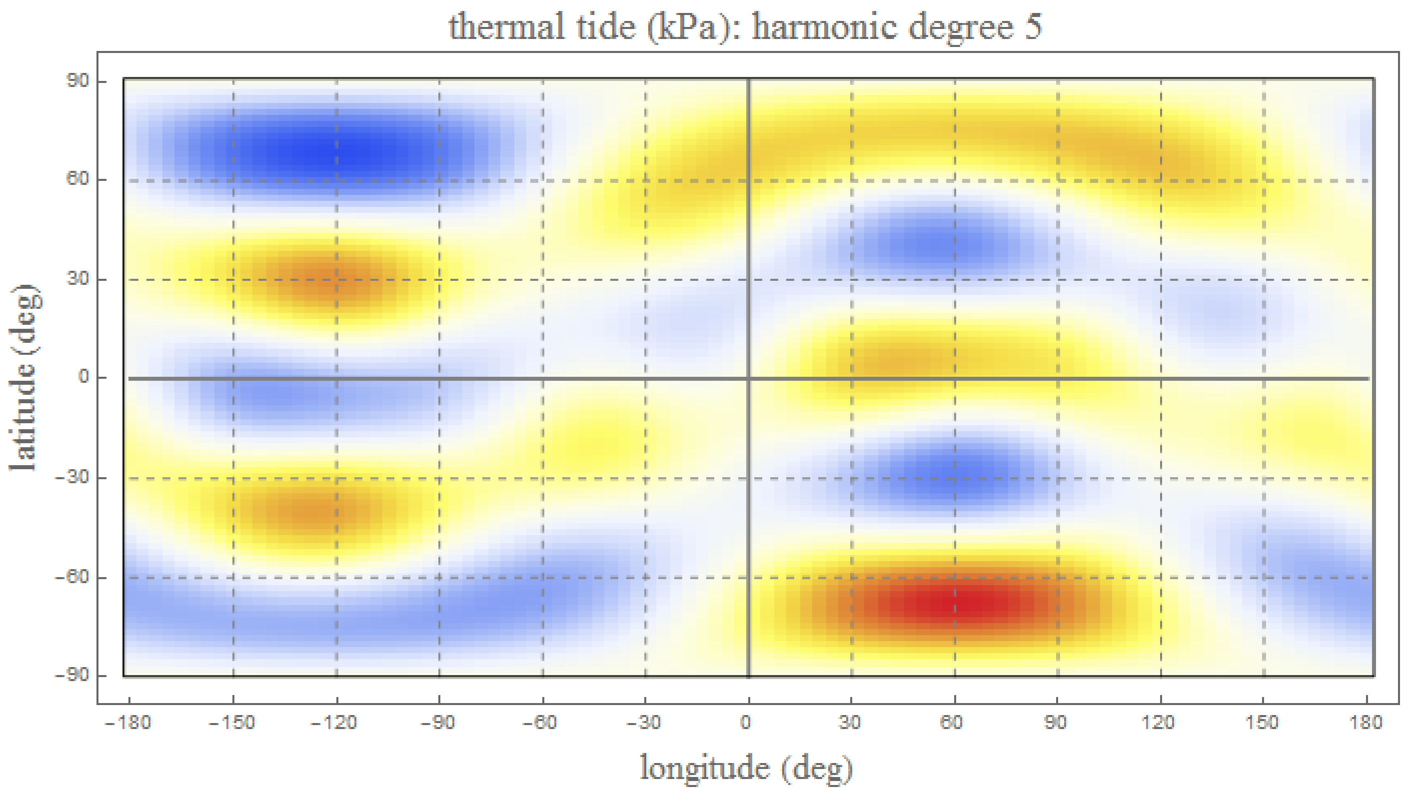

thermal tide (kPa): harmonic degree 1
latitude (deg)
90
60
30
0
−30
−60
−90
−180
−150
−120
−90
−60
−30
0
30
60
90
120
150
180
longitude (deg)

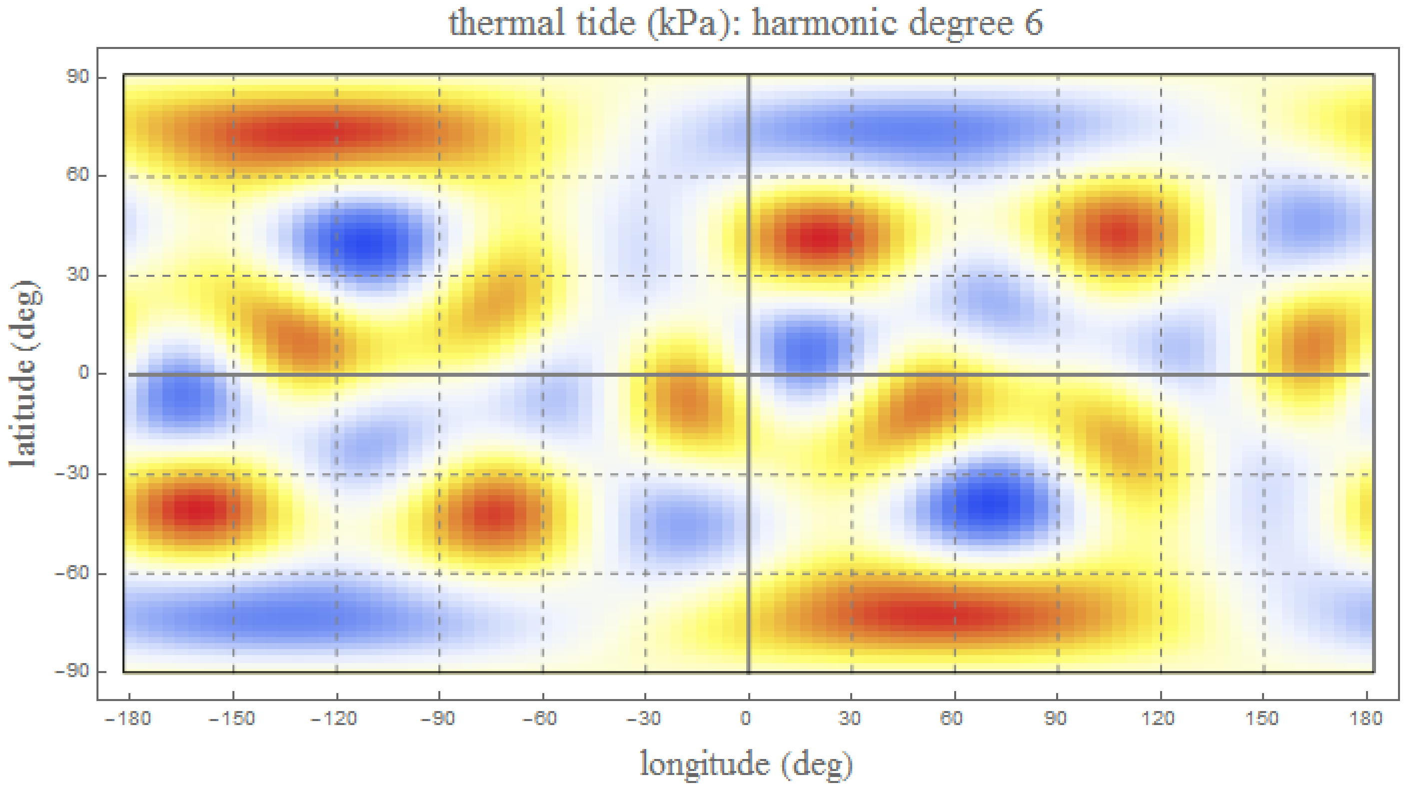

thermal tide (kPa): harmonic degree 2
latitude (deg)
longitude (deg)
90
60
30
0
−30
−60
−90
−180
−150
−120
−90
−60
−30
0
30
60
90
120
150
180

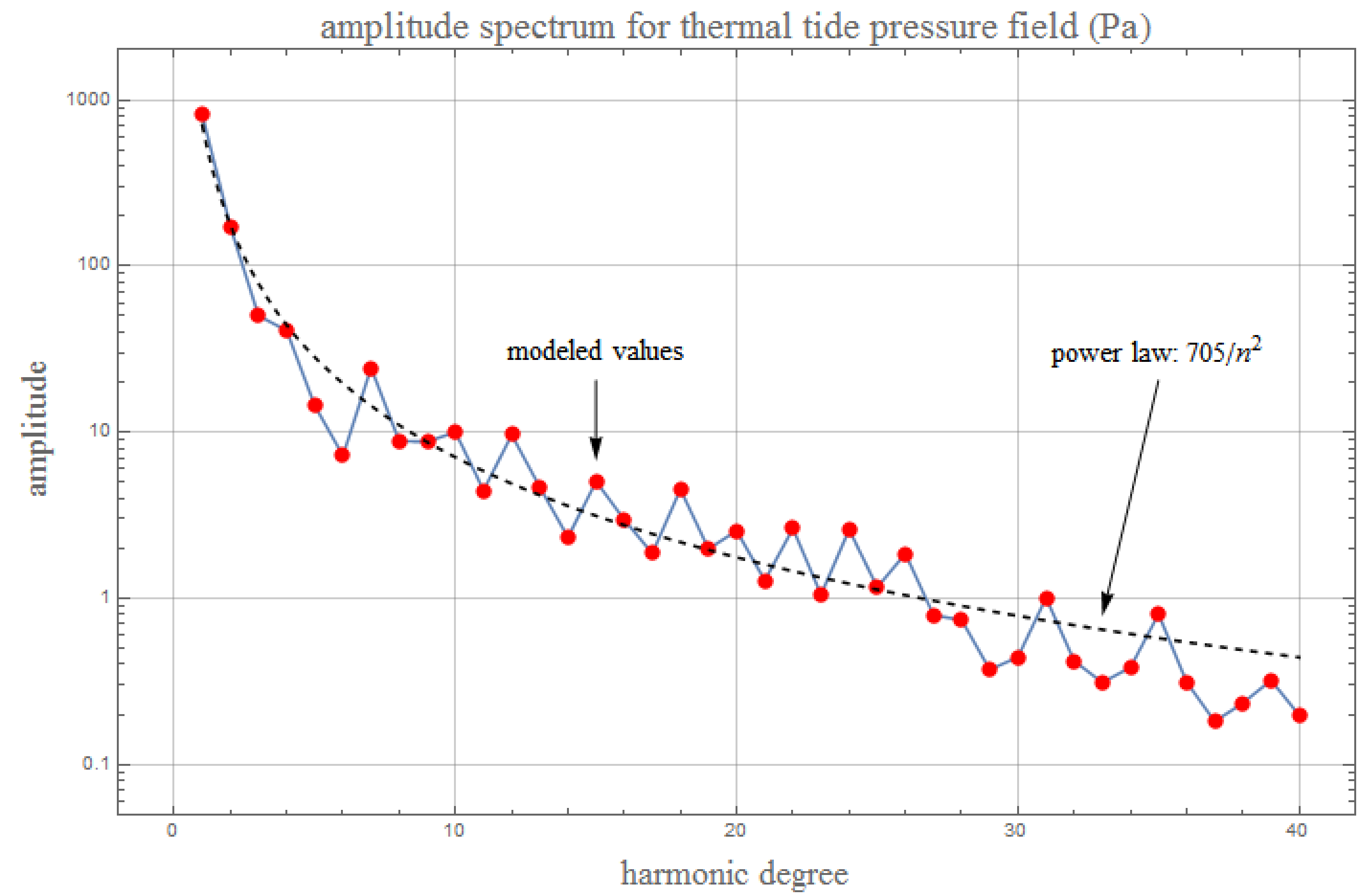

thermal tide (kPa): harmonic degree 3
90
60
30
0
−30
−60
−90
latitude (deg)
−180
−150
−120
−90
−60
−30
0
30
60
90
120
150
180
longitude (deg)

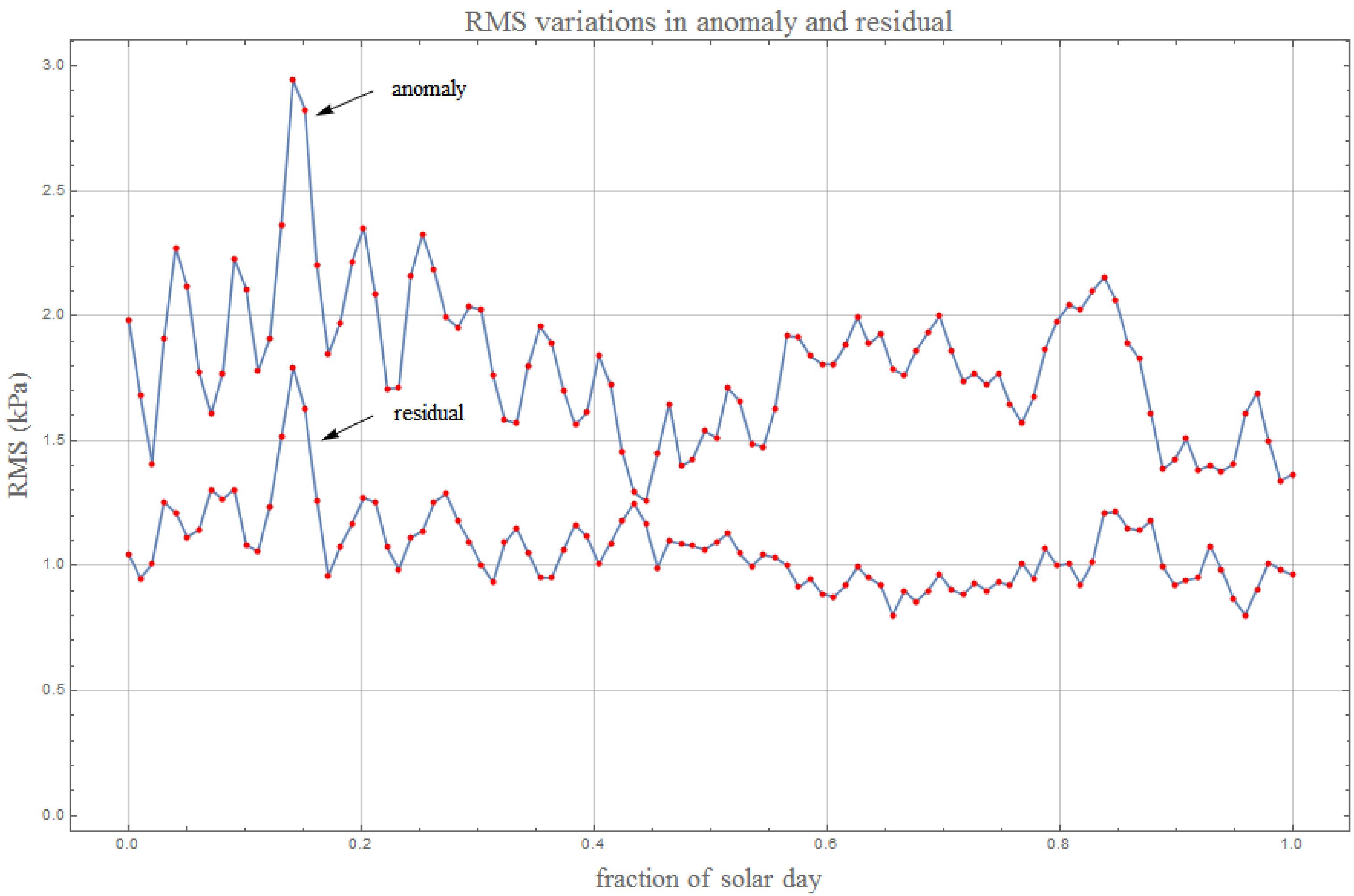


thermal tide (kPa): harmonic degree 4
latitude (deg)
longitude (deg)
90
60
30
0
−30
−60
−90
−180
−150
−120
−90
−60
−30
0
30
60
90
120
150
180


thermal tide (kPa): harmonic degree 5
latitude (deg)
90
60
30
0
-30
-60
-90
longitude (deg)
-180
-150
-120
-90
-60
-30
0
30
60
90
120
150
180


thermal tide (kPa): harmonic degree 6
90
60
30
0
-30
-60
-90
latitude (deg)
-180
-150
-120
-90
-60
-30
0
30
60
90
120
150
180
longitude (deg)


amplitude spectrum for thermal tide pressure field (Pa)
1000
100
10
1
0.1
amplitude
0
10
20
30
40
harmonic degree
modeled values
power law: 705/n^2



RMS variations in anomaly and residual
anomaly
residual
RMS (kPa)
fraction of solar day
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0.0
0.2
0.4
0.6
0.8
1.0

gravitational signature of thermal tide

- convert pressure to equivalent mass surface density
- expand density in spherical harmonic series
- convert mass density to gravitational potential

The gravitational potential Φ, at an external point with spherical coordinates (r, θ, φ),
can be written as a sum of spherical harmonic functions

$$\Phi[r,\theta,\varphi] = \frac{\mu}{r}\left(1 + \sum_{n}\left(\frac{R}{r}\right)^{n}\sum_{m,k} Y_{n,m,k}[\theta,\varphi]\, G_{n,m,k}\right)$$

where

$\mu = GM$ is the monopole moment,

R is the mean planetary radius, and

$G_{n,m,k}$ are dimensionless coefficients

In the present case, we first convert surface pressure $P[\theta, \varphi]$ into an equivalent surface mass density (kg/m^2) via

$$\sigma[\theta, \varphi] = \left(\frac{1}{g}\right) P[\theta, \varphi]$$

where $g = 8.87 \ m/s^2$ is the mean surface gravity.

Then expand the surface density in a harmonic series

$$\sigma[\theta, \varphi] = Z \left(1 + \sum_{n,m,k} Y_{n,m,k}[\theta, \varphi] \ S_{n,m,k}\right)$$

where

$Z = \frac{M}{4\pi R^2} = 1.06 \times 10^{10} \ kg/m^2$ is the monopole value

$S_{n,m,k}$ are dimensionless coefficients

In the last step of the conversion,
the mapping from surface density to potential is

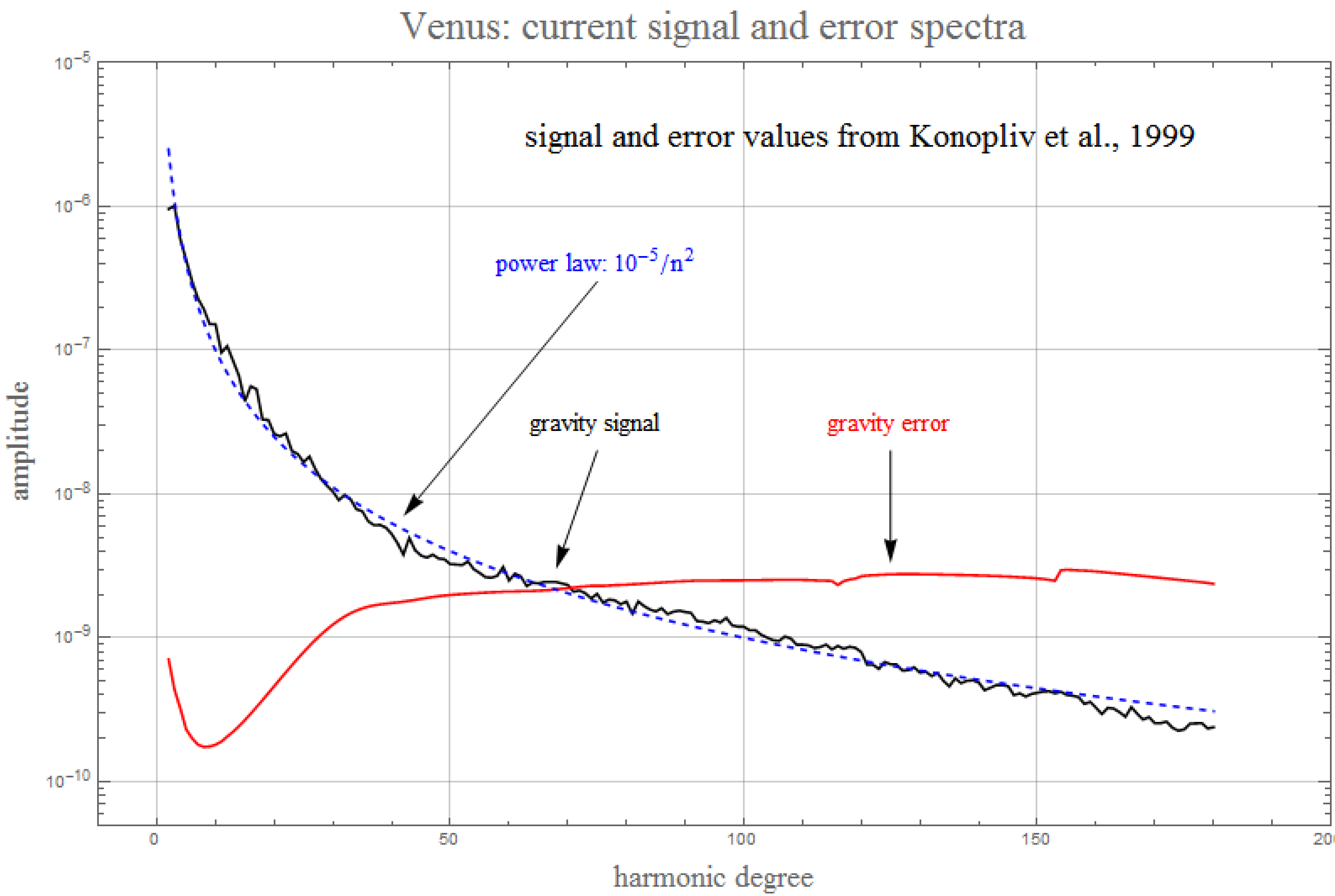
$$G_{n,m,k} = \left(\frac{1}{2n+1}\right) S_{n,m,k}$$

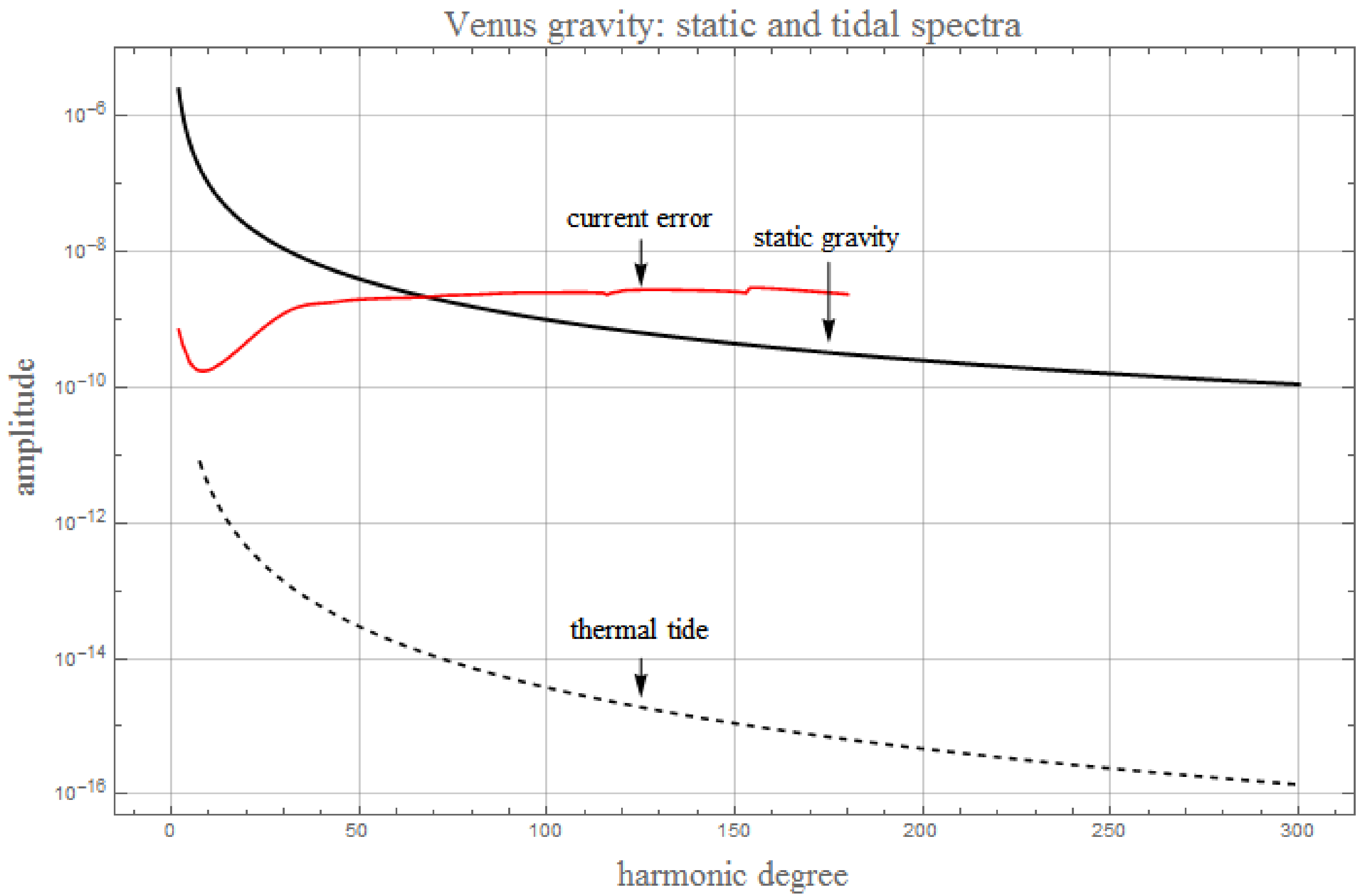
Within each harmonic degree **n**, the spatial patterns of pressure, surface density, and potential are identical.

However, the potential is a smoother function
than the pressure, because the higher degree terms
are diminished in size.

We now compare the spherical harmonic amplitude spectra of

- Venus static potential
  - signal
  - error
- Venus thermal tide


Venus: current signal and error spectra
signal and error values from Konopliv et al., 1999
power law: $10^{-5}/n^2$
gravity signal
gravity error
amplitude
harmonic degree
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
0
50
100
150
200



Venus gravity: static and tidal spectra
amplitude
10^-6
10^-8
10^-10
10^-12
10^-14
10^-16
current error
static gravity
thermal tide
0
50
100
150
200
250
300
harmonic degree

The modeled amplitude spectrum of the gravitational signature of the Venus thermal tide is small.

It is well below:

- static gravity field signal
- current measurement errors

Is it observable by future missions?

We now examine the accuracy to which gravitational potential can be estimated, from a series of

- N independent measurements,
- each with accuracy ε.

In general, we expect the recovered gravity accuracy to scale with

$$\sigma[n] = \frac{\varepsilon}{\sqrt{N}} \left(\frac{r}{R}\right)^{n} \mathrm{F}[\mu, R, r, n]$$

where

- $\mu = GM$ is the monopole moment
- R is the mean radius of the target body
- r is the mean radius of the orbit
- n is the harmonic degree

and $\mathrm{F}[\mu, R, r, n]$ is a function which depends upon mission orbit configuration.

We consider 3 spacecraft orbit configurations for gravity missions.

- The classic case involves Doppler tracking, from Earth,
  of a single satellite orbiting the target body.

- Another approach, used by GRACE and GRAIL,
  measures changes in relative speed
  between a pair of co-orbital satellites

- The third approach uses a gravity gradiometer.

In the first 2 cases, the measurement is a velocity (m/s).
In the third case, it is a gradient of acceleration $(1/s^2)$.

The standard unit for gravity gradients is

$$Eotvos \ = E = \ 10^{-9} \, s^{-2}$$

Modern gradiometers have accuracy of

$$\varepsilon_{grad} = \frac{10^{-3} \ E}{\sqrt{Hz}}$$

Ka-band (32 GHz) Doppler measurements have accuracy

$$\varepsilon_{Dop} = \frac{10^{-6} \, m/s}{\sqrt{Hz}}$$

Based upon a simple covariance analysis, we find

- for single satellite tracking, the configuration function is

$$F_{dop} = \sqrt{\frac{r}{\mu}} \left(\frac{\sqrt{n^2 + n + 1/2}}{n+1} \right)$$

- for a pair of co-orbital satellites, with angular separation γ, the configuration function is

$$F_{co-orb} = \sqrt{\frac{r}{\mu}} \left(\frac{1}{2\,\sin[n\gamma/2]} \right) \left(\frac{\sqrt{n^2 + n + 1/2}}{n+1} \right)$$

- for a gradiometer, the configuration function is

$$F_{grad} = \left(\frac{r^3}{\mu} \right) \sqrt{\frac{(2 + 2\,n + n^2)\,(1 + 2\,n + 2\,n^2)}{n^2\,(5 + 6\,n + 2\,n^2)\,(4 + 12\,n + 13\,n^2 + 6\,n^3 + 2\,n^4)}}$$

A challenge at Venus, compared to Mars and Earth,
is the slow rotation.

It takes more time to obtain complete spatial sampling.

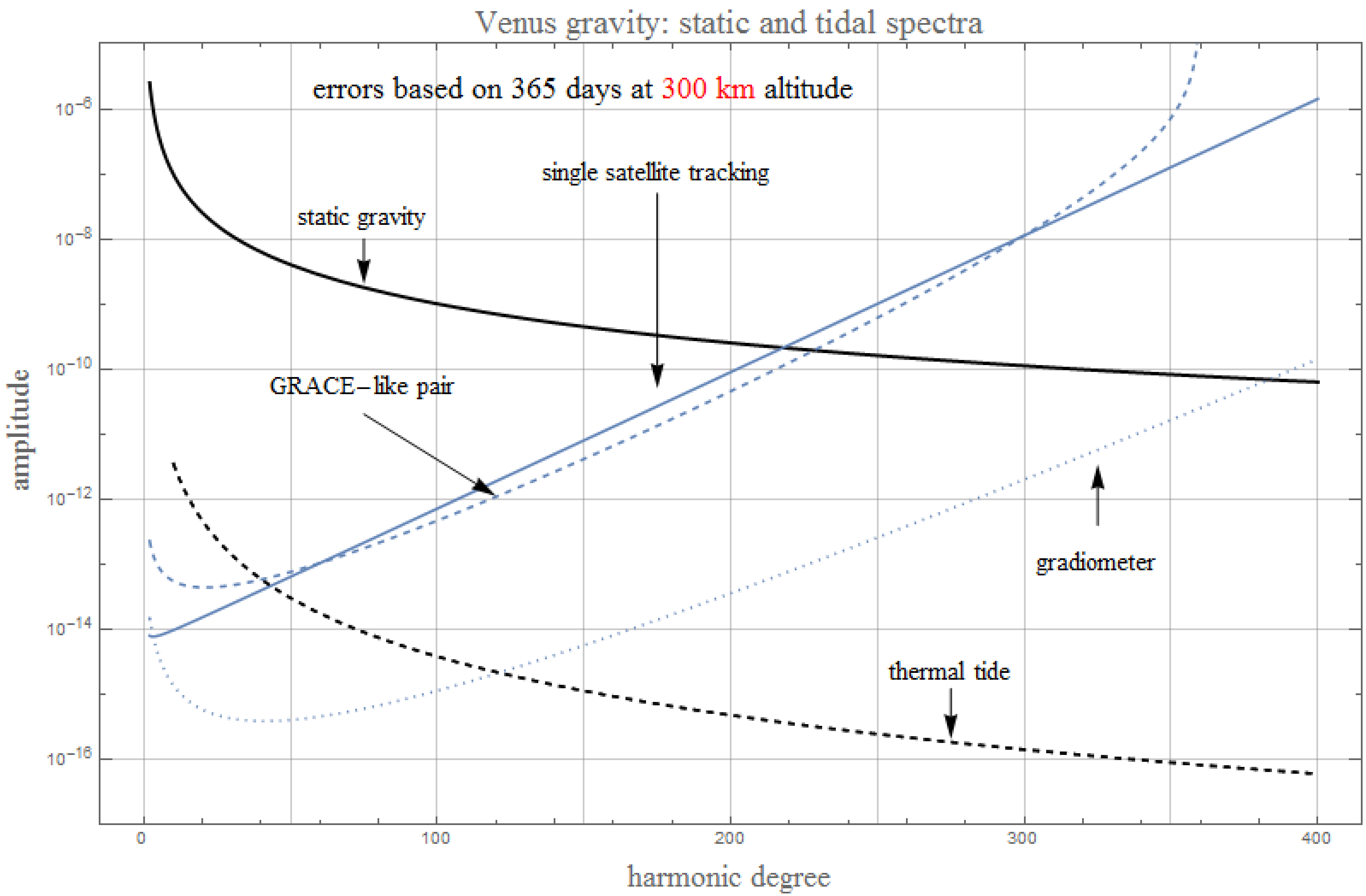
In the present context, we are also attempting
to sample, and separate, two different patterns:

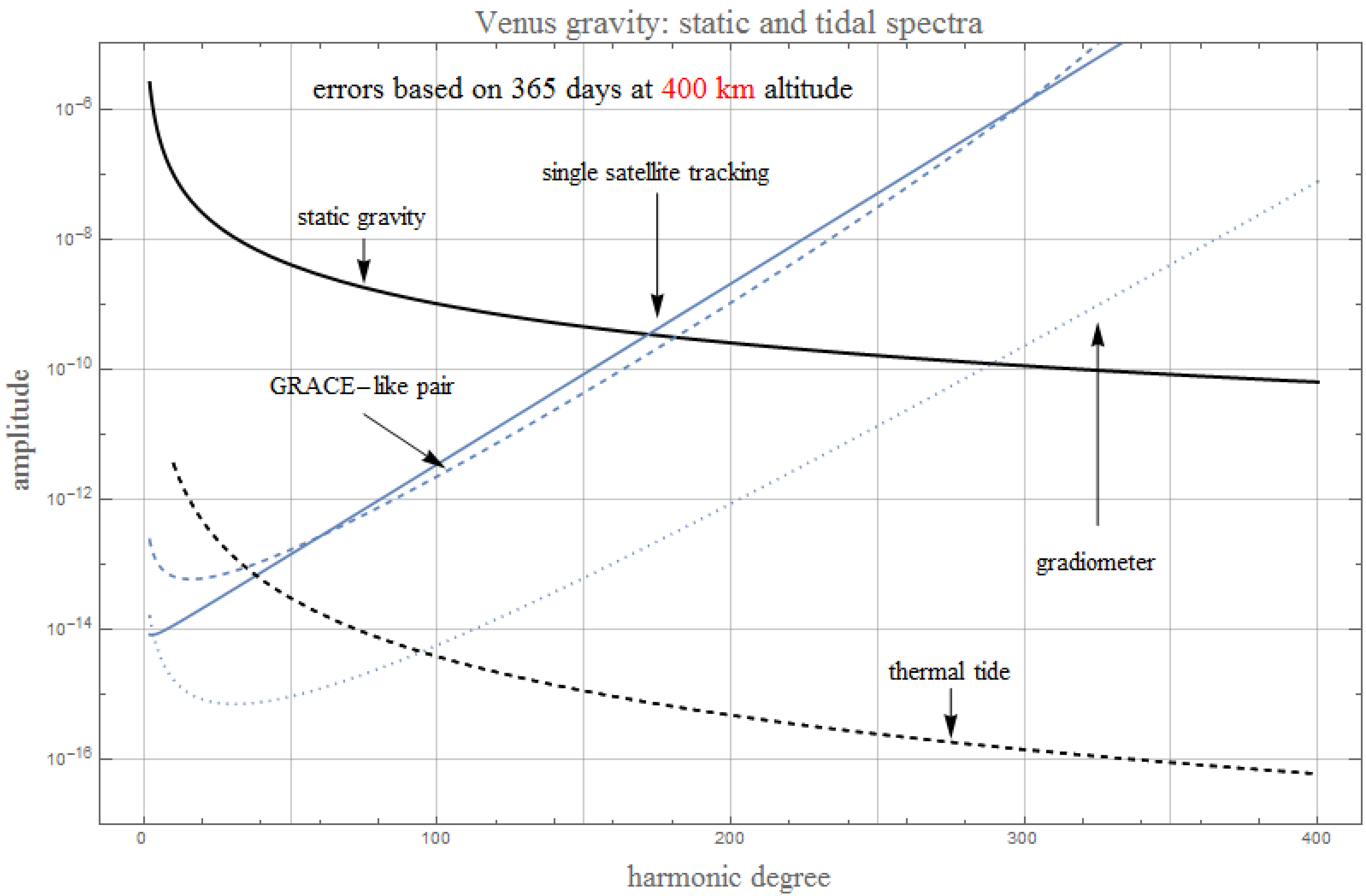
- one fixed to Venus
- another fixed to Sun

The next figure shows

- Venus static gravity signal spectrum
- thermal tide signal spectrum
- error spectra for the 3 measurement configurations

We show results for 2 orbit geometries,
with altitudes above the mean surface of 300 and 400 km.


Venus gravity: static and tidal spectra
errors based on 365 days at 300 km altitude
static gravity
single satellite tracking
GRACE−like pair
gradiometer
thermal tide
amplitude
harmonic degree
10−6
10−8
10−10
10−12
10−14
10−16
0
100
200
300
400


Venus gravity: static and tidal spectra
errors based on 365 days at 400 km altitude
single satellite tracking
static gravity
GRACE−like pair
gradiometer
thermal tide
amplitude
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
0
100
200
300
400
harmonic degree

summary and conclusions

Thermal tide on Venus:

- important aspect of atmospheric dynamics
- gravitational signature
  - has not yet been measured
  - can clearly be measured with future missions