

THERMOSPHERIC DENSITY MODEL BIASES AT SUNSPOT MAXIMUM

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This analysis is based on a previous study, originally presented at the 37th COSPAR Scientific Assembly, in July 2008

- Pardini C., Anselmo L., Moe K., Moe M. M., Drag and energy accommodation coefficients during sunspot maximum, *Adv. Space Res.*, Vol. 45, pp. 638-650, 2010 ([doi:10.1016/j.asr.2009.08.034](https://doi.org/10.1016/j.asr.2009.08.034))

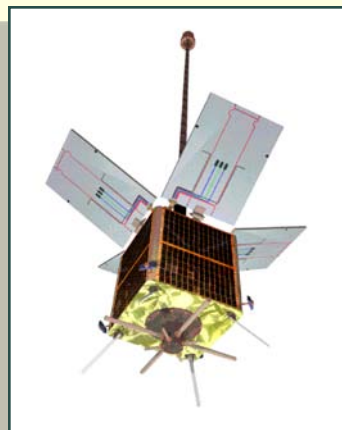
providing accommodation coefficients and “observed” drag coefficients for ten satellites with altitudes between 200 and 630 km, during solar maximum conditions

For this analysis we reused the following satellites

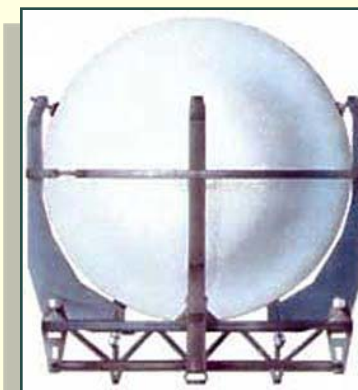
Satellite Name	Catalog Number	Area [m ²]	Mass [kg]	Mean Orbital Elements at the beginning of the time span			Time span over which the orbital decay was analyzed
				Inclination [deg]	Perigee Altitude [km]	Apogee Altitude [km]	
Cylinder-like body with a hexagonal cross section							
SNOE	25233	0.8377	115.5	97.7	515	570	2-Oct-99 30-Dec-02
Spinning box with solar panels and a long rod for gravity-gradient stabilization							
Clementine	25968	0.568	50	98.1	643	663	4-Dec-99 30-Dec-02
TAIFUN YUGS spheres							
Cosmos 2265	22875	3.142	750	82.8	280	1279	2-Oct-99 30-Dec-02
Cosmos 2332	23853	3.242	750	82.9	286	1383	1-Oct-99 30-Dec-02



SNOE



Clementine



Taifun Yug

and we derived the average density biases of the following thermospheric models

■ **JR-71**

Cappellari, J.O., Velez, C.E., Fuchs, A.J. (eds.). Mathematical Theory of the Goddard Trajectory Determination System. NASA/GSFC Report, GSFC X-582-76-77, Greenbelt, Maryland, USA, 1976

■ **MSISE-90**

<http://uap-www.nrl.navy.mil/uap/>

■ **NRLMSISE-00**

<http://uap-www.nrl.navy.mil/uap/>

■ **GOST2004**

Anon.: “Earth’s Upper Atmosphere Density Model for Ballistic Support of the Flight of Artificial Earth Satellites”, National Standard of the Russian Federation, Document number GOST R 25645.166-2004, Gosstandart of Russia, Moscow, 2004 - English translation accomplished by Vasiliy S. Yurasov in 2006 and edited by Paul J. Cefola in 2007

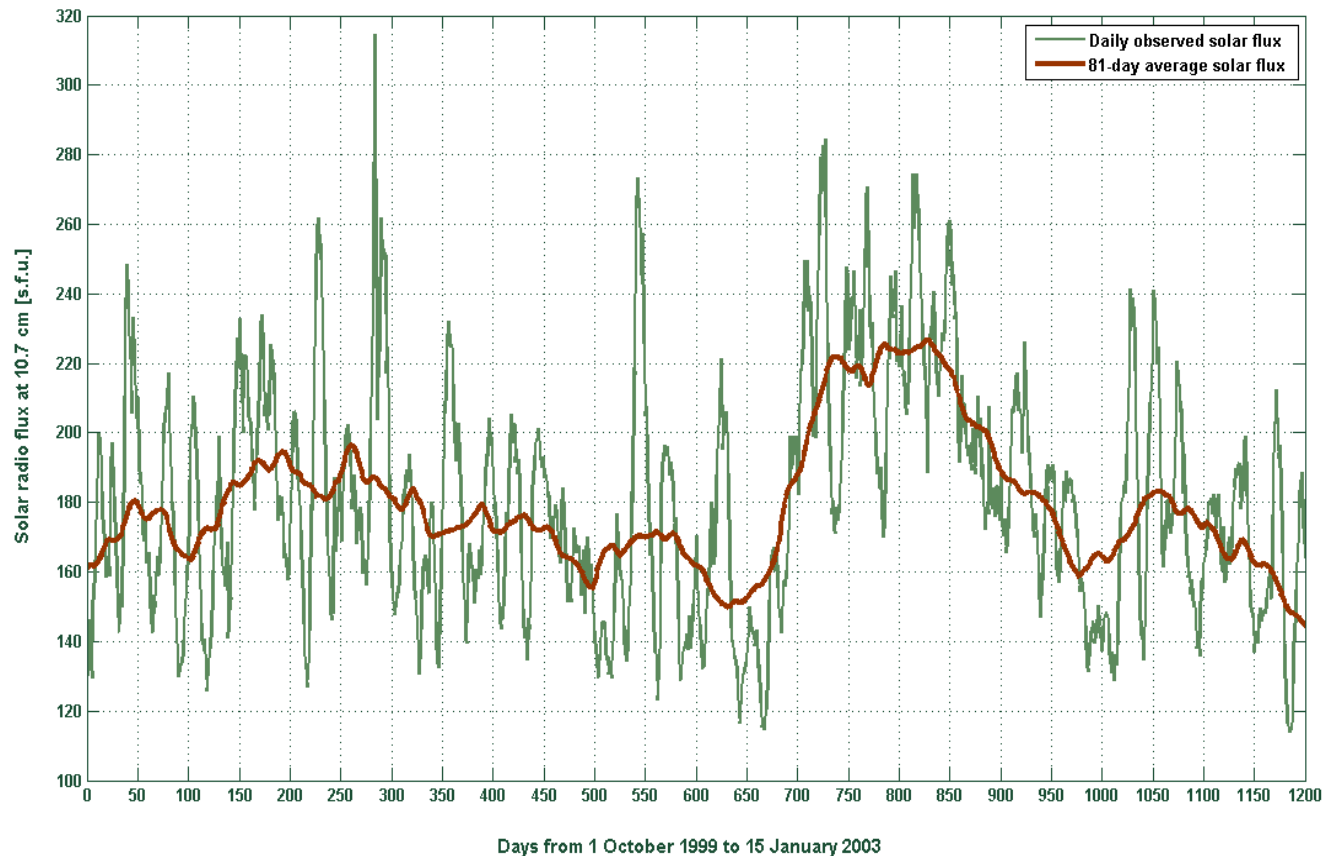
■ **JB2006**

<http://sol.spacenvironment.net/~JB2006/>

during the sunspot maximum of solar cycle 23 [October 1999 - January 2003]

SOLAR FLUX

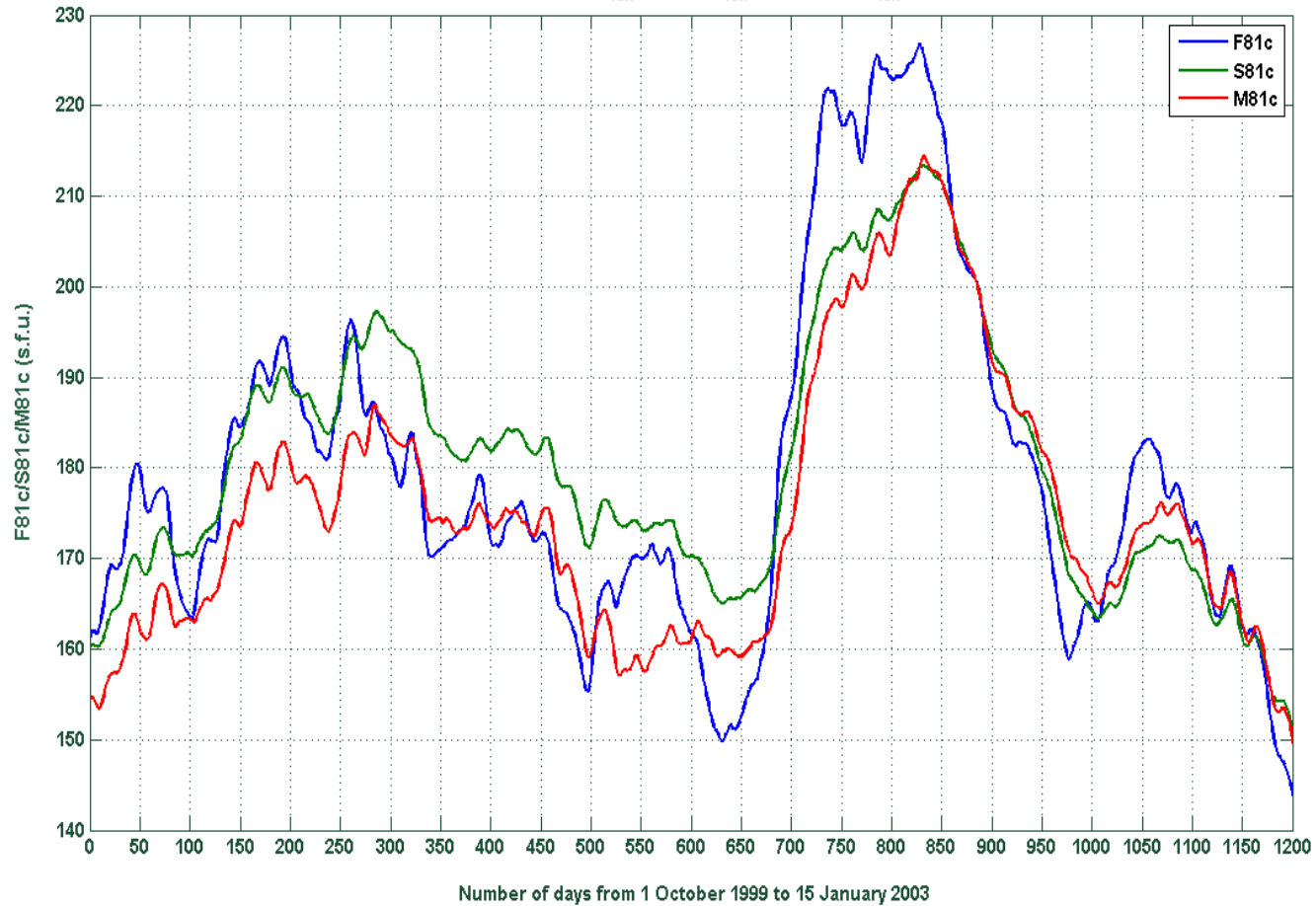
[JR-71, MSISE-90, NRLMSISE-00, GOST2004]



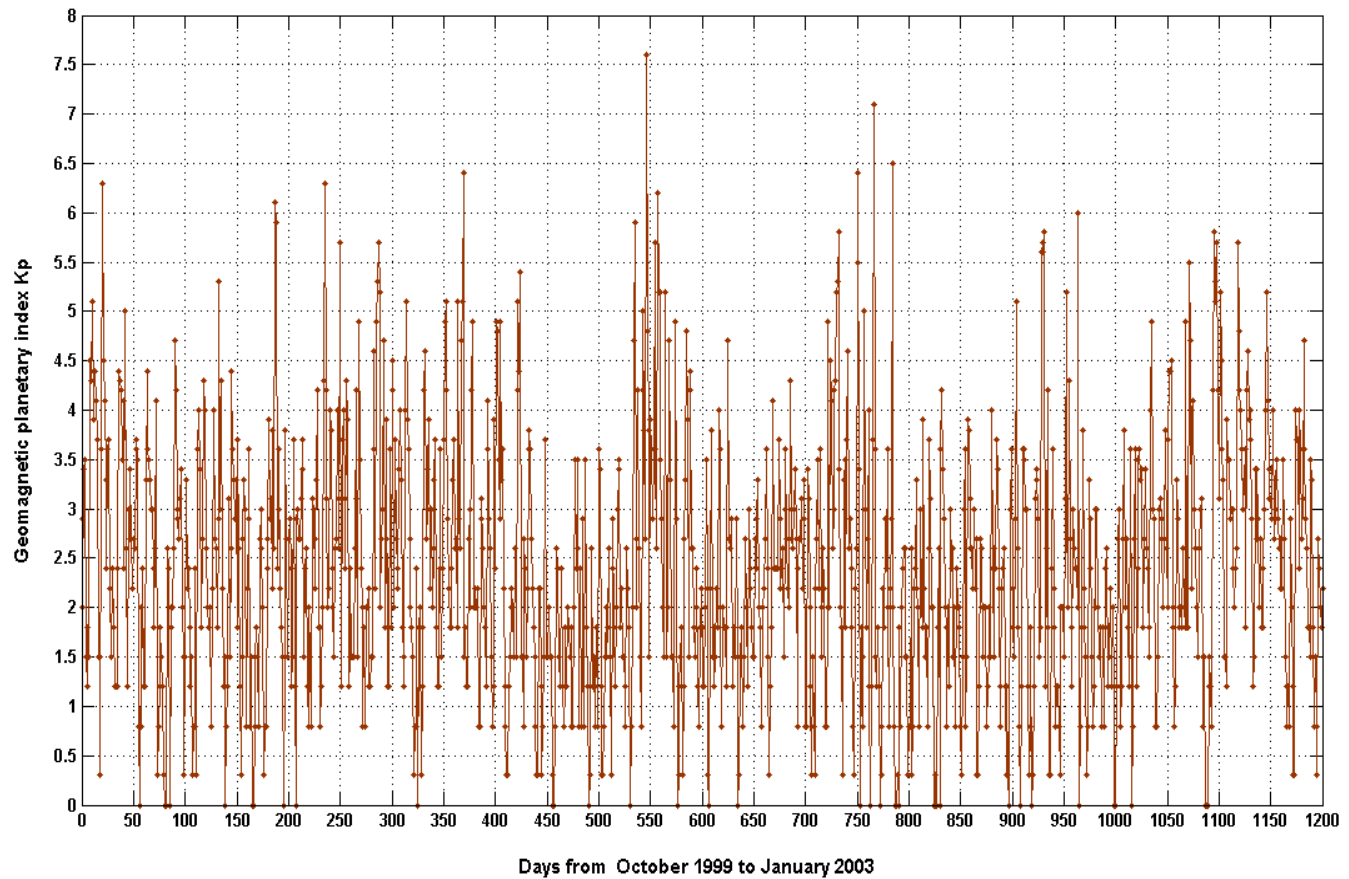
SOLAR FLUX

[JB2006]

81-day centered smoothed values of the v.4.0 JB2006 solar indices $F_{10.7}$ (F81c), $S_{10.7}$ (S81c) and $M_{10.7}$ (M81c) during the sunspot maximum of solar cycle 23



GEOMAGNETIC INDEX



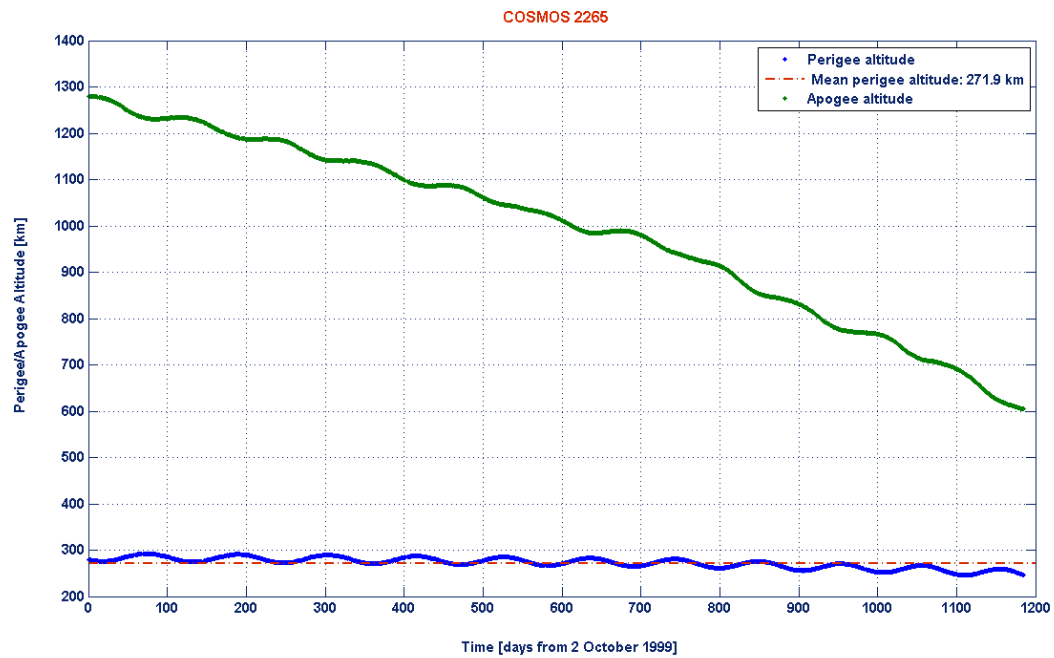
For each satellite and atmospheric density model

- a fitted drag coefficient, $C_D[\textit{fitted}]$, was obtained with CDFIT (*ISTI/CNR software code*), including all the relevant perturbations, by analyzing the observed orbital decay
- $C_D[\textit{fitted}]$ was then compared with the corresponding observed drag coefficient $C_D[\textit{observed}]$, determined in the previous study

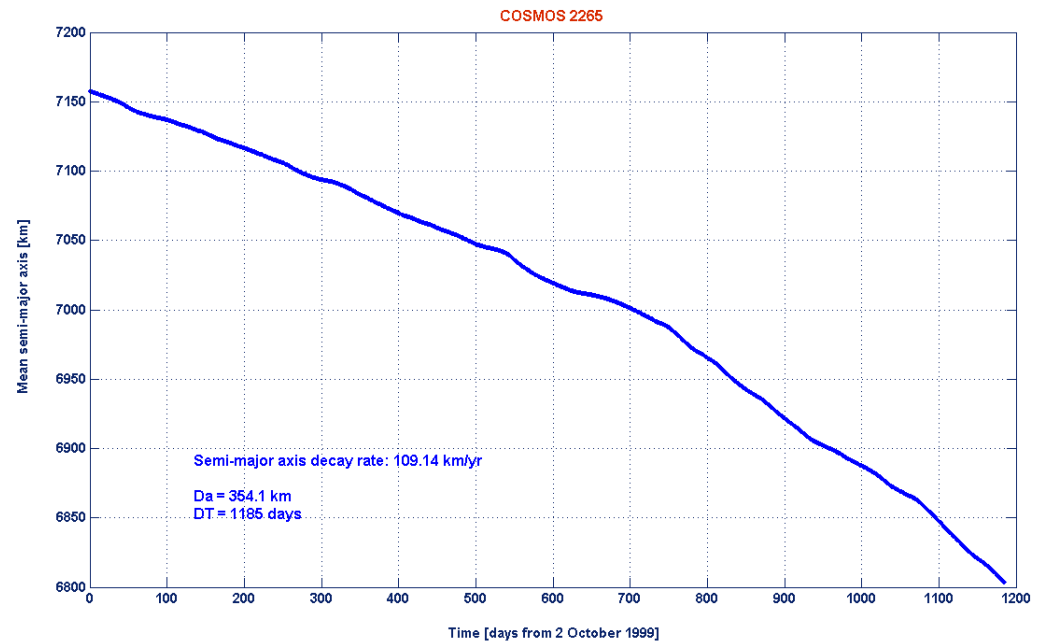
Altitude [km]	Satellite	Observed drag coefficient
275	Cosmos 2265	2.11
275	Cosmos 2332	2.17
480	SNOE	2.54
630	Clementine	2.63

- The average density bias (%) of the thermospheric model was derived from

$$100 \times \frac{C_D[\textit{observed}] - C_D[\textit{fitted}]}{C_D[\textit{observed}]}$$



Cosmos 2265



Cosmos 2265

Observed Drag Coefficient: $C_D [observed] = 2.11$

Drag coefficient fitted over 1185 days: 2 October 1999 – 30 December 2002

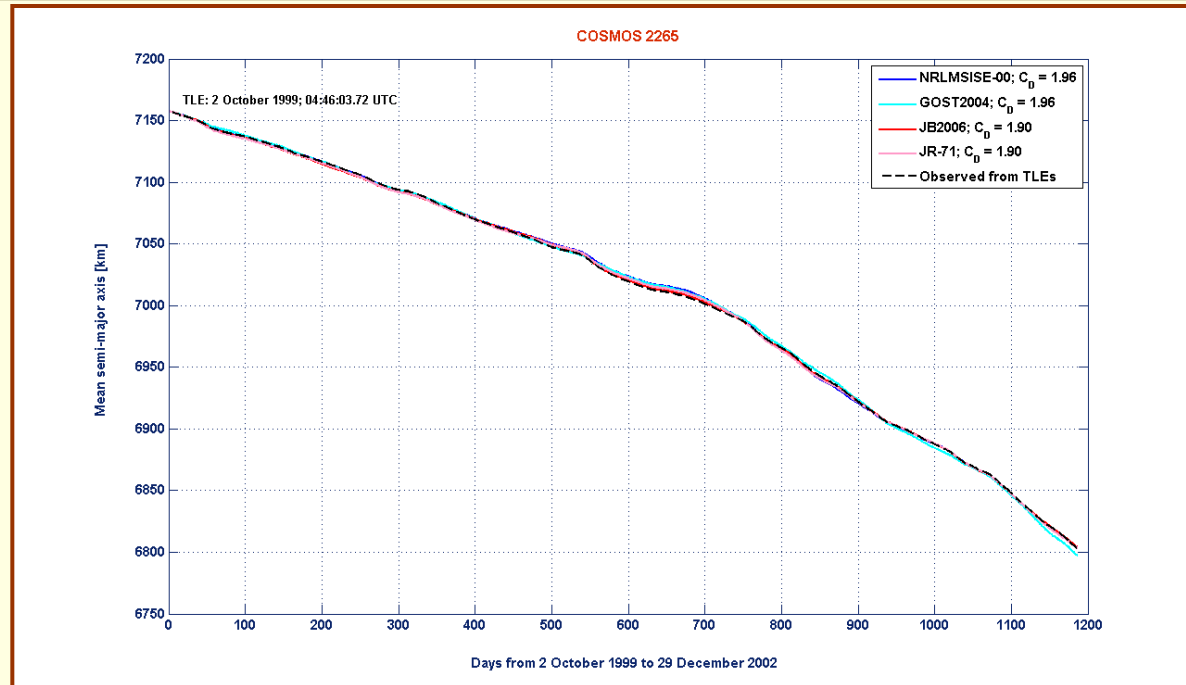
Observed semi-major axis decay: $\Delta a = 354.1$ km

Fitted Drag coefficient ($C_D [fitted]$)
with root mean square residuals (rms) on semi-major axis

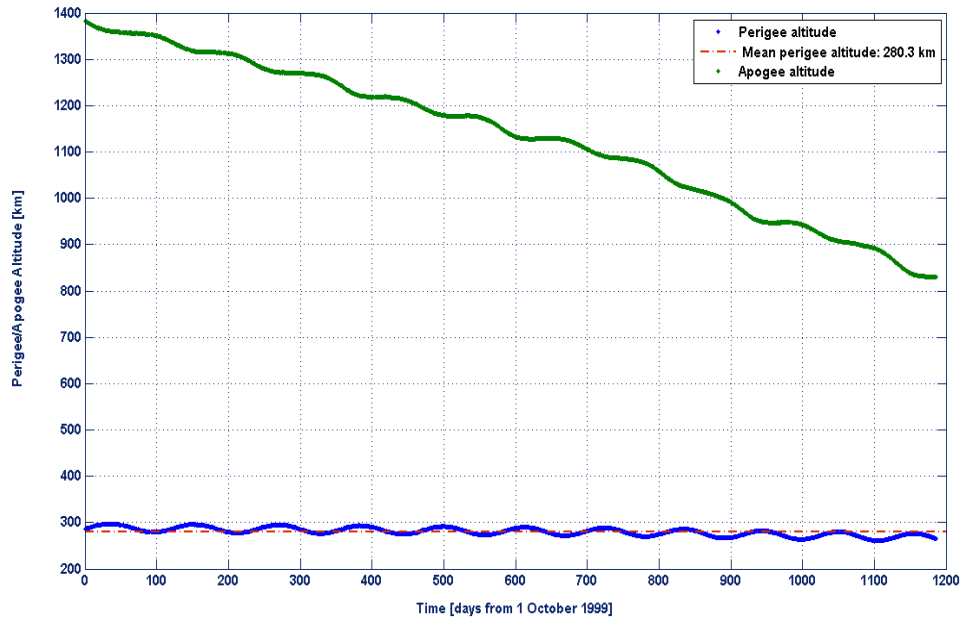
JB2006	GOST2004	NRLMSISE-00	JR-71	MSISE-90
1.90	1.96	1.96	1.90	1.93
(990 m)	(2.3 km)	(1.9 km)	(1.5 km)	(2.4 km)

Average biases of thermospheric density models

+9.95 **+7.11** **+7.11** **+9.95** **+8.53**

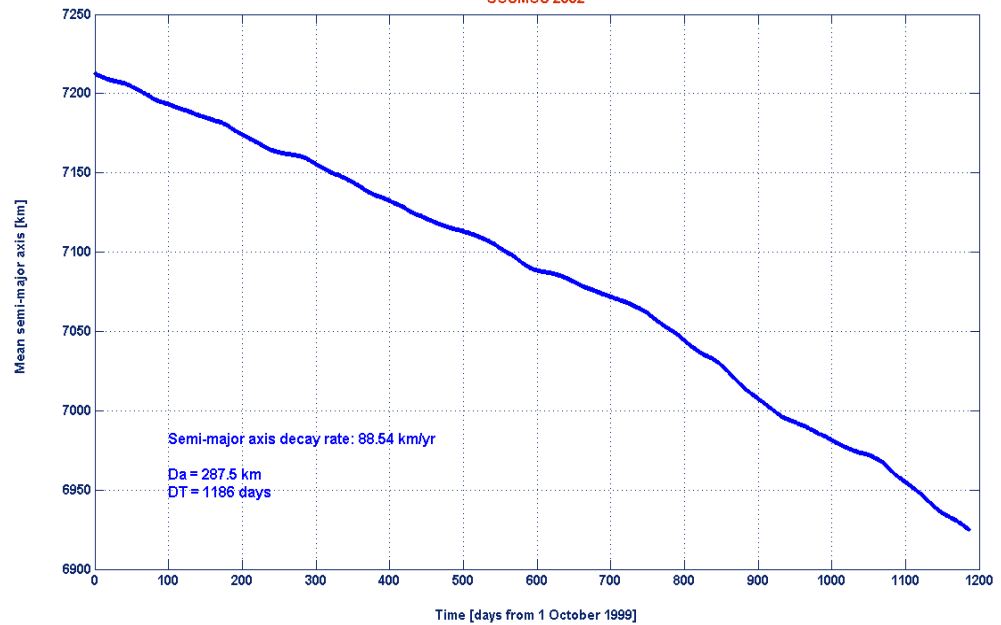


COSMOS 2332



Cosmos 2332

COSMOS 2332



Cosmos 2332

Observed Drag Coefficient: $C_D [observed] = 2.17$

Drag coefficient fitted over 1186 days: 1 October 1999 – 30 December 2002

Observed semi-major axis decay: $\Delta a = 287.5$ km

Fitted Drag coefficient ($C_D [fitted]$)

with root mean square (rms) residuals on semi-major axis

JB2006

GOST2004

NRLMSISE-00

JR-71

MSISE-90

1.91

1.97

1.97

1.91

1.93

(1.0 km)

(2.0 km)

(1.7 km)

(1.4 km)

(2.2 km)

Average biases of thermospheric density models

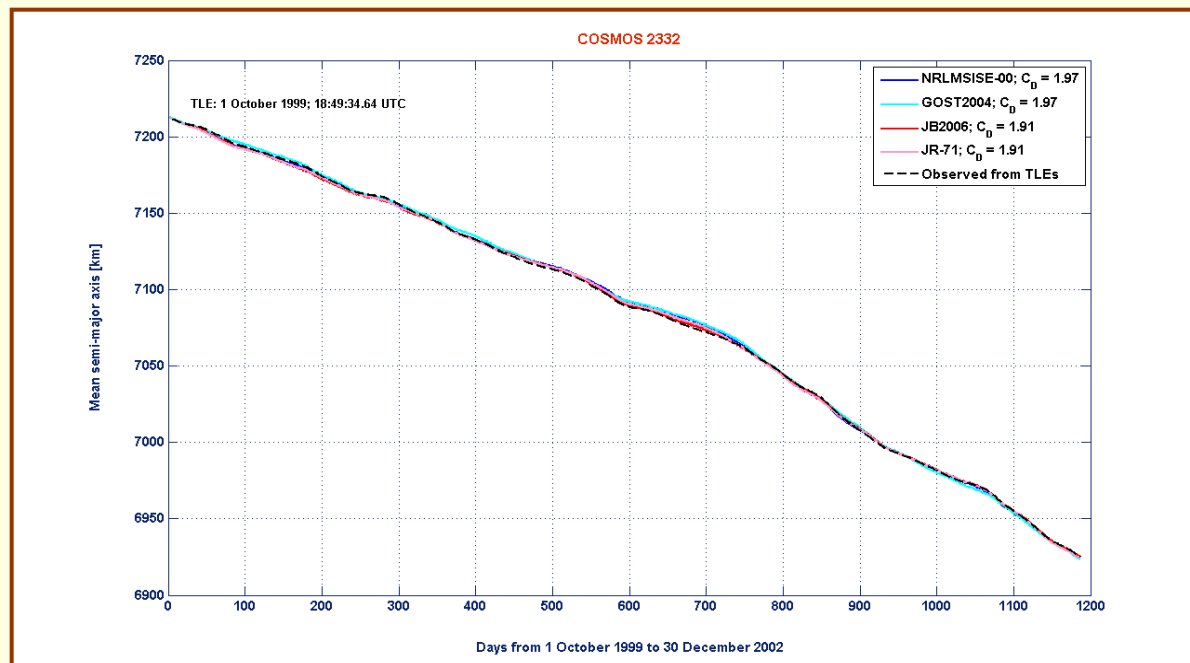
+11.98

+9.22

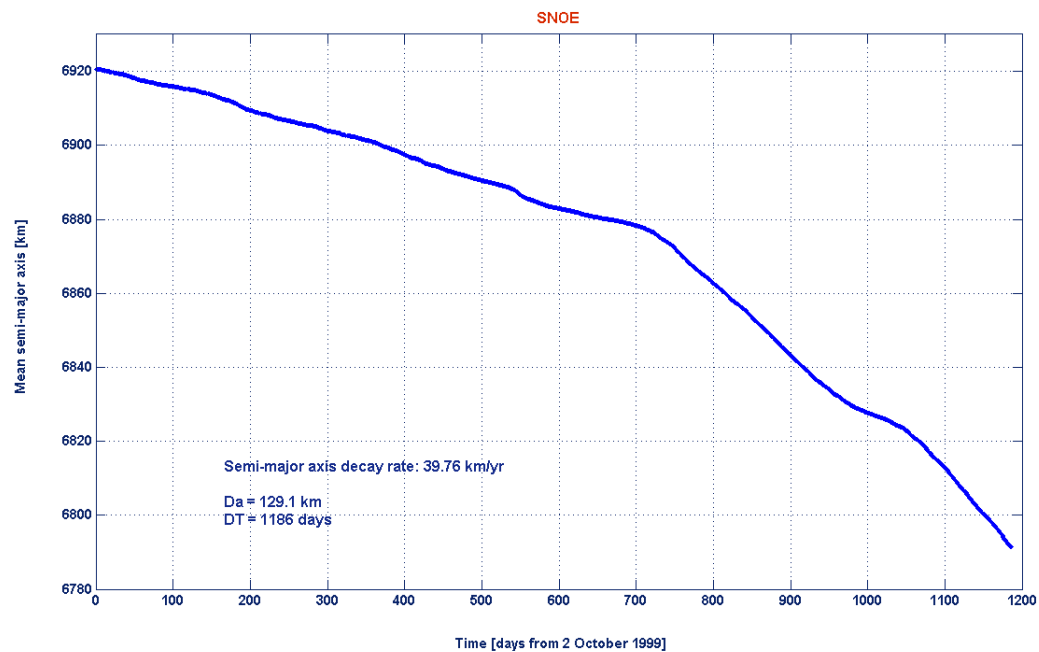
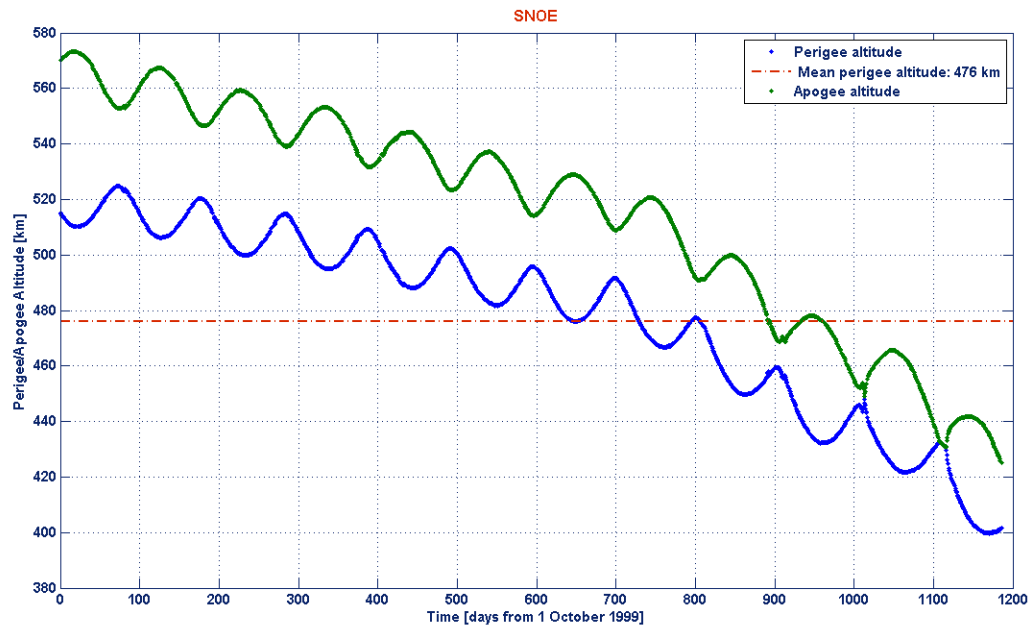
+9.22

+11.98

+11.06



SNOE



SNOE

Observed Drag Coefficient: $C_D [observed] = 2.54$

Drag coefficient fitted over 1186 days: 1 October 1999 – 30 December 2002

Observed semi-major axis decay: $\Delta a = 129.1$ km

Fitted Drag coefficient ($C_D [fitted]$)

with root mean square (rms) residuals on semi-major axis

JB2006

GOST2004

NRLMSISE-00

JR-71

MSISE-90

2.13

2.33

2.34

2.02

2.24

(654 m)

(894 m)

(1.2 km)

(917 m)

(1.2 km)

Average biases of thermospheric density models

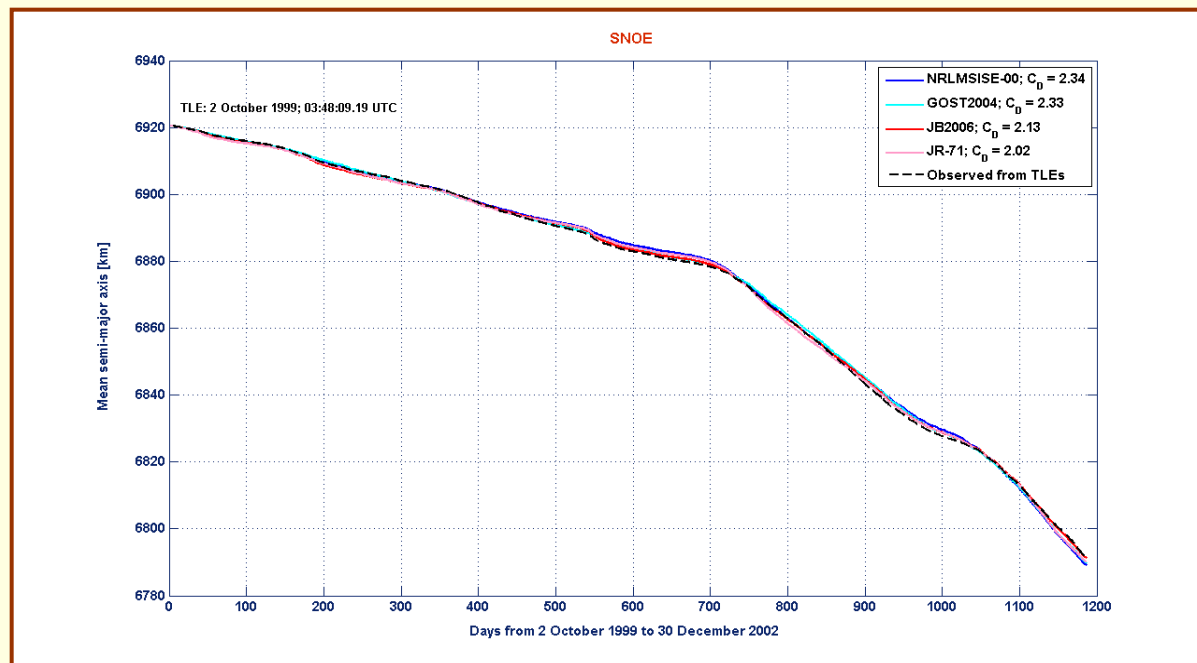
+16.14

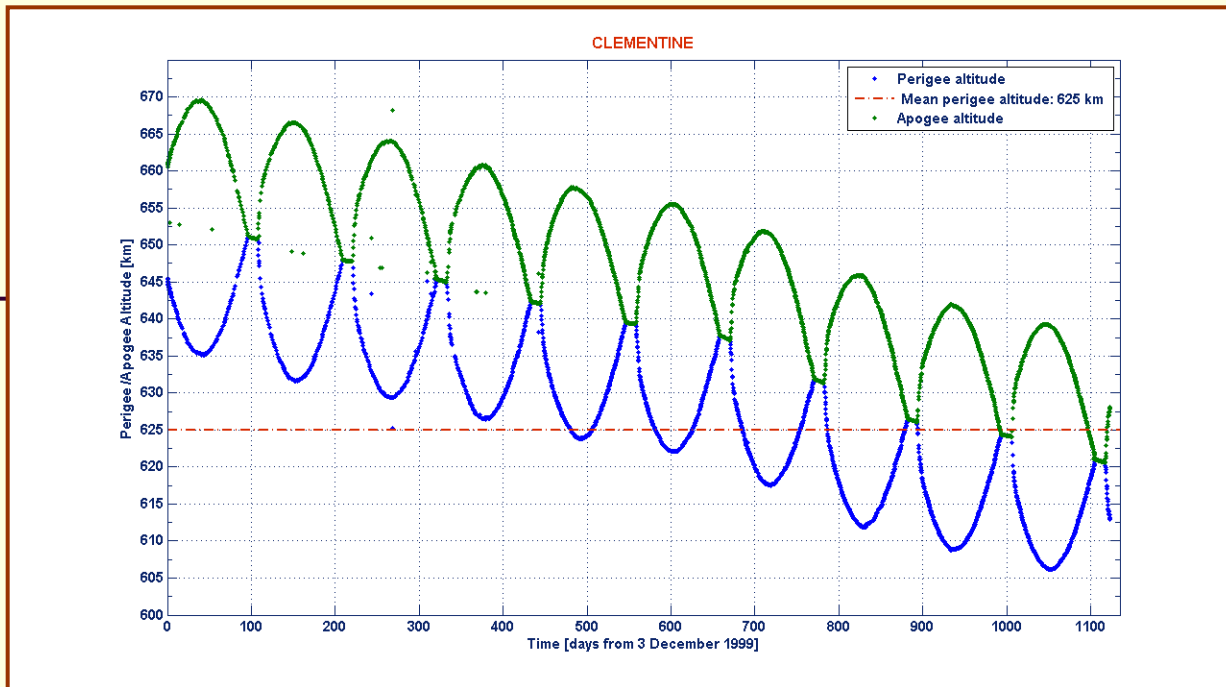
+8.27

+7.87

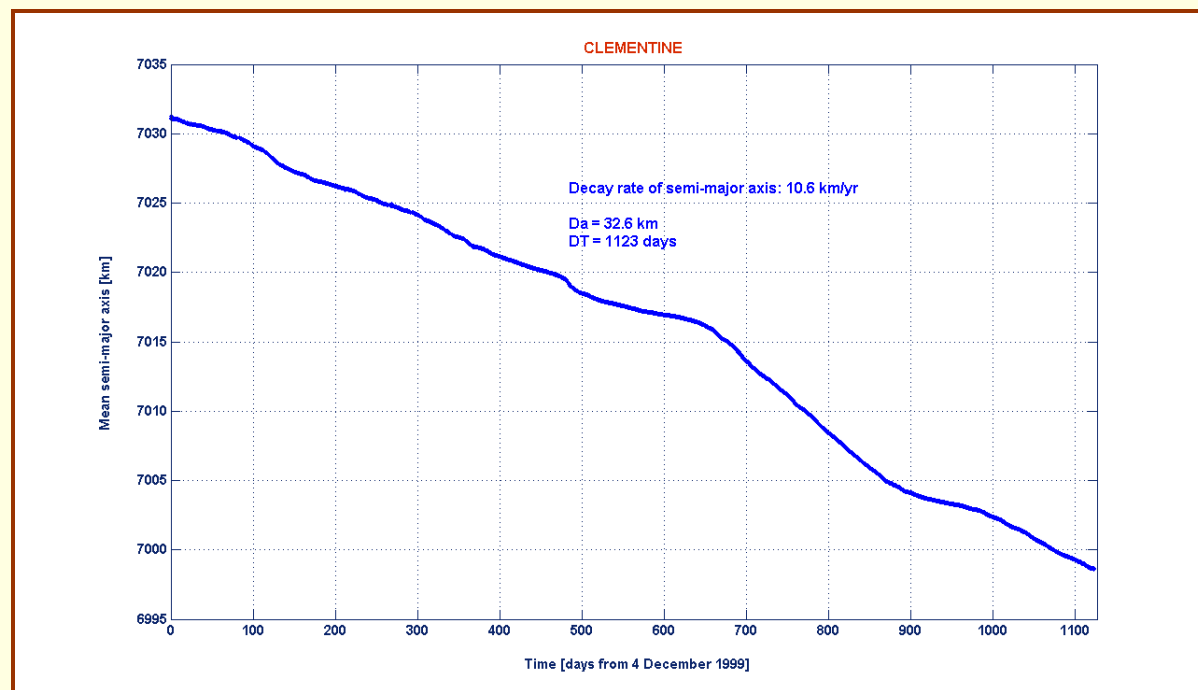
+20.47

+11.81





Clementine



Clementine

Observed Drag Coefficient: $C_D [observed] = 2.63$

Drag coefficient fitted over 1123 days: 4 December 1999 – 30 December 2002

Observed semi-major axis decay: $\Delta a = 32.6$ km

Fitted Drag coefficient ($C_D [fitted]$)

with root mean square (rms) residuals on semi-major axis

JB2006

GOST2004

NRLMSISE-00

JR-71

MSISE-90

2.24

2.93

2.63

2.21

2.48

(259 m)

(367 m)

(409 m)

(493 m)

(476 m)

Average biases of thermospheric density models

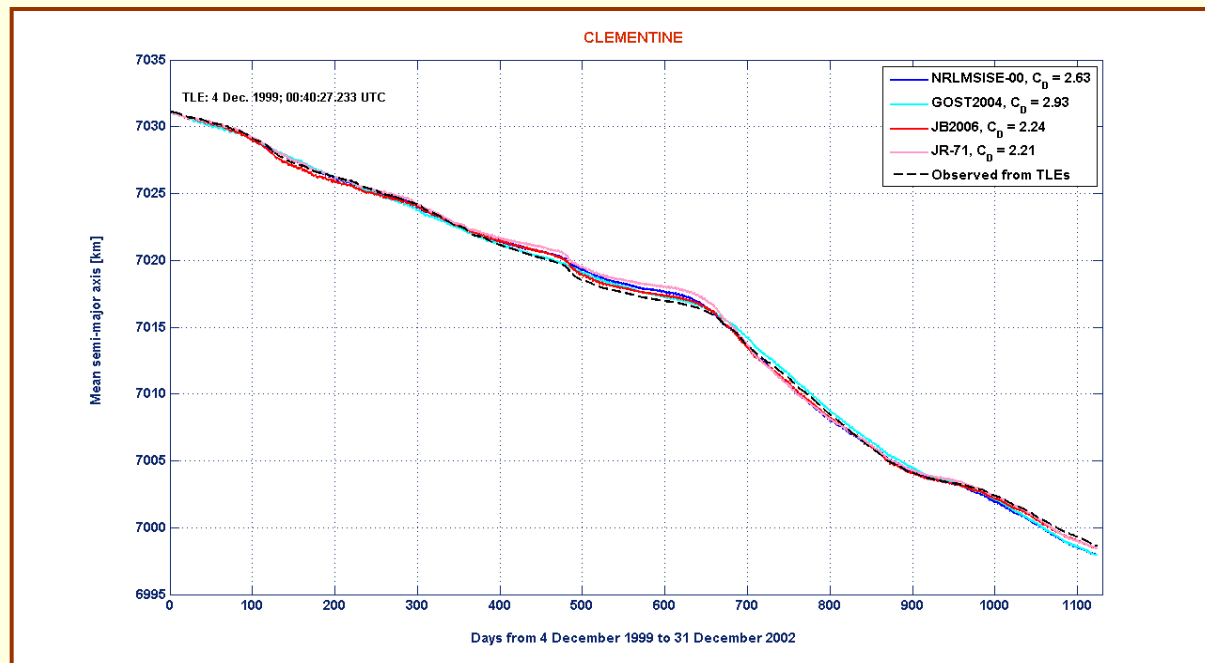
+14.83

-11.41

0

+15.97

+5.70



Average biases of the thermospheric density models at sunspot maximum

Satellite (Altitude)	NRLMSISE-00	JB2006	GOST2004	JR-71	MSISE-90
Cosmos 2265 (275 km)	+7.1%	+10.0%	+7.1%	+10.0%	+8.5%
Cosmos 2332 (275 km)	+9.2%	+12.0%	+9.2%	+12.0%	+11.1%
SNOE (480 km)	+7.9%	+16.1%	+8.3%	+20.5%	+11.8%
Clementine (630 km)	~0%	+14.8%	-11.4%	+16.0%	+5.7%

The sign “+” means that the atmospheric density is overestimated by the model, while the sign “-” means that the atmospheric density is underestimated

Short term analysis

Trying to better characterize and compare the density models during the analyzed sunspot maximum

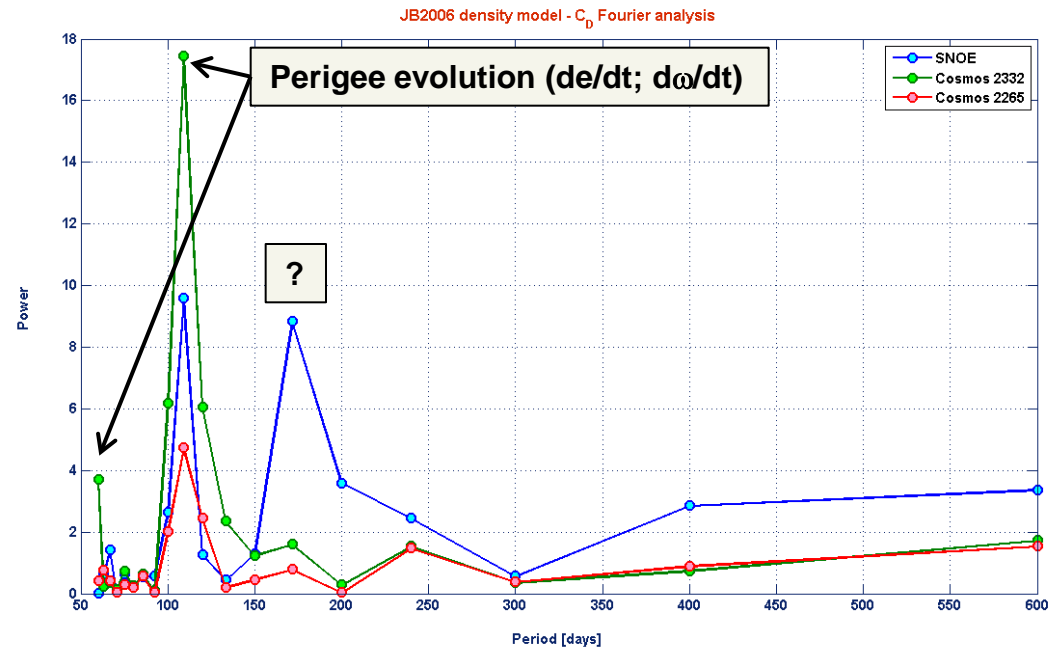
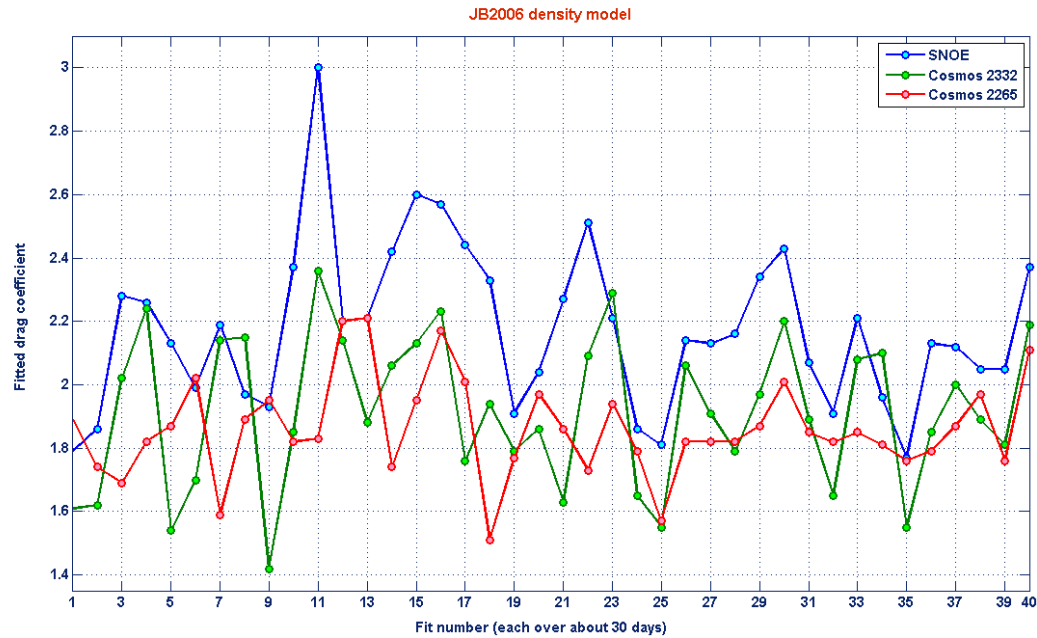
fitted drag coefficients were also computed over forty 30-day arcs for the following satellites

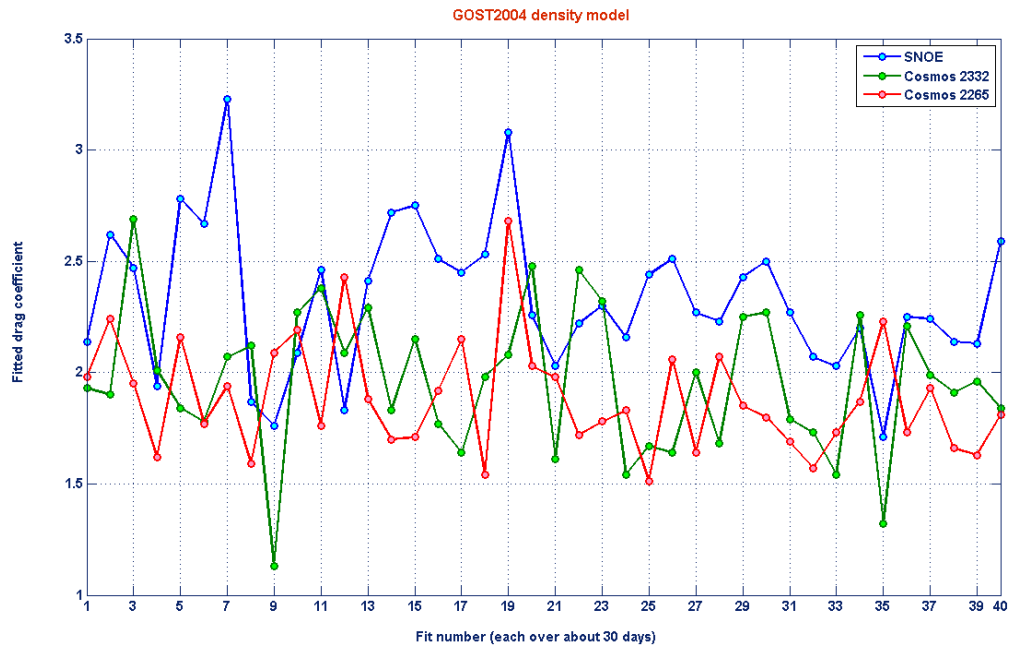
- SNOE
- Cosmos 2332
- Cosmos 2265

where the effects of air drag on semi-major axis were significant over relatively short periods as well

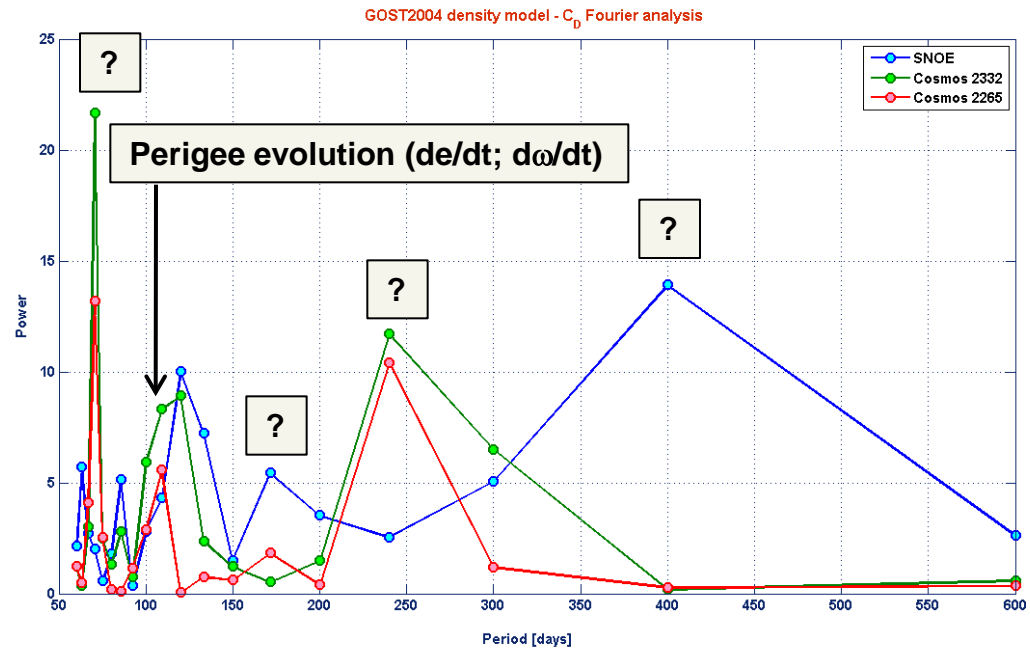
For each density model and satellite, a Fourier analysis of the fitted drag coefficients was carried out, in order to investigate the possible origin of the observed periodicities

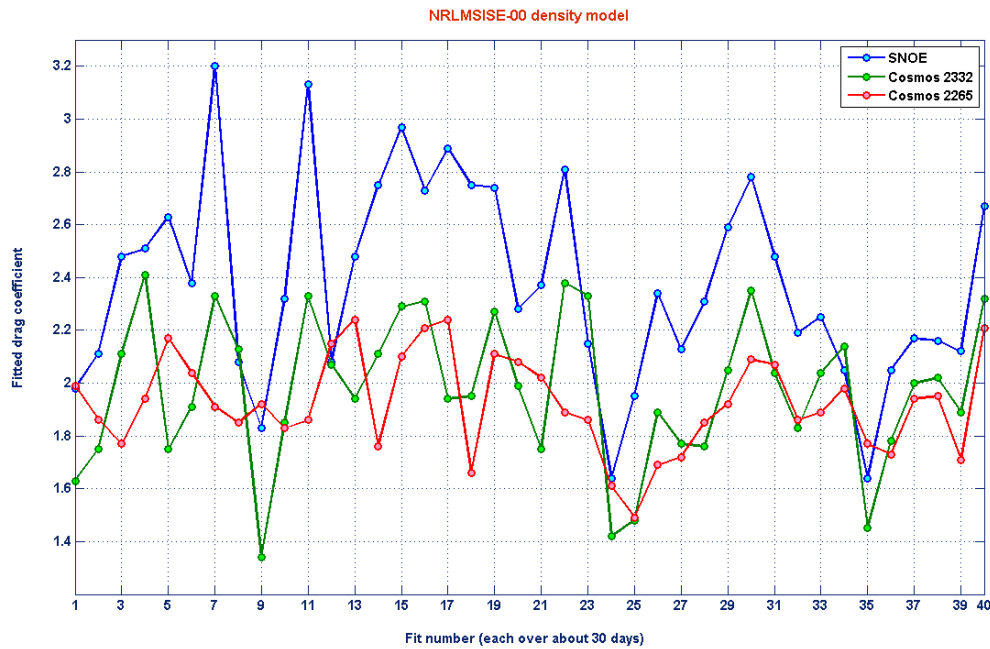
JB2006



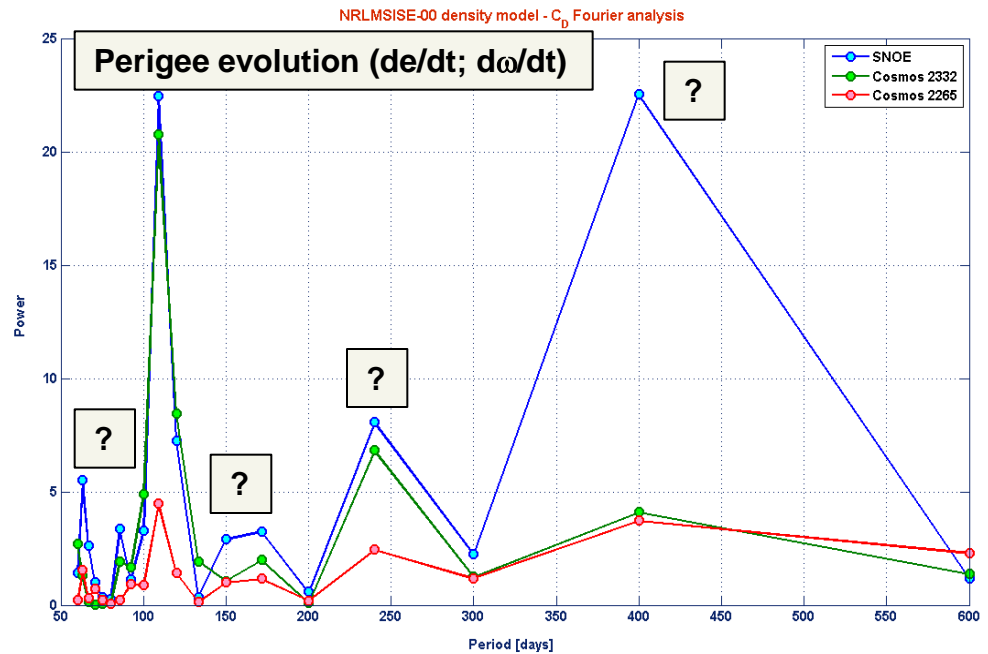


GOST2004

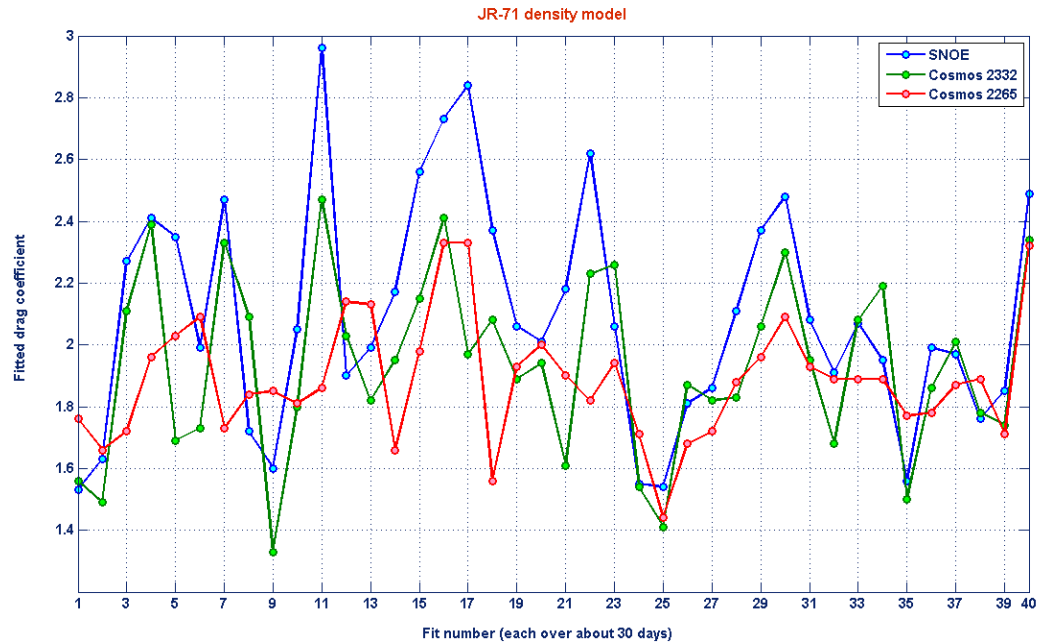




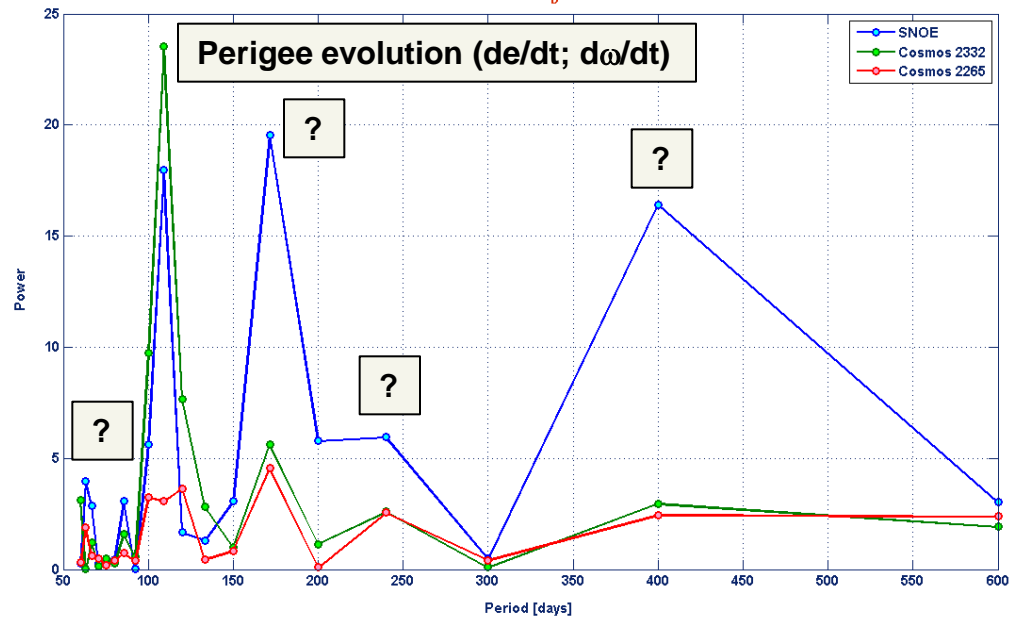
NRLMSISE-00

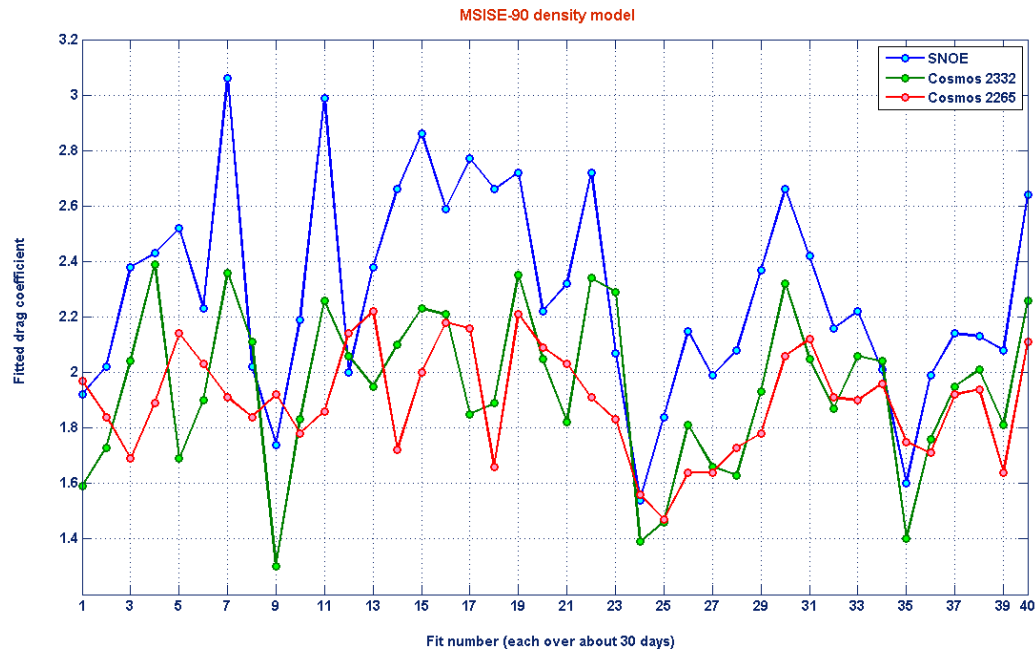


JR-71

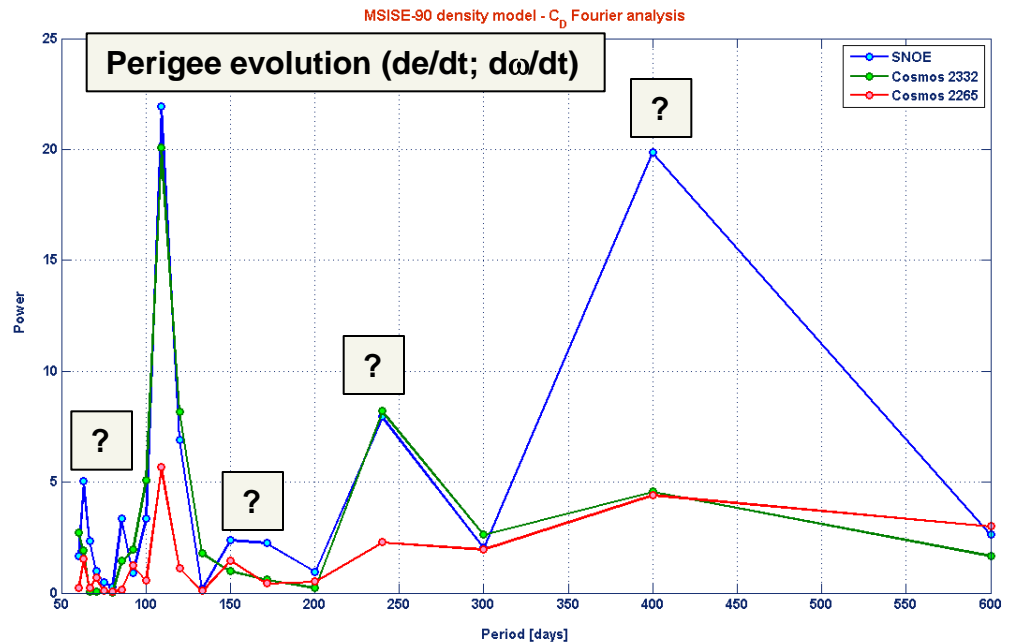


JR-71 density model - C_D Fourier analysis





MSISE-90



Summary of short arc results (I)

- All the models presented a significant short term variability
- The variability was minimum for JB2006 (8.3-12.5% 1σ), maximum for GOST2004 (13.4-16.6% 1σ)
- The variability was not random, but periodic, with most of the power concentrated at certain periods
- Due to the arc length (30 days) and observation period (1200 days), there was a Nyquist cutoff period of 60 days and the high period terms were affected by a significant uncertainty
- Therefore, the value of the Fourier analysis was only indicative
- However, all the models showed a variability probably linked to the evolution of the perigee
- For JB2006 this was the only significant periodicity, apart from another one of unknown origin observed only in the case of SNOE
- The other models displayed at least five periodic terms of unknown origin

Summary of short arc results (II)

- There was a substantial correspondence among the periodicities observed in NRLMSISE-00, JR-71 and MSISE-90
- The behavior of GOST2004 was more complex, in terms of periods and satellite dependence
- In any case, the variation of the angle between the orbit plane and the sun (β angle) did not play an evident role
- A (probably small) correlation with some frequencies observed in the solar flux proxies, corresponding to some multiples of solar rotation (e.g. 3, 4, 5 and 6 times) cannot be excluded
- The similarities among most of the models possibly suggest that yearly and seasonal density variations are not accurately accounted for
- However, it seems that most of these sources of “short term” variation were removed from JB2006
- Significant density (or C_D estimation) biases, probably linked to the perigee height and argument evolution, were found in all the cases

Conclusions

- Below 500 km all the models overestimated the atmospheric density during the last sunspot maximum (solar cycle 23)
 - The biases were comparable at the lowest altitude considered (275 km)
 - A wider spread of values was obtained at 480 km
 - NRLMSISE-90 and GOST2004 provided the most accurate average density estimations
- At 630 km NRLMSISE-00 was the best, with a negligible bias, followed by MSISE-90, while GOST2004 exhibited a negative bias (density underestimation)
- However, in all cases JB2006 presented the smallest residuals in semi-major axis evolution and the smallest “short term” variability of the density bias at just a few frequencies
- The robustness of the drag coefficient fits was checked against geopotential truncation (16×16 vs. 40×40), luni-solar perturbations (on/off) and solar radiation pressure (on/off)