The influence of considering atmospheric wind field for atmospheric drag on SLR orbit determination

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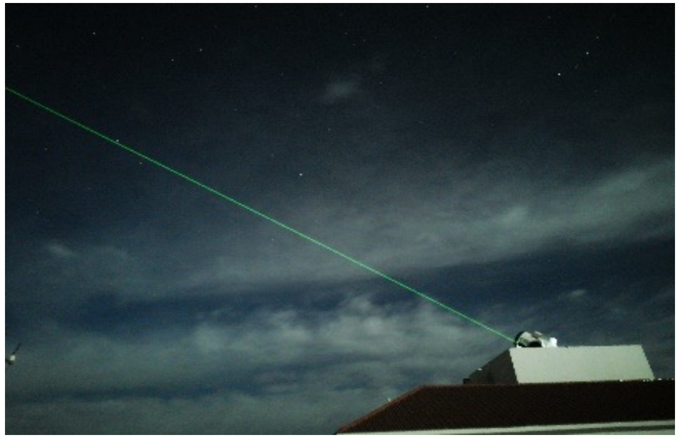
Contents

1. Background and significance

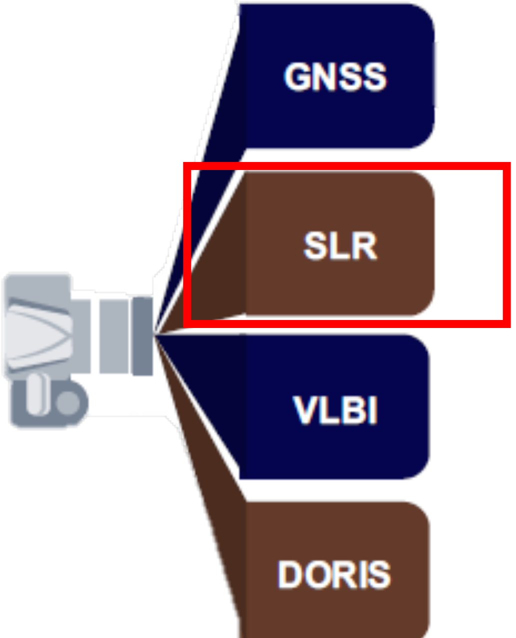
■ High accuracy spatiotemporal reference requires to improve SLR data processing

The Terrestrial Reference Fame (TRF) and EOP are determined by the 4 space geodesy techniques SLR/VLBI/GNSS/DORIS. SLR is one kind of important space geodesy technique. It determines the origin and scale of TRF. The accuracy and stability of TRF are required to be 1mm and 0.1mm/yr respectively. This requires to improve the present accuracy of SLR dada processing. Some refined perturbative models should be considered for mm POD.



SLR

TRF and EOP



one kind of important space geodesy technique; origin and scale of TRF ; EOP

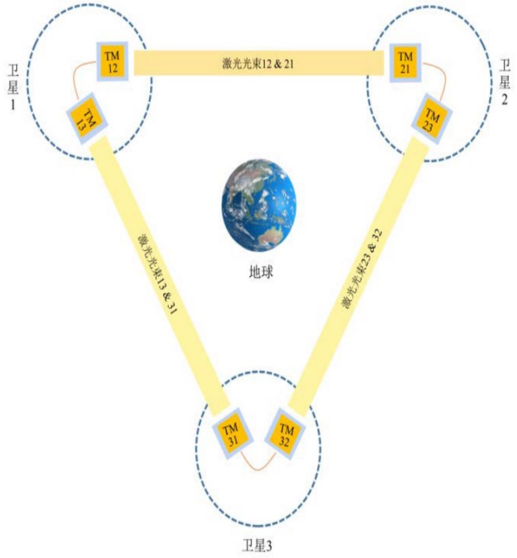
SLR station network

1. Background and significance

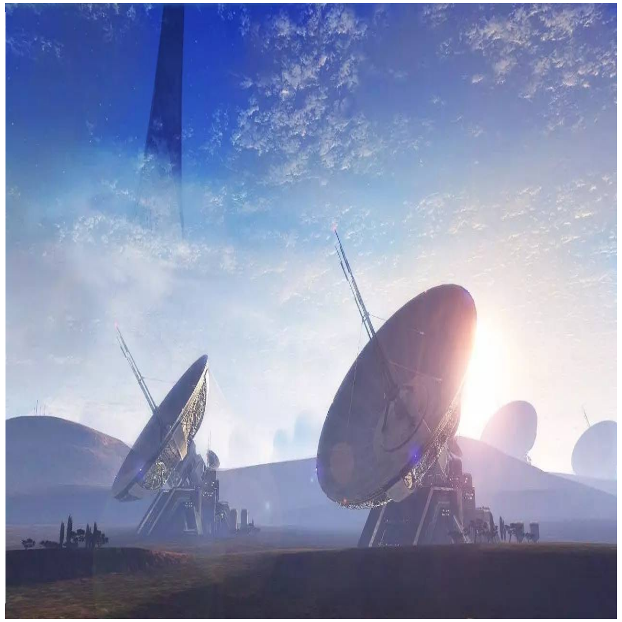
■ **mm precise orbit determination(POD) are required by many fields.**

SLR is one important means of POD. Many fields such as space VLBI, Space gravitational wave detection，space situational awareness, low orbit navigation enhancement and so on require mm order POD. Such high POD accuracy also needs refined perturbative force models considered.

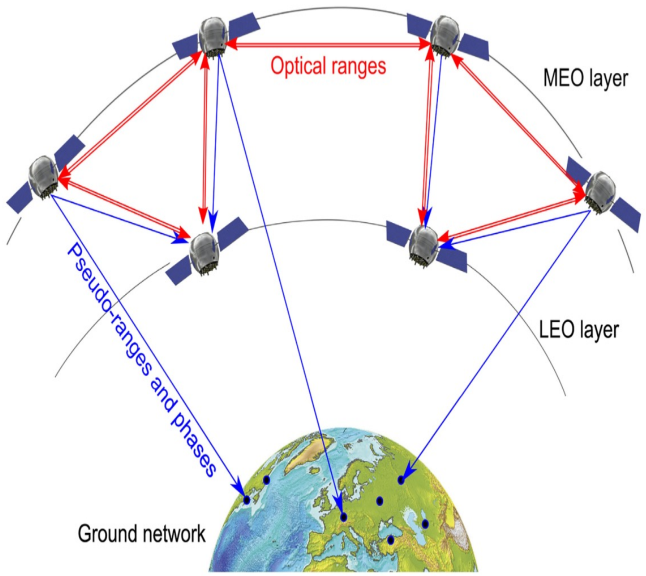
Space VLBI



Space gravitational wave detection



Space Situational awareness



Low orbit navigation enhancement

1. Background and significance

More satellites to be used for TRF and EOP under higher accuracy atmospheric drag

There are over 100 satellites with laser reflector array. But only several satellites with spherical structure, uniform materials and higher orbit height are used to determine the TRF and EOP. There are a lot of SLR data from some non-spherical satellites with lower orbit height and complicated materials. They face bigger and more complicated atmospheric drag, ERP, SRP and so on. If we could improve their accuracy these satellites are hopeful to be used for TRF and EOP too.

Yang, H., Wang, X. *, & Li, Y. (2024). Impact of Earth Radiation Pressure Physical Analytical Model on Satellite Laser Ranging Orbit Determination. **Earth and Planetary Science, 3(1), 9–20.**

Atmospheric drag

SLR Geo-dynamic satellites

2. The Atmospheric drag

(1) Atmospheric drag formular

$$a_{dg} = -\frac{1}{2} C_D \rho \frac{A}{m} V_{Rel} |V_{Rel}|$$

C_D is atmospheric drag coefficient; ρ is atmospheric density; A is satellite cross-section area; m is satellite mass; V_{Rel} is the speed of the satellite relative to the atmosphere.

origin model： $V_{Rel} = V_R - \Omega \times R$ when the atmosphere is at rest relative to the solid Earth.

real status： $V_{Rel} = V_R - \Omega \times R - v_{wind}$ when the atmospheric wind speed is considered

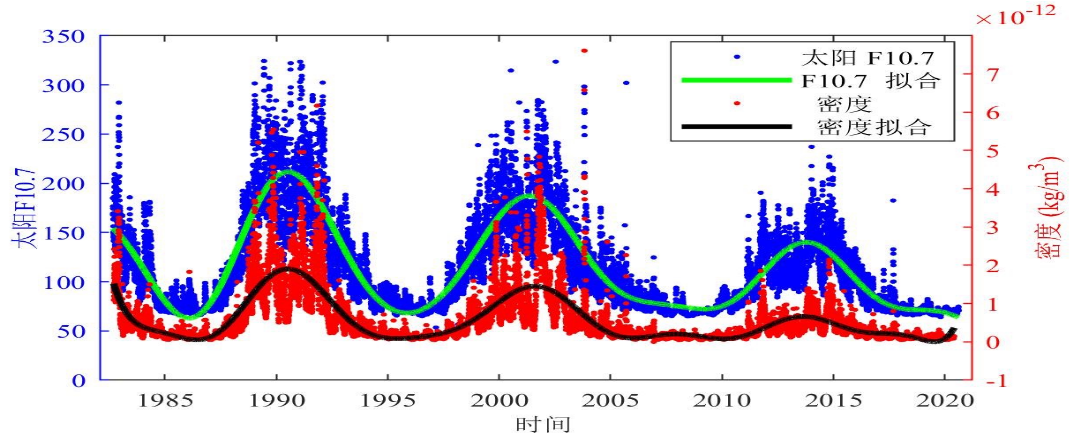
V_R the velocity of the satellite relative to the Earth; ， Ω is Earth rotation， R is satellite coordite

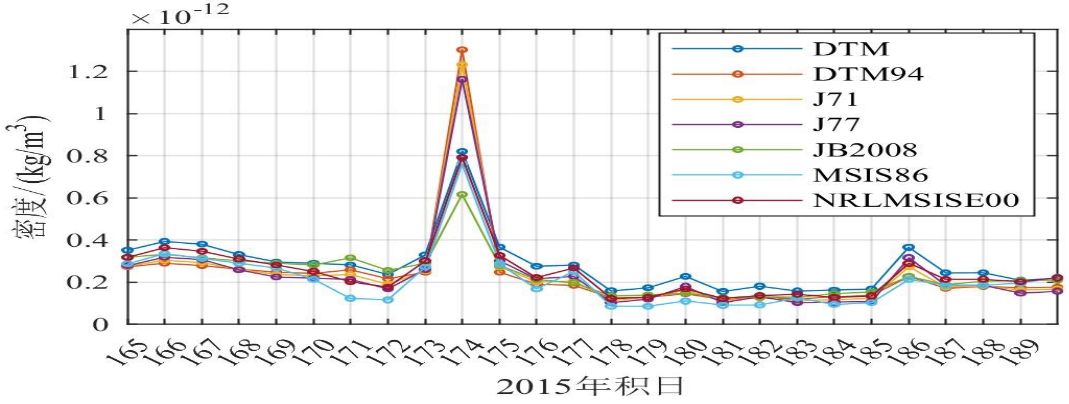
2. The Atmospheric drag

(2) Atmospheric density models

model	Input parameters
exp	Satellite altitude
J71 /J77	year, doy, kp, F10.7 solar flux, smooth F10.7 solar flux, local solar time, latitude, Solar declination
JB2008	year, doy, h,m,s,kp, F10.7,S10,Mg10 solar flux, longitude, latitude, altitude
DTM78 /DTM94	doy, kp, F10.7, smooth F10.7 solar flux, longitude, latitude, altitude
MSIS86 /NRLMSISE00	year, doy, ut, kp, previous F10.7 solar flux, 81-day F10.7 mean solar flux, local solar time, longitude, latitude, altitude

Variation and fitting curve of solar F10.7 and atmospheric density



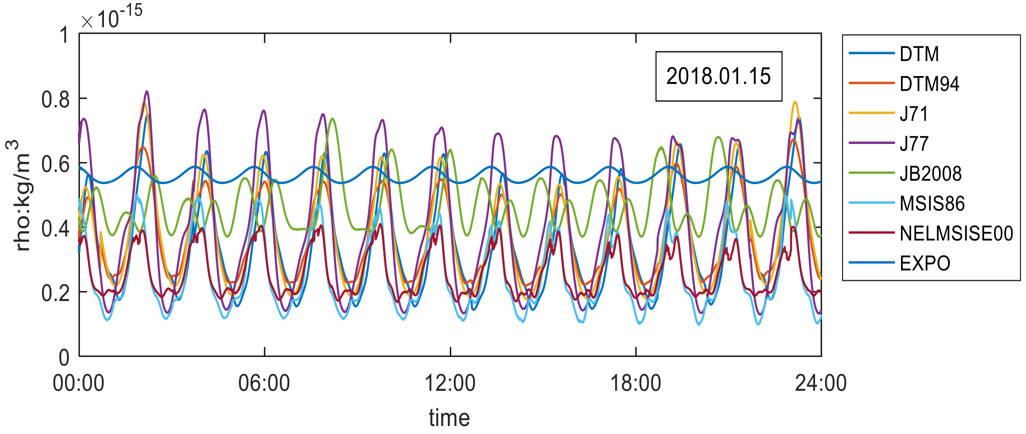


Different atmospheric density models in 25 days before and after the magnetic storm in 2015, doy174

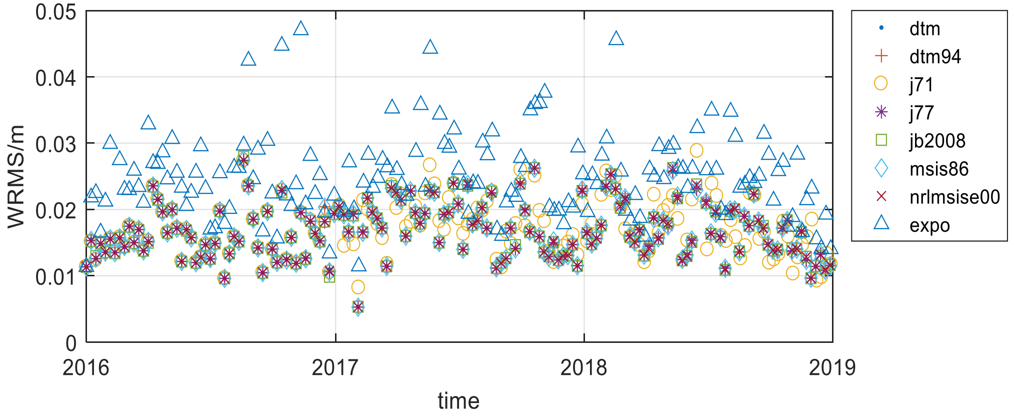
strongly related to geomagnetic Index and solar radiation Flux

2. The Atmospheric drag

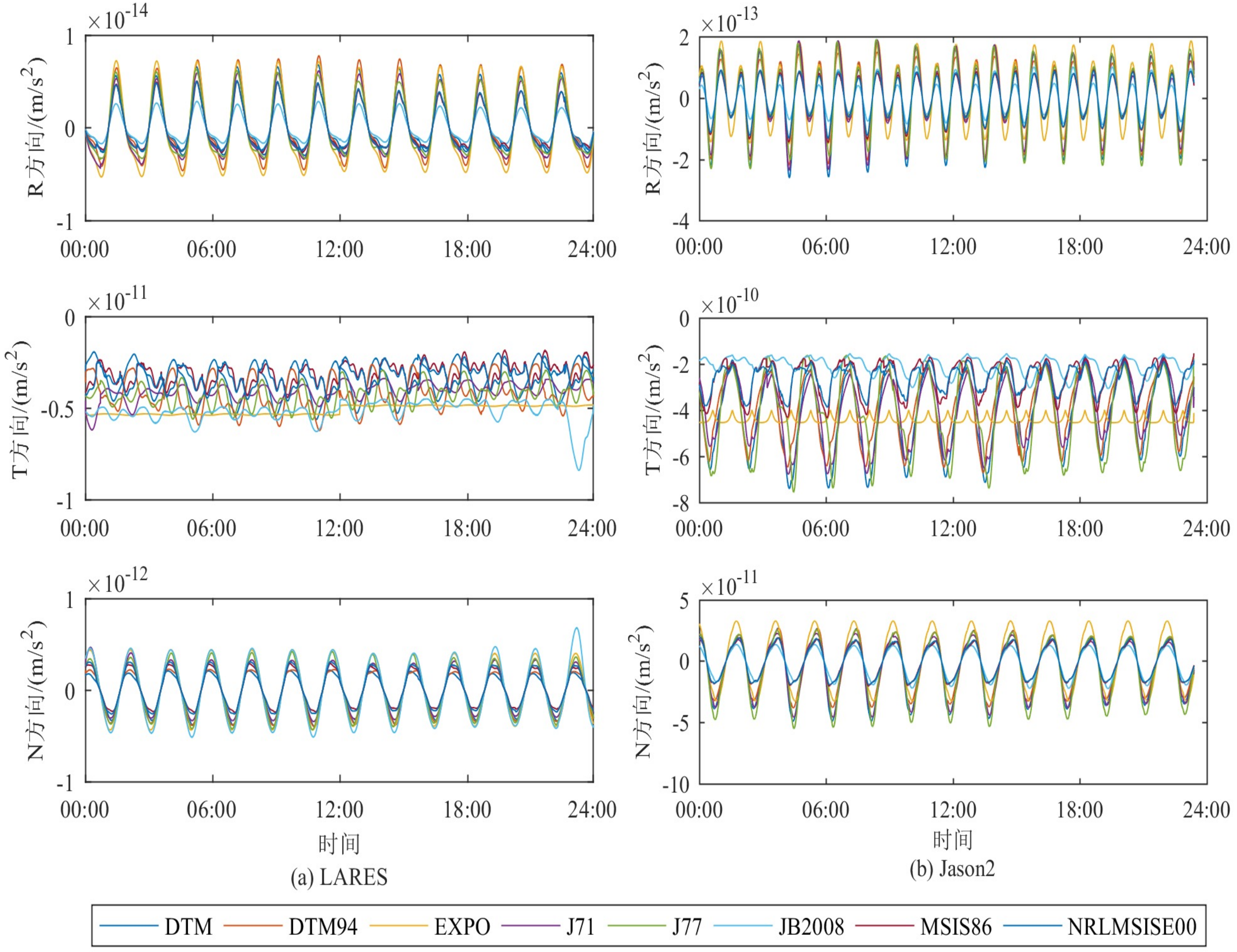
(3)Atmospheric density model test



LARES atmospheric density models



LARES POD residual RMS by different atmospheric drag models



atmospheric drag

2. The Atmospheric drag

(4)Summary of different atmospheric density model experiments

- Eight atmospheric density models were analyzed for LARES, Jason2, Ajisai and HY2A. The prediction accuracy of spherical satellites with simple structure and smaller area/mass was higher than that of satellites with complex structure.
- MSIS86 and NRLMSISE00 models are the best for LARES and Jason2.
- The JB2008 model has the best performance for Ajisai.
- The J71 model has the best performance for HY2A.

3. Atmospheric wind HWM14 model

The HWM14 model :

Drob et al., 2015， An update to the horizontal wind Mo-del (HWM): The quiet time thermosphere. **Earth Space Sci. vol.2, 301–319.**

The HWM14 model can provide average horizontal winds, which are a function of day of year τ, solar local time δ, latitude θ, longitude ϕ and altitude z from the ground (Drob et al., 2015). The zonal wind U can be expressed as:

$$U(\tau,\delta,\theta,\phi,z)=\sum_j \beta_j(z)\mu_j(\tau,\delta,\theta,\phi)$$

$$\mu_j(\tau,\delta,\theta,\phi)=\sum_{s=0}^{S}\sum_{n=1}^{N}\psi_j^1(\tau,\theta,s,n)$$

$$+\sum_{s=0}^{S}\sum_{l=1}^{L}\sum_{n=1}^{N}\psi_j^2(\tau,\delta,\theta,s,l,n)+\sum_{s=0}^{S}\sum_{m=1}^{M}\sum_{n=m}^{N}\psi_j^3(\tau,\phi,\theta,s,m,n)$$

where the annual and semiannual harmonics $\psi_j^1(\tau,\theta,s,n)$ for the zonal mean general circulation expressed in terms of the seasonal wave number s up to S=2; the westward migrating diurnal, semidiurnal and terdiurnal harmonics $\psi_j^2(\tau,\delta,\theta,s,l,n)$ expressed in tidal wave number l up to L=3; the stationary planetary wave harmonics $\psi_j^3(\tau,\phi,\theta,s,m,n)$ with longitudinal wave number m up to M=2. The maximum order in latitude for all three sums is N=8.

$$\psi_j^1(\tau,\theta,s,n)=-C_{r,j}^{s,n}\cdot\sin(n\theta)\cdot\cos(s\tau)+C_{i,j}^{s,n}\cdot\sin(n\theta)\cdot\sin(s\tau)$$

$$\begin{aligned}\psi_j^2(s,l,n,\tau,\delta,\theta)=&-C_{a_r,j}^{s,l,n}\cdot V_n^l(\theta)\cdot\cos(l\delta)\cdot\cos(s\tau)\\&+C_{a_i,j}^{s,l,n}\cdot V_n^l(\theta)\cdot\sin(l\delta)\cdot\cos(s\tau)\\&-B_{a_r,j}^{s,l,n}\cdot W_n^l(\theta)\cdot\cos(l\delta)\cdot\cos(s\tau)\\&-B_{a_i,j}^{s,l,n}\cdot W_n^l(\theta)\cdot\sin(l\delta)\cdot\cos(s\tau)\\&-C_{b_r,j}^{s,l,n}\cdot V_n^l(\theta)\cdot\cos(l\delta)\cdot\sin(s\tau)\\&+C_{b_i,j}^{s,l,n}\cdot V_n^l(\theta)\cdot\sin(l\delta)\cdot\sin(s\tau)\\&-B_{b_r,j}^{s,l,n}\cdot W_n^l(\theta)\cdot\cos(l\delta)\cdot\sin(s\tau)\\&-B_{b_i,j}^{s,l,n}\cdot W_n^l(\theta)\cdot\sin(l\delta)\cdot\sin(s\tau)\end{aligned}$$

The meridional wind speed V and zonal wind speed U can be calculated by the HWM14 model, the rotation matrix from local to inertial coordinate system is

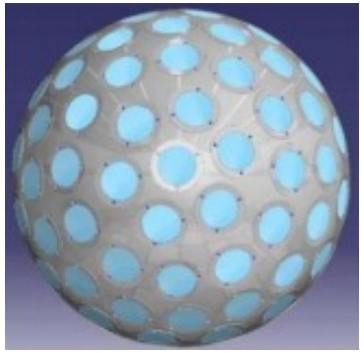
$$\boldsymbol{MLT}^{\mathrm{T}}\times\boldsymbol{HG}^{\mathrm{T}}$$

$\psi_j^3(\tau,\phi,\theta,s,m,n)$ is replacing l with m, replacing δ with φ

3. Atmospheric wind HWM14 model

The following 5 LEO satellites regularly observed for several decades by ILRS SLR network

Ajisai
JAXA



LARES
ASI

Starlette / Stella
CNES

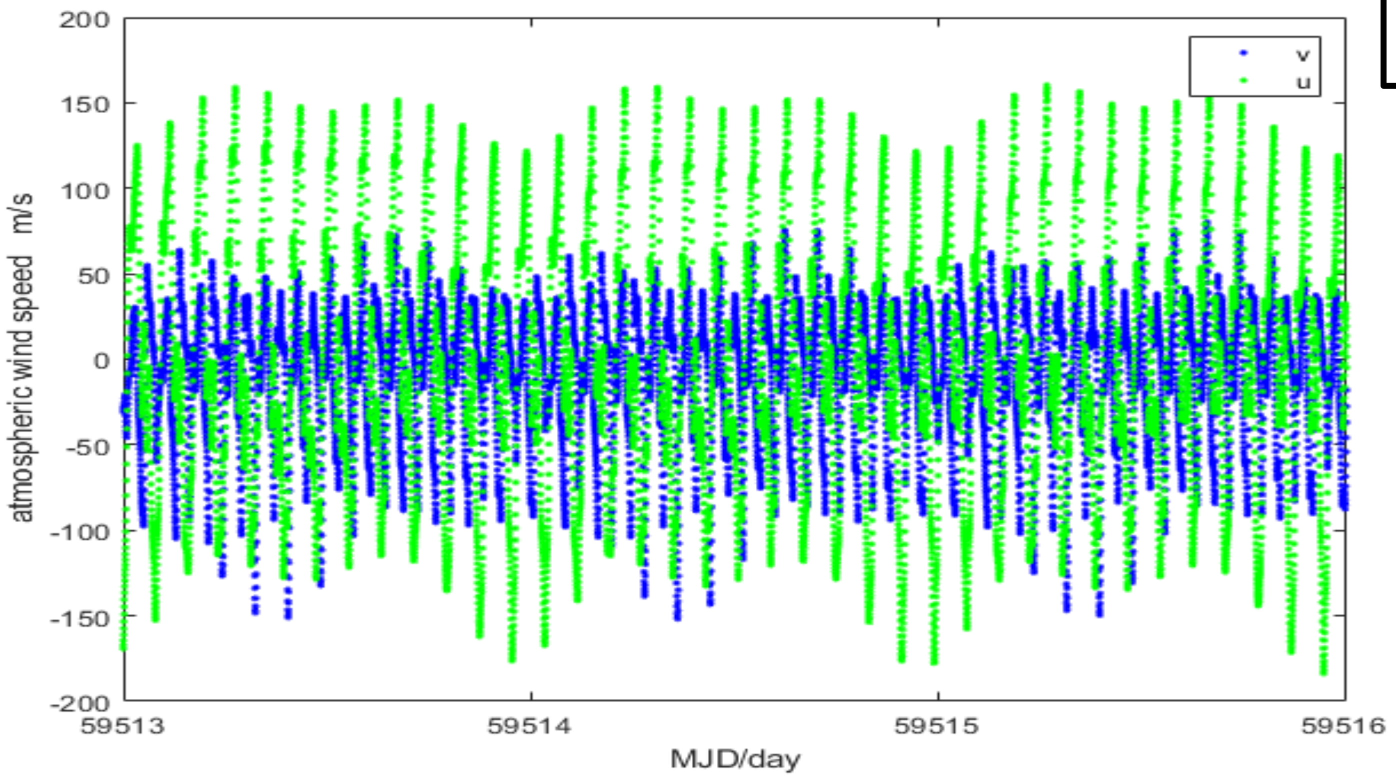
Larets
IPIE

SLR Geo-dynamic LEO satellites information

Sat. Name	Diameter (cm)	Launch year	Altitude (km)	Mass (kg)	Inclination (°)	Reflectors	Area/mass (m^2kg^{-1})
LARES	36.4	2012	1450	386.8	69.5	92 corner cubes	$2.7*10^{-4}$
Ajisai	215.0	1986	1485	685.0	50.0	1436(+318mirrors)	$58*10^{-4}$
Starlette	24.0	1975	790-1100	47.5	48.8	60 corner cubes	$9.6*10^{-4}$
Stella	24.0	1993	815	48.0	98.6	60 corner cubes	$9.4*10^{-4}$
Larets	24.0	2003	691	23.3	98.2	60 corner cubes	$19*10^{-4}$

3. Atmospheric wind HWM14 model

The atmospheric wind speed of LARES satellite for thee days in October 2021.



LARES satellite zonal (U) /meridional (V) wind speed from HWM14 model

Yabo Li, Xiaoya Wang*, Shengjian Zhong, et al., The influence of considering atmospheric wind field for atmospheric drag in SLR orbit determination, **Advances in Space Research, 2024, Vol.74 (2): 975-986**

For LARES, the effect of the wind field compared to the atmospheric drag (without the HWM14) is 17.5% in the T direction, 15.4% in the N direction, 4% in the R direction, respectively. It acts mostly in the T direction and also slightly in the N direction.

4. SLR Precise Orbit Determination experiments and results analysis with/without wind field considered

Models and solve strategies of SLR POD

background models	strategy
Tropospheric	Mendes&Pavlis (Mendes and Pavlis, 2004)
Satellite center-of-mass correction	LARES/Starlette/Stella: the station-dependent Ajisai: 0.982 m (Otsubo et al., 1999) Larets: 0.0562 m
A priori terrestrial reference frame	SLRF2014 (Luceri and Pavlis, 2016)
Ocean load	FES2004 (Lyard et al., 2006)
Earth's gravity field model	GOCO05S (Mayer-Gürr et al., 2015) geopotential truncation level of n=m=90 for Larets and 95 for other satellites
Ephemeris	JPL DE403 (Standish et al., 1995)
Tides (solid earth, ocean, pole)	IERS conventions 2010 (Petit and Luzum, 2010)
Atmospheric drag	atmospheric density DTM94 (Berger et al., 1998), atmospheric wind speed HWM14 (Drob et al., 2015)
Solar radiation pressure	Cannonball (Montenbruck and Gill, 2000)
Earth radiation pressure	Cannonball (Montenbruck and Gill, 2000)
Data span	LARES:2019-2021 Starlette/Stella:2019-2021 Ajisai:2019 Larets:2019
estimated parameters	
Satellite orbit elements $a, e, i, \omega, \Omega, M$	7 days
Solar radiation pressure	3 days
Earth radiation pressure	3 days
Atmospheric drag	1 day
Empirical acceleration (T/N)	3 days
Earth Orientation Parameters (EOP)	1 day

Yabo Li, Xiaoya Wang*, Shengjian Zhong, et al., The influence of considering atmospheric wind field for atmospheric drag in SLR orbit determination, **Advances in Space Research, 2024, Vol.74 (2): 975-986**

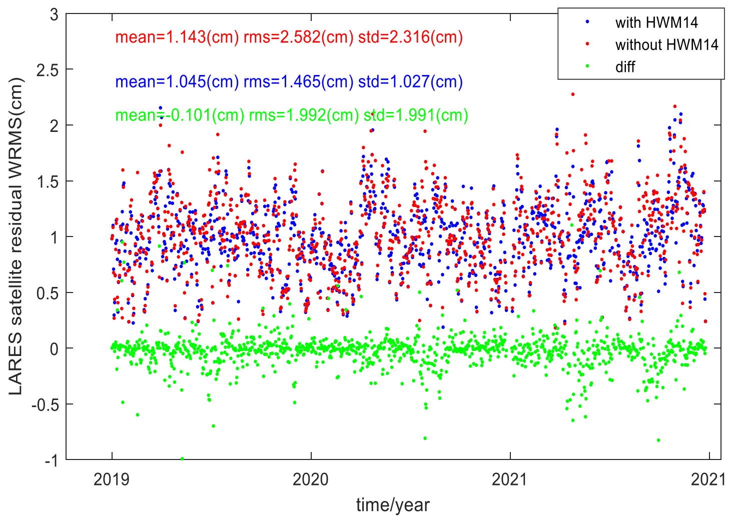
accuracy evaluation:

1. SLR POD observation residuals WRMS
2. orbit overlapping arcs error evaluation
3. orbit prediction precision

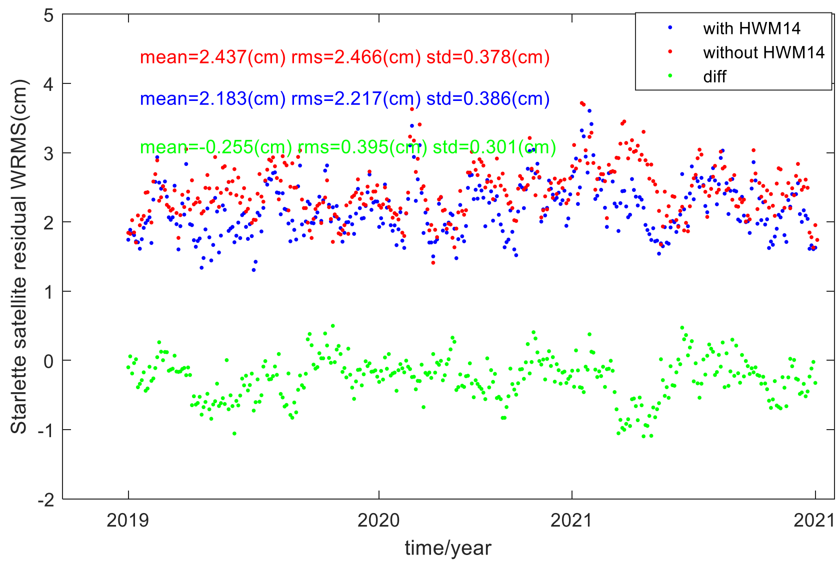
4. SLR Precise Orbit Determination experiments and results analysis with/without wind field considered

HWM14 effects on SLR POD: residuals WRMS

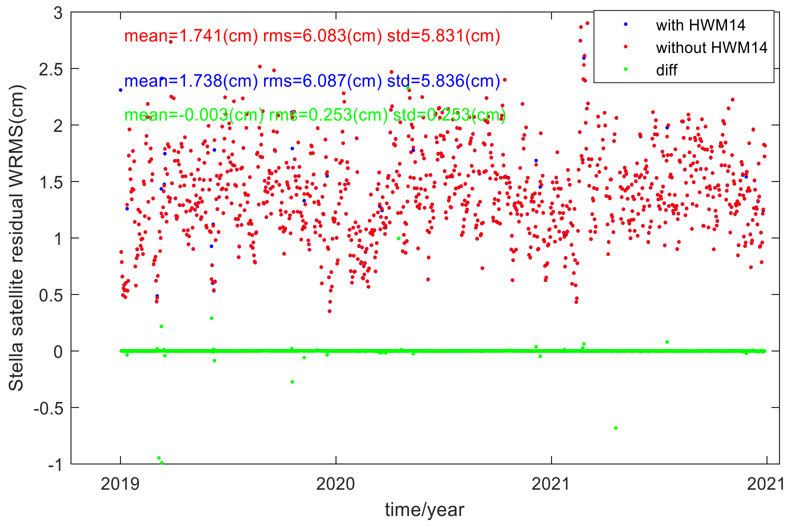
The results show that after applying HWM14 atmospheric wind speed model, residuals WRMS for LARES, Starlette, Stella, Larets reach 1.04 cm, 2.13 cm, 1.73 cm, 3.36 cm, respectively. The mean of SLR observation residual WRMS is decreased by about 0.10 cm, the accuracy is improved by 8.7 %.



Reduce 0.10 cm for LARES



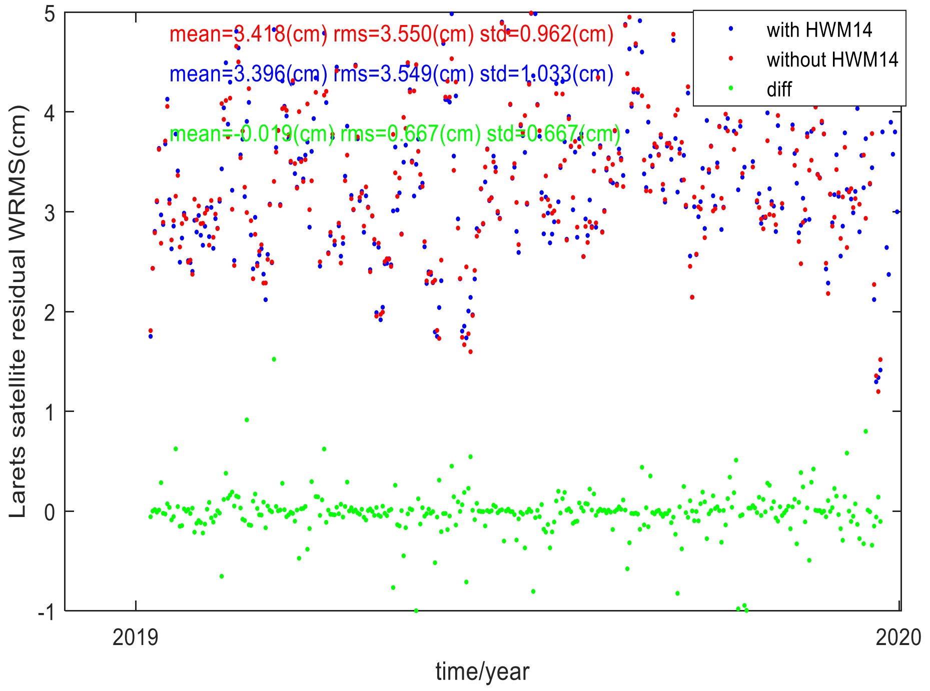
Reduce 0.30 cm for Starlette



Reduce 0.03 cm for Stella

4. SLR Precise Orbit Determination experiments and results analysis with/without wind field considered

HWM14 effects on SLR POD: residuals WRMS



Reduce 0.05 cm for Larets

Satellite	with HWM14 WRMS (cm)	without HWM14 WRMS (cm)
LARES	1.045	1.143
Ajisai	2.884	2.884
Starlette	2.138	2.437
Stella	1.738	1.741
Larets	3.369	3.418

Ajisai has an almost same orbit residual WRMS value of 2.88 cm. It maybe because the influence of atmospheric wind field on Ajisai ’s orbit is overwhelmed by the atmospheric drag.

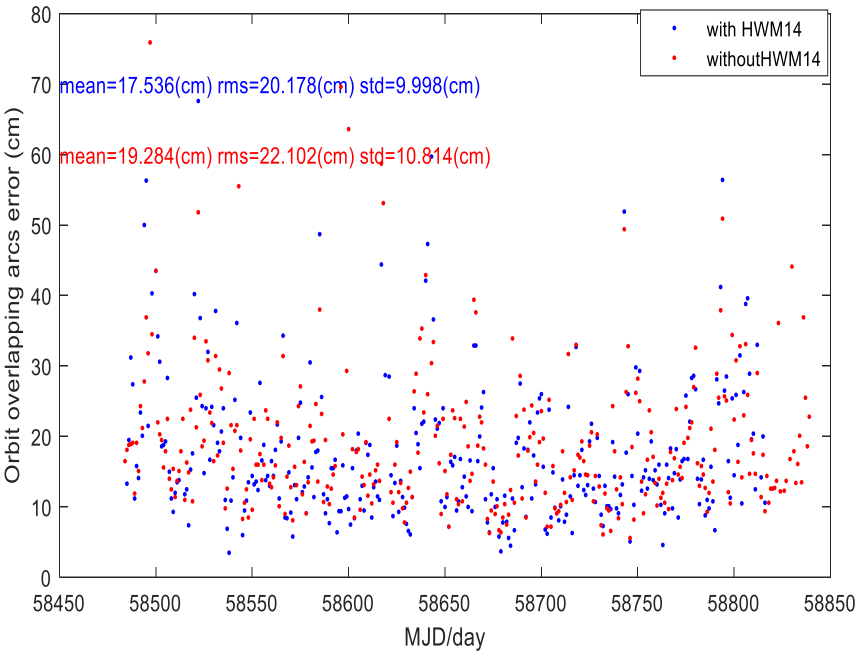
SLR observation residuals WRMS(continued)

4. SLR Precise Orbit Determination experiments and results analysis with/without wind field considered

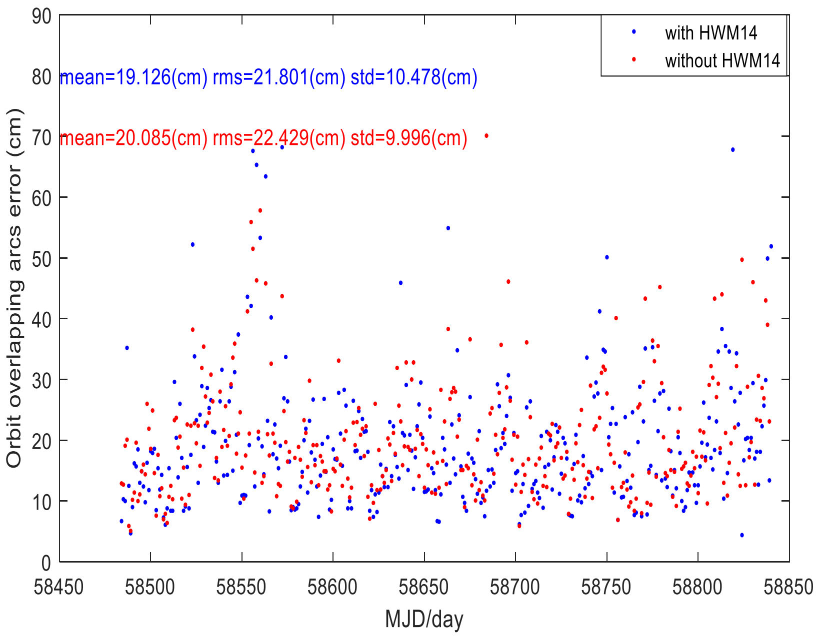
HWM14 effects on SLR POD: Orbit overlapping arcs error

The overlapping arcs error (3D)

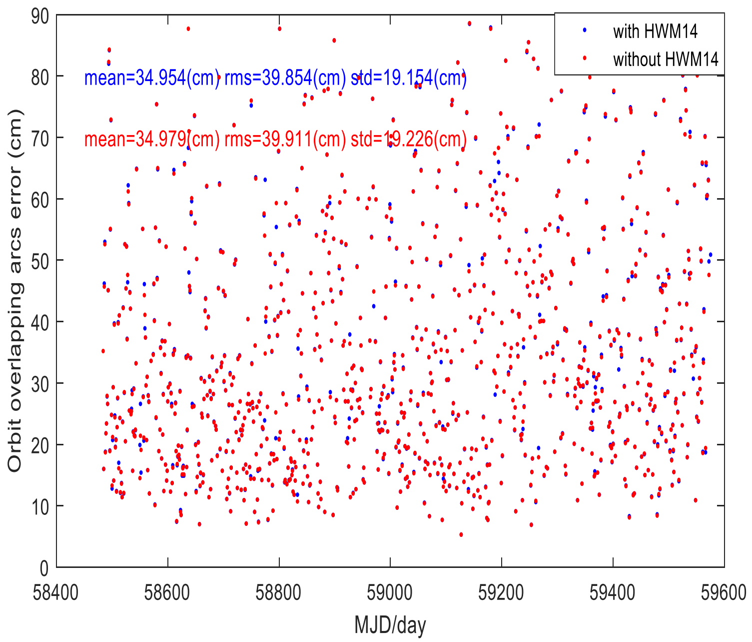
The orbit overlapping arcs errors in 3D for LARES, Starlette, Stella are decreased by 1.75 cm,0.96 cm, 0.02 cm, respectively.



LARES



Starlette



Stella

4. SLR Precise Orbit Determination experiments and results analysis with/without wind field considered

LARES orbit prediction precision in the R/T/N directions with/without the HWM14 in 2019.

LARES with the HWM14	prediction length	R direction (cm)	T direction (cm)	N direction (cm)
Yes	1 day	0.69	−147.57	−2.97
No	1 day	−0.69	−147.61	−2.97
Yes	3 days	−4.62	−163.96	11.86
No	3 days	−7.91	−184.69	13.27

Stella orbit prediction precision in the R/T/N directions with/without the HWM14 in 2019.

Stella with the HWM14	prediction length	R direction (cm)	T direction (cm)	N direction (cm)
Yes	1 day	2.76	191.77	−2.27
No	1 day	2.79	193.72	−2.27
Yes	3 days	0.36	308.52	−2.21
No	3 days	−0.42	315.26	−2.23

Larets orbit prediction precision in the R/T/N directions with/without the HWM14 in 2019.

Laretswith the HWM14	prediction length	R direction (cm)	T direction (cm)	N direction (cm)
Yes	1 day	13.06	−618.56	−328.87
No	1 day	20.19	−1399.40	−749.50
Yes	3 days	168.50	−14526.70	−101.46
No	3 days	755.76	−61887.66	−233.82

The orbit prediction accuracy for 1 day and 3 days for LARES is improved by 0.04 cm and 20.73 cm in T, respectively.

The orbit prediction accuracy for 1 day and 3 days for Stella is improved by 1.95 cm and 6.74 cm in T, respectively.

The orbit prediction accuracy for 1 day and 3 days for Larets is improved by 7.81 m and 473.61 m in T, respectively.

4. SLR Precise Orbit Determination experiments and results analysis with/without wind field considered

Starlette orbit prediction precision in the R/T/N directions with/without the HWM14 in 2019.

Starlettewith the HWM14	prediction length	R direction (cm)	T direction (cm)	N direction (cm)
Yes	1 day	19.69	−77.49	3.28
No	1 day	18.23	−79.69	3.36
Yes	3 days	13.63	−235.65	5.50
No	3 days	12.11	−222.96	−5.41

The Starlette eccentricity: 0.021; perigee: 790 km; apogee: 1100 km
significant variation in orbital altitude.

The T direction acceleration undergoes substantial changes due to the large difference in altitude between the perigee and apogee. However, the HWM14 atmospheric wind speed model may not adapt well to the orbital variations of Starlette. Therefore, 3 days orbit forecast using the HWM14 for Starlette brings a degradation in the T direction compared to the case without the HWM14.

5. Conclusions and outlook

- The best atmospheric density model should be tested for different satellites.
- After introducing the HWM14 atmospheric wind speed model into atmospheric drag, the orbit residual WRMS value of LARES, Starlette, Larets are decreased by 0.10 cm, 0.30 cm,0.05 cm, respectively.
- The HWM14 atmospheric wind speed model may not adapt well to the orbital variations of Starlette and should be further improved.
- The orbit overlapping arcs errors in 3D for LARES, Starlette, Stella are decreased by 1.75 cm,0.96 cm, 0.02 cm, respectively.
- The 1-day and 3-day orbit prediction precision for LARES/Stella/Larets are all improved by 0.04 cm/1.95 cm/7.81m and 20.73cm/6.74cm/473.61m in the T direction, respectively.

These results show that considering atmospheric wind speed has a certain improvement for POD of SLR LEO satellites. Therefore, the influence of atmospheric wind speed on atmospheric drag should be taken into consideration in LEO satellite POD and SLR regular data processing.

Outlook

- Beside the above research and ERP, we still need modified other models (e.g. solar radiation pressure for non-spherical satellites) to improve the accuracy of SLR data processing.

- After all models have been updated, we will process more SLR satellites' data for determination of TRF and EOP, and also evaluate their accuracy. We hope there will be some SLR stations to satisfy the accuracy requirements of future TRF (1mm for position; 0.1mm/yr for velocity).

- In future POD of SLR satellites will maybe satisfy the requirements of mm order level.

THANK YOU FOR YOUR ATTENTION!