ITRF2020 seasonal geocenter motion model

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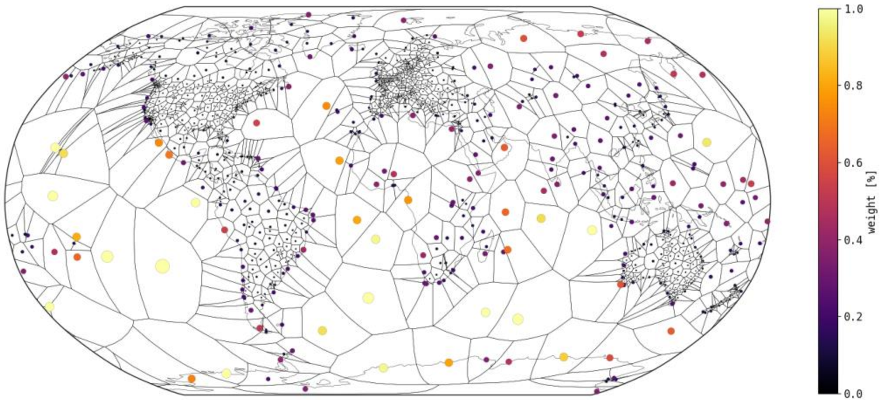
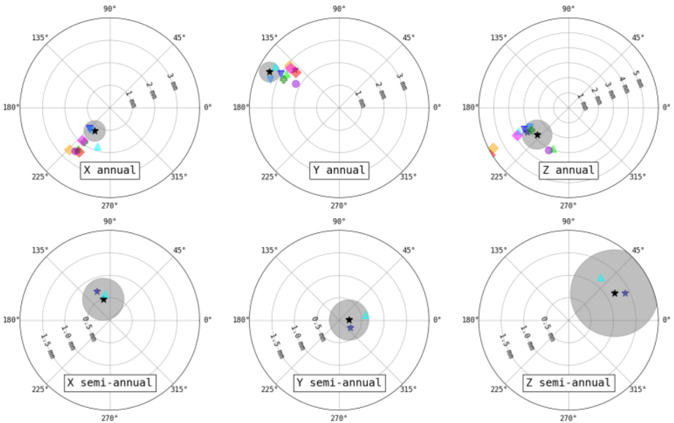




Estimation of ITRF2020 seasonal station motions

- **(Simplified) ITRF2020 kinematic model for station i:**

$$X_i(t) = \underbrace{X_i(t_0) + (t - t_0)\dot{X}_i}_{\text{linear part (actually piecewise)}} + \underbrace{\delta X_{PSD,i}(t)}_{\text{post-seismic deformation}} + \overbrace{\underbrace{a_{1,i}\cos(2\pi t) + b_{1,i}\sin(2\pi t)}_{\text{annual motion}} + \underbrace{a_{2,i}\cos(4\pi t) + b_{2,i}\sin(4\pi t)}_{\text{semi-annual motion}}}^{\delta X_i(t)}$$

- **Seasonal motion coefficients $a_{1,i}$, $b_{1,i}$, $a_{2,i}$, $b_{2,i}$:**
  - Estimated for every station **i** (with sufficient time span)
  - Equated within co-location sites at ± 0.1 mm
  - Looser constraint levels in case of seasonal motion discrepancies between techniques
  - See Collilieux et al., ‘Consistency evaluation of seasonal signals in ITRF2020’, this afternoon

- **Frame definition of seasonal motions**
  - No net seasonal rotation of selected core station network
  - No seasonal scale variations between selected input SLR solutions and ITRF2020
  - No seasonal translations between selected input SLR solutions and ITRF2020
  - → Estimated seasonal station motions are expressed with respect to CM (as sensed by SLR).

Estimation of seasonal geocenter motion – Principle

- The seasonal motion of a point (ϕ,λ) of the Earth's surface w.r.t. CM can be decomposed into:

$$\underbrace{\delta X_{/CM}(\varphi,\lambda,t)}_{} = \underbrace{\delta X_{/CF}(\varphi,\lambda,t)}_{\text{seasonal motion w.r.t. CF}} + \underbrace{\delta X_{CF/CM}(t)}_{\text{seasonal geocenter motion}}$$

- Besides, by definition of CF: $\frac{1}{4\pi r^2}\int \delta X_{/CF}(\varphi,\lambda,t)\,d\Omega = 0$

$$\rightarrow \frac{1}{4\pi r^2}\int \delta X_{/CM}(\varphi,\lambda,t)\,d\Omega = \delta X_{CF/CM}(t)$$

- An estimate of seasonal geocenter motion can be obtained by discretizing the above integral at ITRF sites: $\delta X_{CF/CM}(t) \approx \frac{1}{4\pi r^2}\sum_i \delta X_i(t)\, w_i$

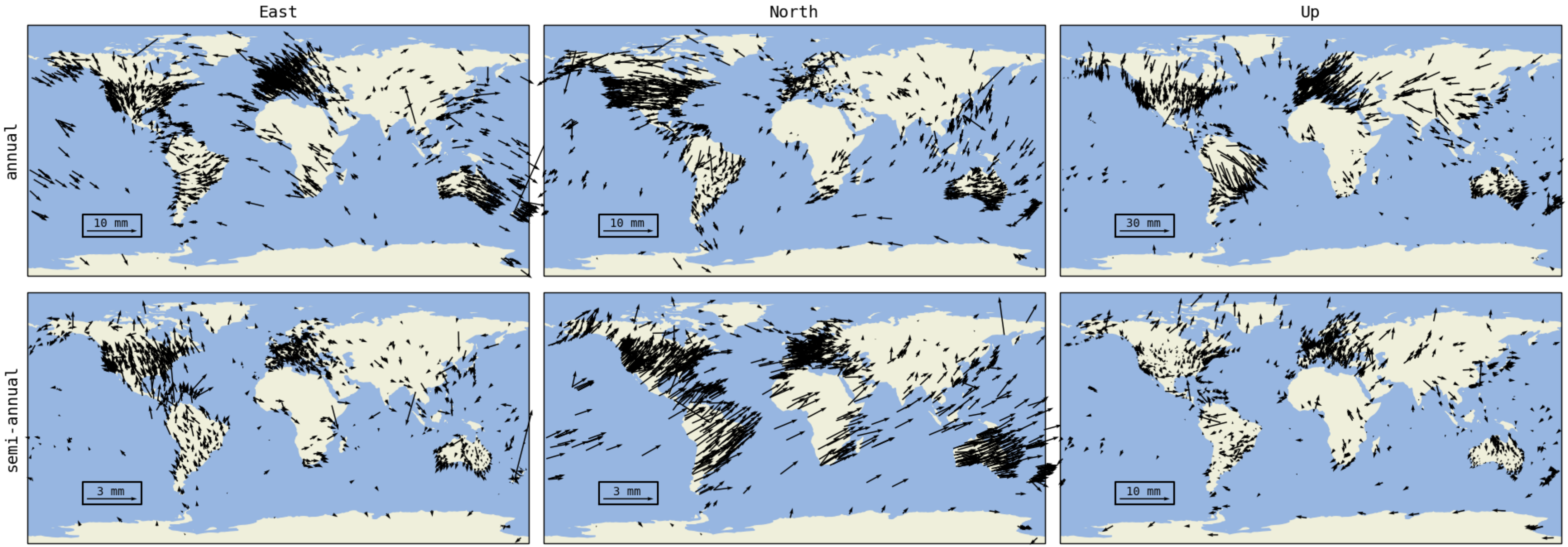
  where the w_i's are weights corresponding to small surface elements around each ITRF site (and summing up to $4\pi r^2$).

Station selection (1/2)

- **Initial selection:**
  - **Discard stations with ITRF2020 seasonal motions constrained to zero (due to short time spans)**
  - **Keep only one station per site (the one for which the trace of the formal covariance matrix of seasonal coefficients is minimal)**
  - **Discard stations whose seasonal coefficients have unusually large formal errors**
  - → **1142 stations**

Station selection (1/2)

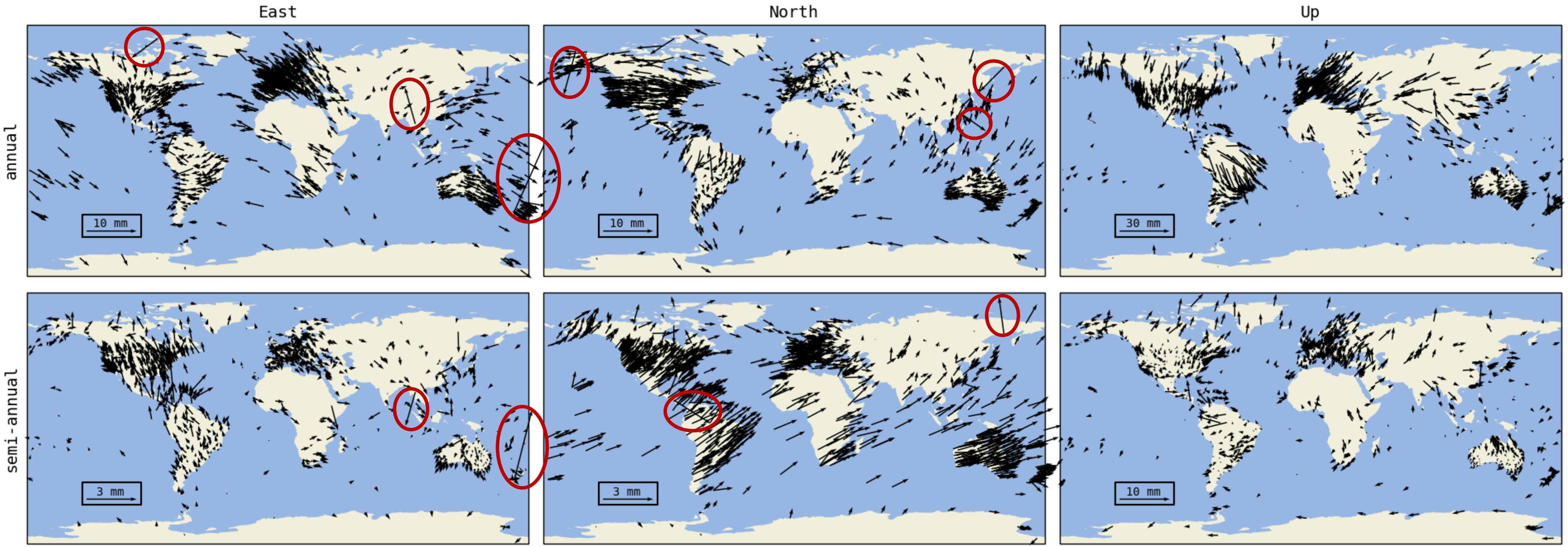
- **Initial selection:**



Arrow length ↔ **Amplitude of seasonal motion (sqrt(a²+b²)). Note different scales for different components.**
Arrow orientation ↔ **Phase of seasonal motion (arctan(b/a)). Counted anticlockwise from East direction.**

Station selection (1/2)

- **Initial selection:**



Arrow length ↔ Amplitude of seasonal motion (sqrt(a²+b²)). Note different scales for different components.
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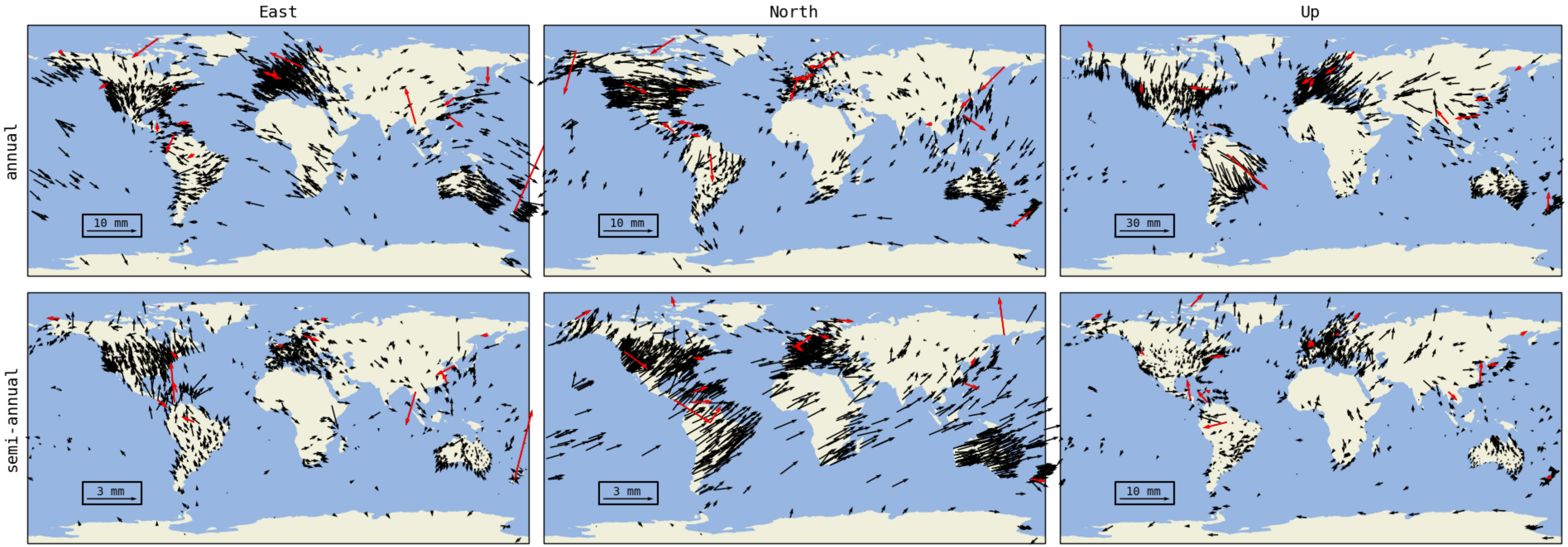
Station selection (2/2)

- **Outlier detection:**
  - Model field of seasonal coefficients as: low-degree vector spherical harmonic terms + spatially white noise
  - Estimate vector spherical harmonic coefficients by least-squares and white noise variances by VCE
  - Select n_{max} = 7 as truncation degree, as a compromise between whiteness of residuals and overfitting
  - Iteratively reject stations with normalized residuals > 7 in at least one component
  - → 18 outliers / 1124 stations kept

- **Note:**
  - Alternative seasonal geocenter motion estimates can be obtained from the degree-1 coefficients of a vector spherical harmonic expansion such as described above (see slide 14).

Station selection (2/2)

- **Outlier detection:**



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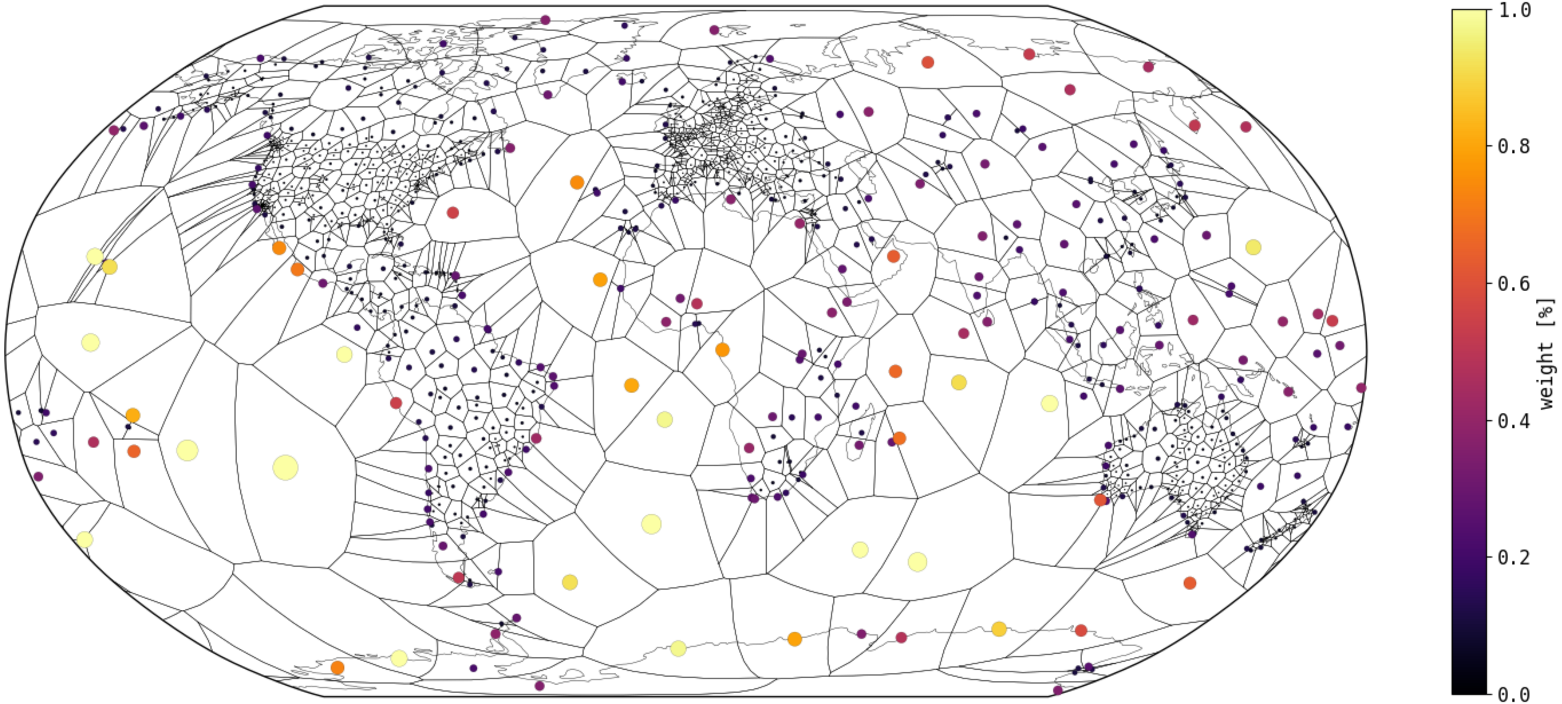
Station weights (w_i's)

1. **Spherical Voronoï diagram of selected station network**
   - **Station weights = areas of their Voronoï cells**



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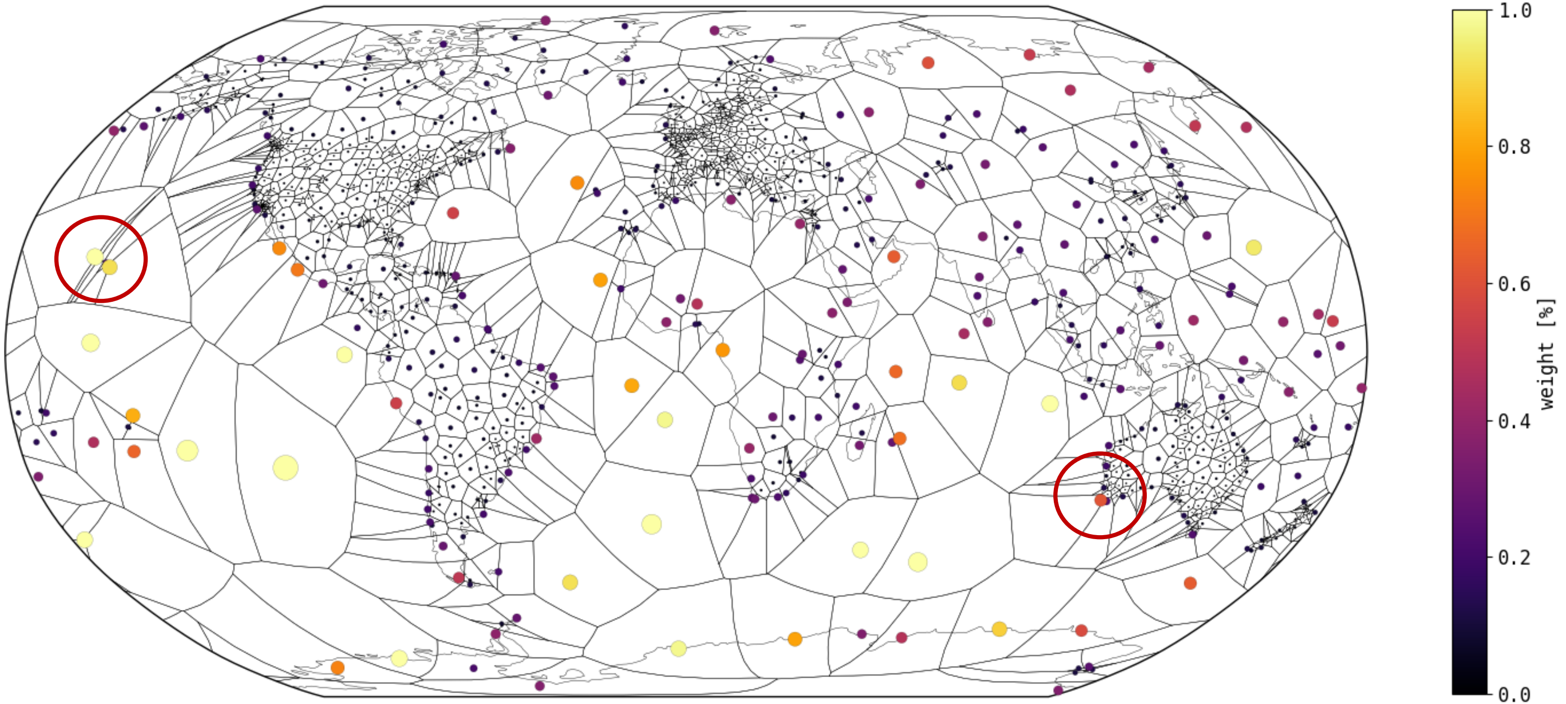
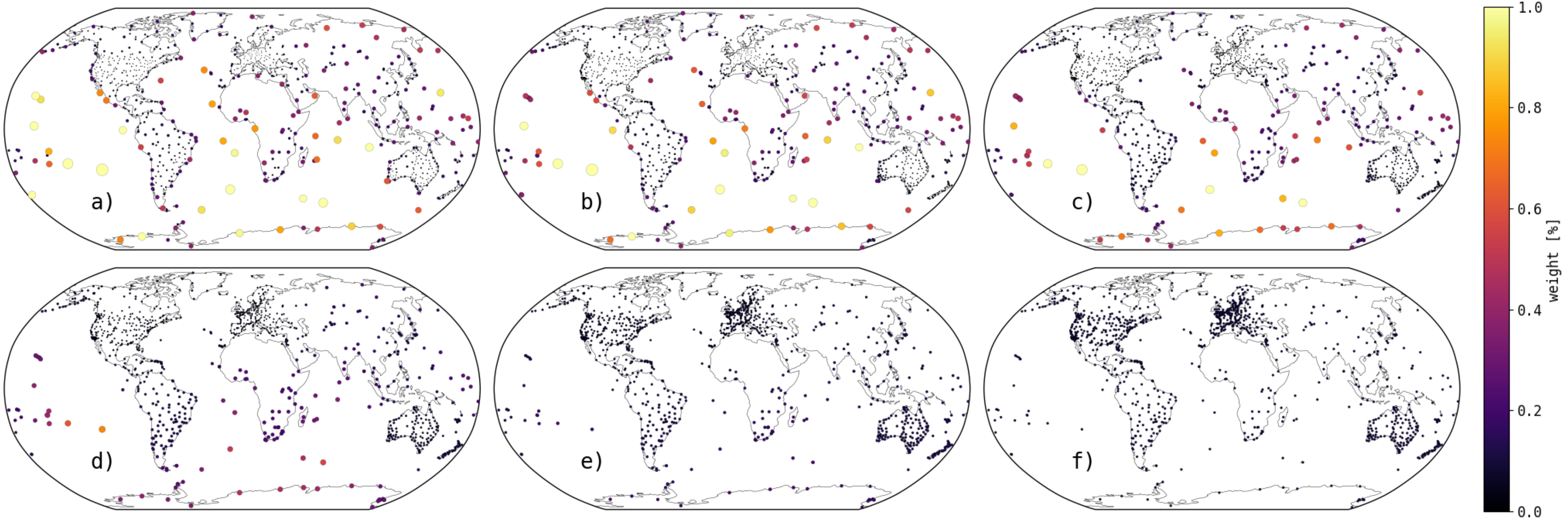


- Problem: Nearby stations sometimes have highly different weights.

Station weights (w_i's)

1. **Spherical Voronoï diagram of selected station network**
2. **Smooth 'Voronoï weights'**
   - For any two neighbour stations (i, j) separated by a spherical distance $\psi_{i,j}$, impose: $w_i = w_j \pm \sigma\psi_{i,j}$
   - Vary weight of smoothing constraints (i.e., $1/\sigma^2$) by powers of 10



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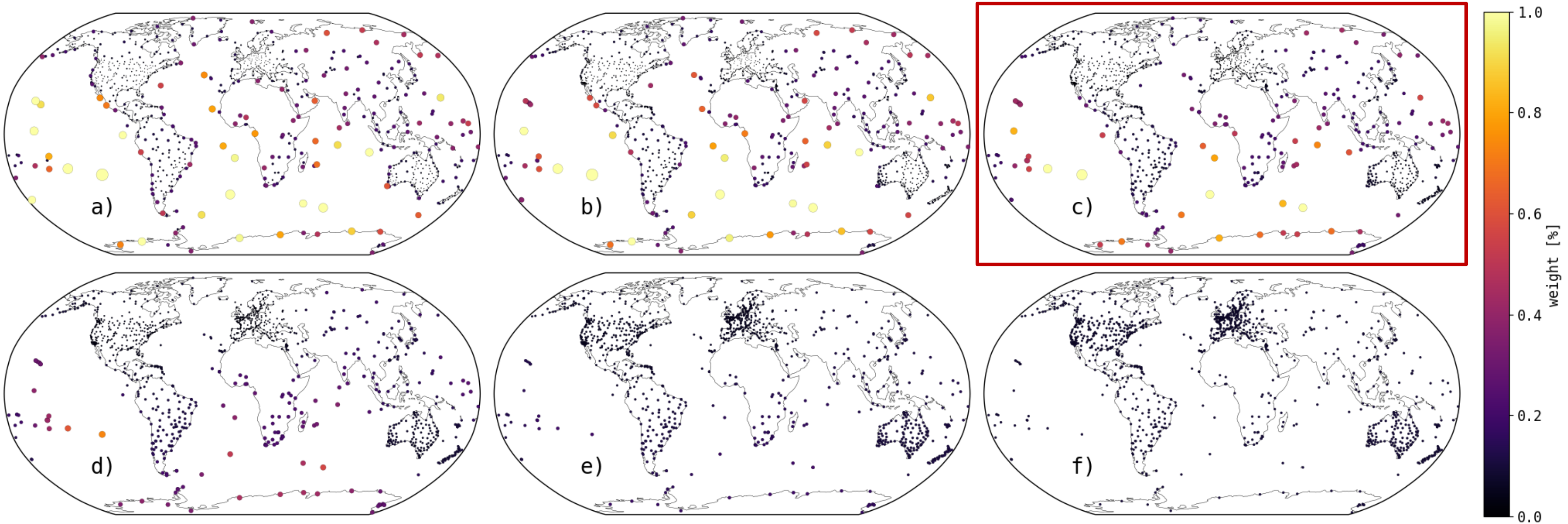
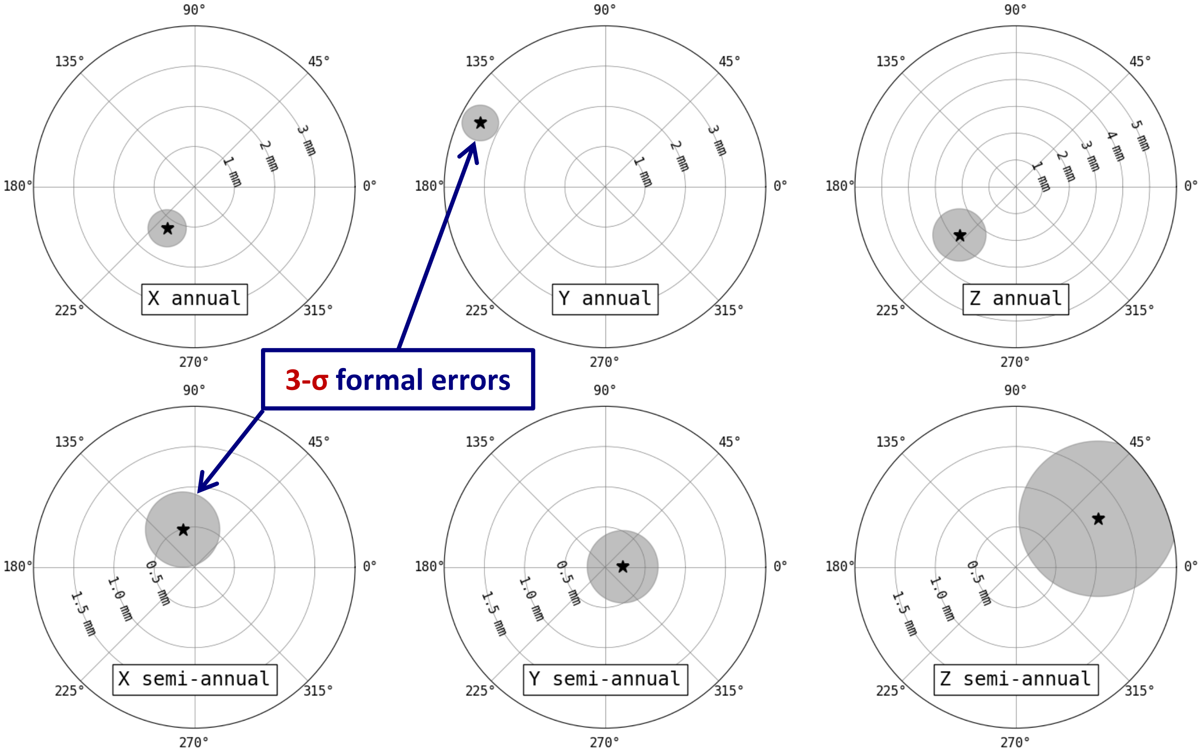


- Choose smoothing level c): regionally homogeneous weights still accounting for large-scale density heterogeneities

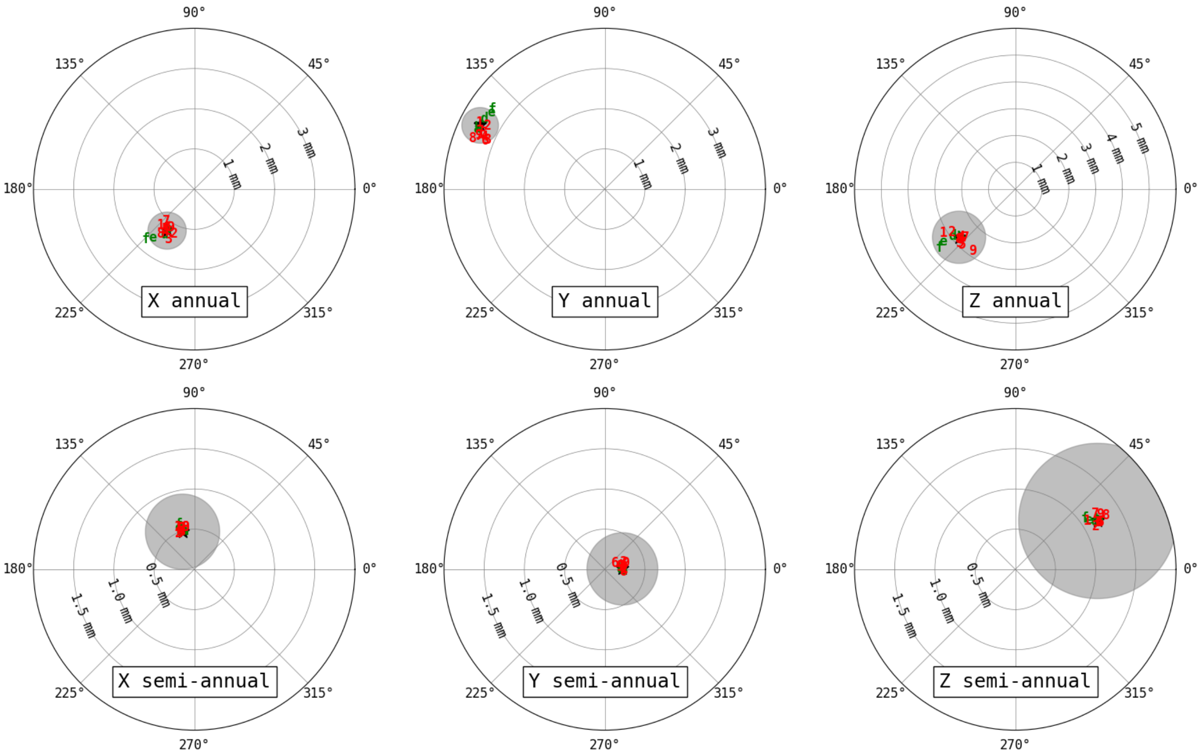
Result: ITRF2020 seasonal geocenter motion model

		amp. [mm]	phase [deg]
annual	X	1.23 ± 0.16	-123.2 ± 7.2
	Y	3.48 ± 0.15	152.9 ± 2.5
	Z	2.76 ± 0.33	-139.5 ± 6.8
semi-annual	X	0.49 ± 0.15	107.2 ± 18.1
	Y	0.22 ± 0.15	1.6 ± 39.0
	Z	1.19 ± 0.33	30.5 ± 15.5



- Sign and phase conventions are such that the seasonal motion of CF w.r.t. CM is given by:
  $A_1 \cos(2\pi t - \phi_1) + A_2 \cos(4\pi t - \phi_2)$
- Errors in the table are 1-σ formal errors stemming from the propagation of the covariance matrix of the ITRF2020 seasonal station motion coefficients.
- They account for:
  - the intrinsic uncertainty of the seasonal CM sensed by SLR,
  - the uncertainty of its transfer to the whole ITRF2020 network,
  - random errors in the ITRF2020 station-specific seasonal motions.
- They do not account for:
  - biases of the geocenter motion estimation method used,
  - systematic errors in the ITRF2020 station-specific seasonal motions (i.e., unphysical seasonal motions seen by the geodetic techniques).

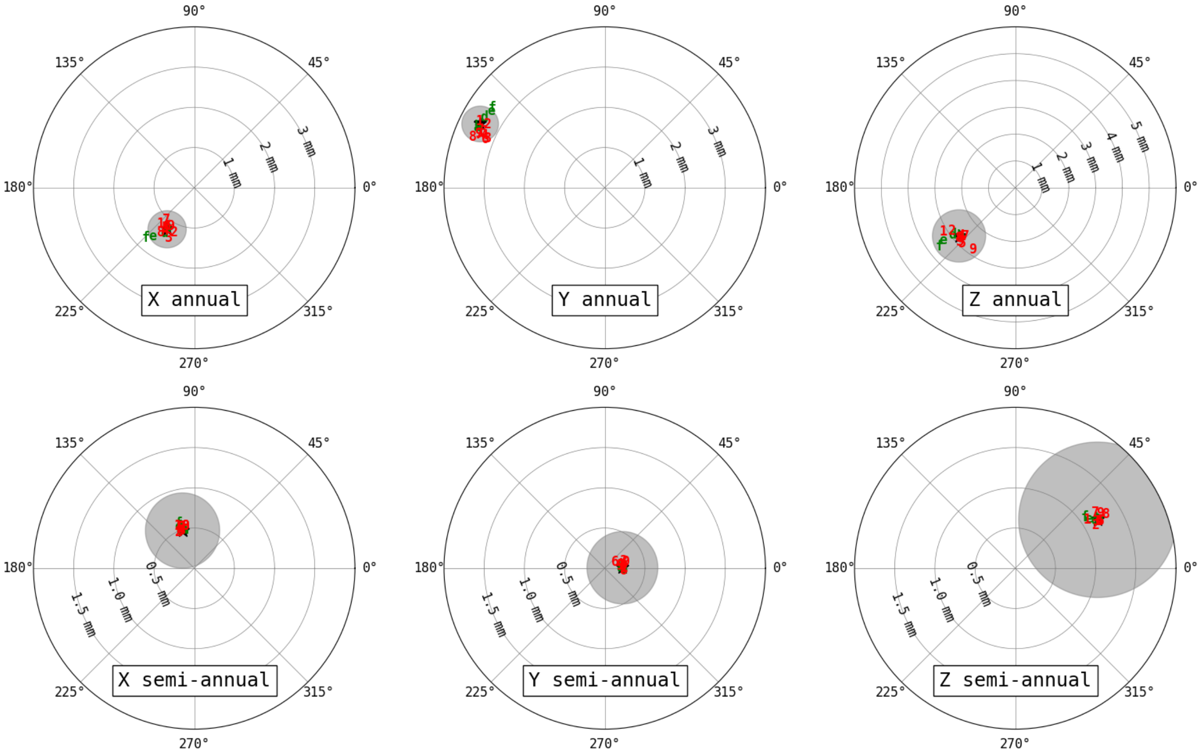
Alternative estimates



a – f : Estimates obtained with different smoothing levels of the Voronoï weights (see slide 12)

1 – 9 : Estimates obtained from vector spherical harmonics expansions with different truncation degrees (see slide 7)

Alternative estimates



– Estimates obtained with reasonable smoothing levels (a – d) and reasonable truncation degrees (4 – 6) are in good agreement.

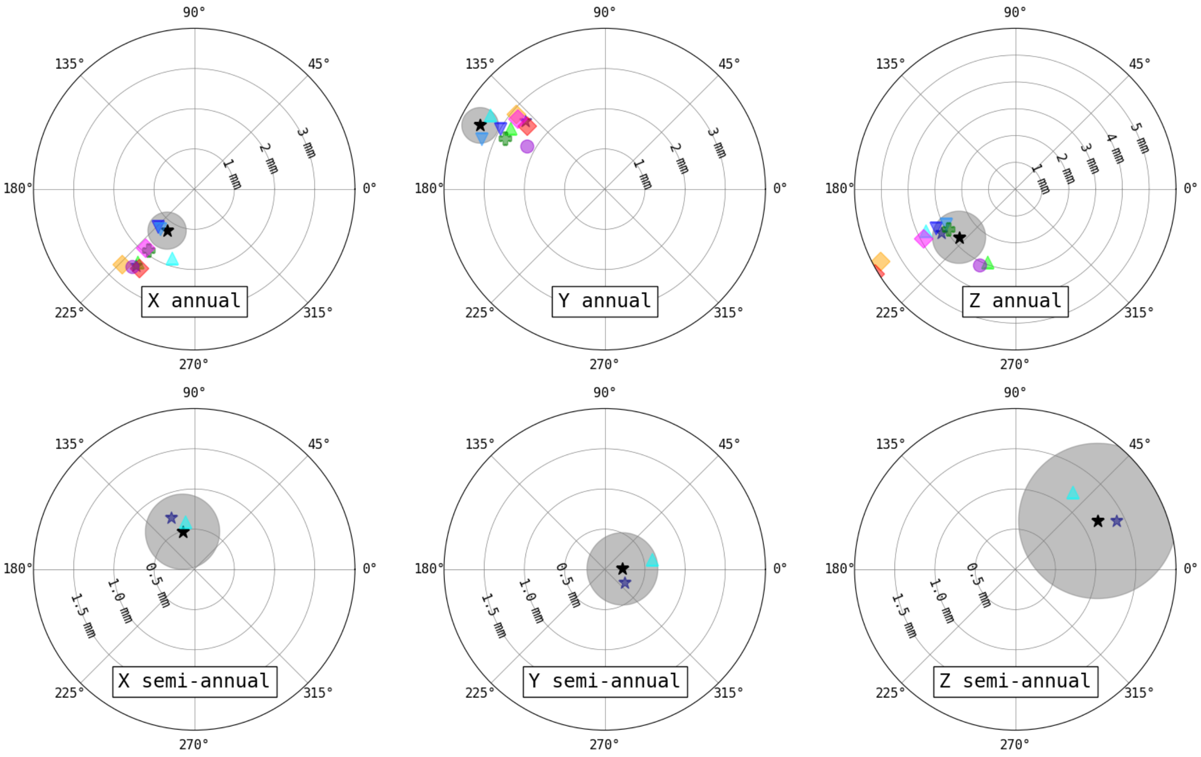
– Biases of the estimation method seem small compared to (or at least commensurate with) the formal errors.

– Contribution of systematic errors in ITRF2020 station-specific seasonal motions is also likely small compared to the formal errors.

→ Formal errors provide reasonable estimates of the total errors in the ITRF2020 seasonal geocenter motion model.

a – f : Estimates obtained with different smoothing levels of the Voronoï weights (see slide 12)
1 – 9 : Estimates obtained from vector spherical harmonics expansions with different truncation degrees (see slide 7)

Comparison with other estimates



This study	
Abbondanza et al. (2017)	Similar approach, but with 80 stations & uniform weights
Wu et al. (2017)	Similar as above + degree-1 deformation + GRACE
Wu et al. (2020)	Similar as above, refined
Wu et al. (2015)	GNSS degree-1 deformation + GRACE + OBP
Sun et al. (2016)	GRACE + OBP
Kuang et al. (2019)	GRACE GPS tracking + accelerometer data
Altamimi et al. (2016)	SLR CN/CM (no attempt to mitigate network effect)
Ries et al. (2016)	SLR CN/CM (no attempt to mitigate network effect)
Ries et al. (2016)	SLR with network effect mitigated
Zhang et al. (2018)	Geophysical model predictions

– ITRF2020 annual geocenter model in good agreement with other estimates, especially the recent global inversions by Wu et al. (2017, 2020).

Summary

- **ITRF2020 seasonal geocenter motion model = weighted average of ITRF2020 seasonal station motions referred to CM (as sensed by SLR)**
  - Station weights designed to provide an approximation CF/CM (rather than CN/CM)

- **Dominant error source likely to be the intrinsic uncertainty of CM sensed by SLR (+ the uncertainty of its transfer to the whole ITRF2020 network)**
  - Biases of the estimation method and contribution of systematic errors in ITRF2020 station-speficic station motions are likely secondary.

- **ITRF2020 seasonal geocenter motion model in good agreement with other recent estimates**
  - In particular the global inversions by Wu et al. (2017, 2020)

- **ITRF2020 website (https://itrf.ign.fr/en/solutions/ITRF2020) provides:**
  1. Seasonal station motions referred to CM
  2. Seasonal geocenter motion model
  3. Seasonal station motions referred to CF (1 *minus* 2)