Validation of boxwing models for GNSS satellites

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- About the scalable boxwing model
  - Scale Factors
  - Plate Groupings
- Results
- Conclusion

Background

Background

- Radiation Pressure a significant source of error in orbit modeling
  - Solar Radiation
  - Earth Reflected/Emitted Radiation
- New Empirical CODE Orbit Model (ECOM2) [Arnold et al. 2015, J. Geod.]
  - Effective for GPS & GLONASS outside of eclipse season
  - Less effective for Galileo, etc.
- Adjustable boxwing model
  [Solano, 2014, PhD Thesis]; [Montenbruck et al. 2015, J. Geod.]; [Montenbruck et al. 2017, Adv. Space Research]
  - Semi-Analytical model for radiation pressure
  - Improved performance during eclipse season

Approach

Approach

- Implement Scalable-boxwing model in development version of Bernese GNSS Software
- Compute scale factors per satellite, plate, etc.
  - Investigate various plate groupings
  - Identify long-term trends in scale factors per SVN
- Analyze improvements over ECOM2
  - ECOM2-only
  - ECOM2-plus-boxwing
  - ECOM2-plus-scaled-boxwing:
    - Satellite-specific, Yearly-average Scale Factors

Scalable-Boxwing Model Definition

Radiation Pressure force calculation per plate:

Without immediate thermal re-radiation: $\vec{F} = -\frac{\Phi}{c} \cdot A \cos\theta \cdot \left[(\alpha + \delta)\vec{e}_{\odot} + \frac{2}{3}\delta\vec{e}_n + 2\rho\cos\theta \cdot \vec{e}_n\right]$

With immediate thermal re-radiation (MLI): $\vec{F} = -\frac{\Phi}{c} \cdot A \cos\theta \cdot \left[(\alpha + \delta)\left(\vec{e}_{\odot} + \frac{2}{3}\vec{e}_n\right) + 2\rho\cos\theta \cdot \vec{e}_n\right]$

Constants:
- Φ = solar flux
- c = speed of light

Macromodel definition ($\alpha + \delta + \rho = 1$):
- A = surface area of plate
- α = absorptivity of plate
- δ = diffuse reflectivity of plate
- ρ = specular reflectivity of plate
- $\vec{e}_n$ = unit vector normal to plate

Attitude geometry:
- $\vec{e}_n$ = unit vector normal to plate
- $\vec{e}_{\odot}$ = unit vector towards radiation source
- θ = angle between $\vec{e}_{\odot}$ and $\vec{e}_n$

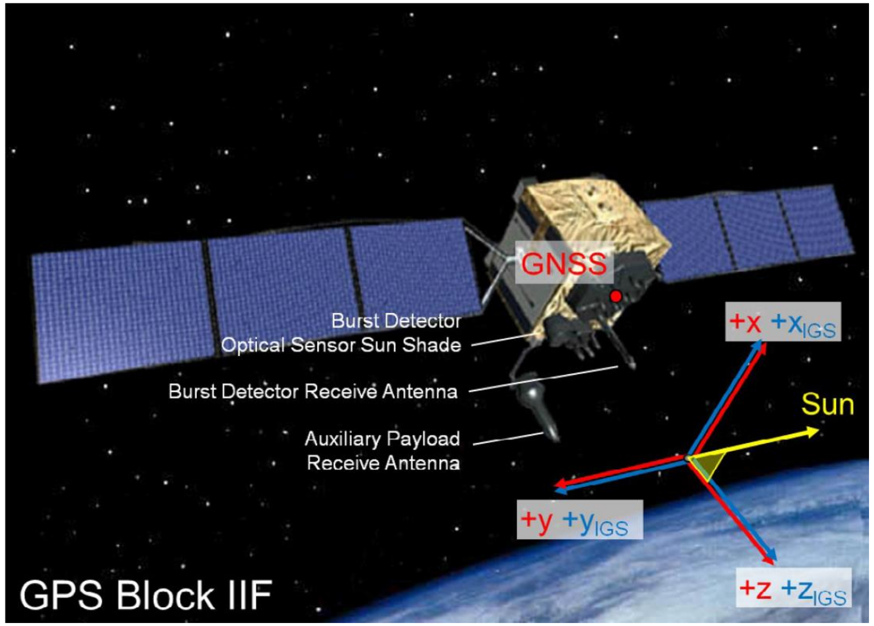
Exact geometry and material properties are not necessarily known. A single scale factor multiplied by the force on a given plate can compensate for uncertainties in all four plate properites.

Scale factors can be introduced as solveable parameters in the least squares model.

Example Boxwing Macromodel & Plate Groupings: GPS

Macromodel Definitions:

- By SV block
  - Example is GPS IIF
- As collection of plates
  - Geometrical and optical properties for each plate
  - Force calculated on any plate where $\cos\theta > 0$ and summed together
  - Only specular and diffuse reflectivity are specified
  - Absorptivity is Calculated



[Montenbruck et al, 2015. Adv. In Space Research]

Multiscale

Plate	Mod	Area (A) [m^2]	Normal ($\vec{e}_n$)	Specularity (ρ)	Diffusivity (δ)	Rotation Sys.	Description
1	1	5.720	[+1, 0, 0]	0.112	0.448		+X
2	1	5.720	[−1, 0, 0]	0.112	0.448		-X
3	1	7.010	[0, +1, 0]	0.112	0.448		+Y
4	1	7.010	[0, −1, 0]	0.112	0.448		−Y
5	1	5.400	[0, 0, +1]	0.112	0.448		+Z
6	1	5.400	[0, 0, −1]	0.000	0.000		−Z
7	0	22.250	[+1, 0, 0]	0.195	0.035	+SUN: [0,+1, 0]	Solar panels front
8	0	22.250	[−1, 0, 0]	0.196	0.034	−SUN: [0,+1, 0]	Solar panels back

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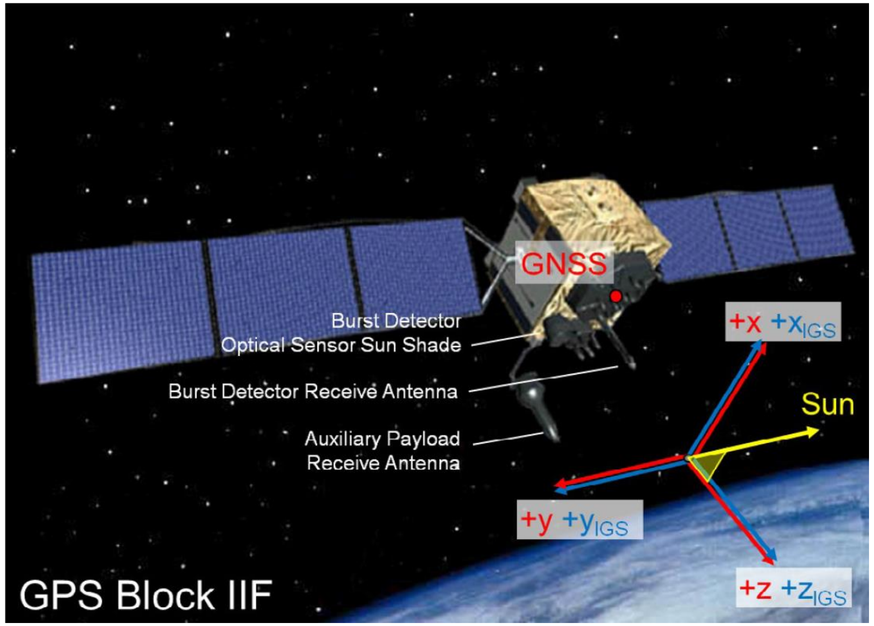

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Monoscale

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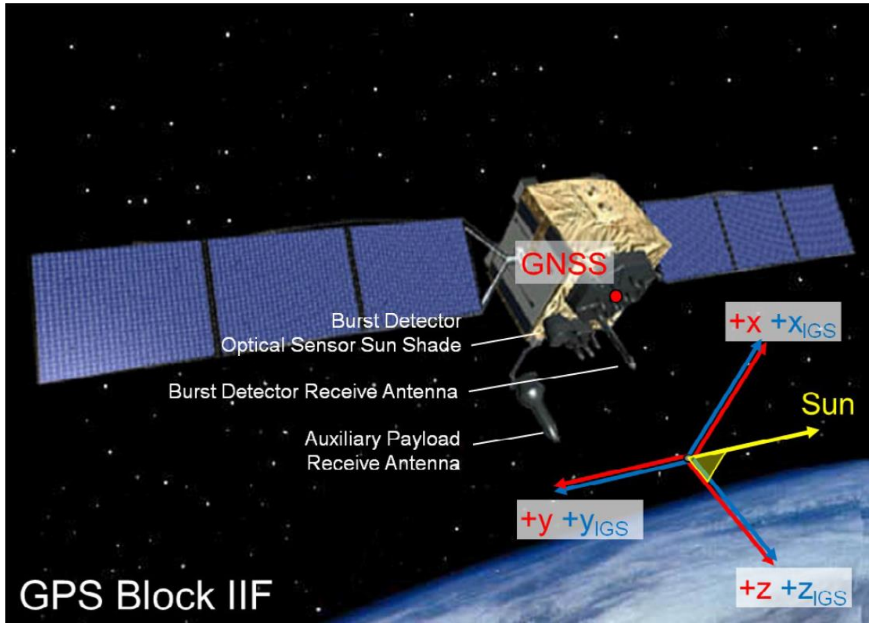

[Montenbruck et al, 2015. Adv. In Space Research]

Smartscale–2

Plate	Mod	Area (A) [m^2]	Normal ($\vec{e}_n$)	Specularity (ρ)	Diffusivity (δ)	Rotation Sys.	Description
1	1	5.720	[+1, 0, 0]	0.112	0.448		+X
2	1	5.720	[–1, 0, 0]	0.112	0.448		–X
3	1	7.010	[0, +1, 0]	0.112	0.448		+Y
4	1	7.010	[0, –1, 0]	0.112	0.448		–Y
5	1	5.400	[0, 0, +1]	0.112	0.448		+Z
6	1	5.400	[0, 0, –1]	0.000	0.000		–Z
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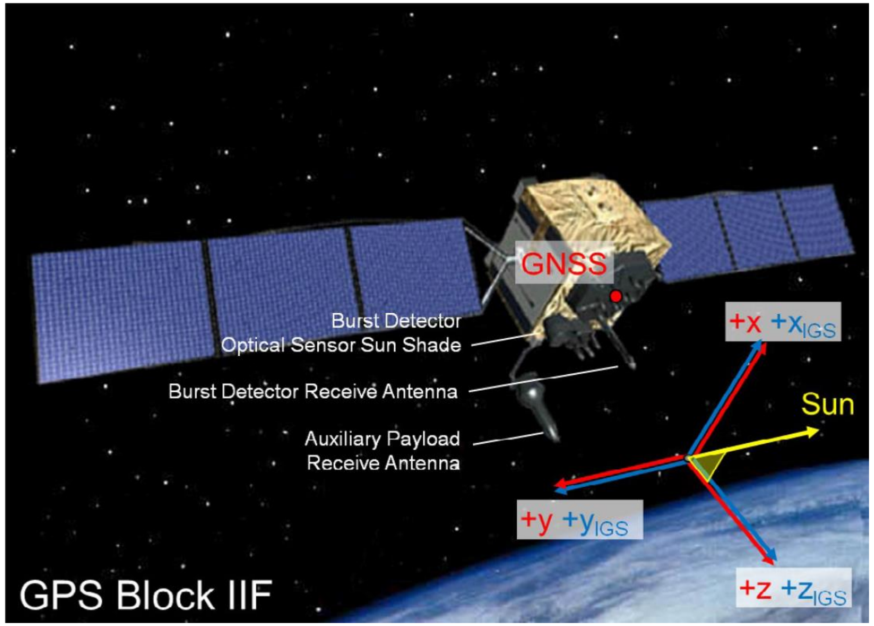

[Montenbruck et al, 2015. Adv. In Space Research]

Smartscale−4

Plate	Mod	Area (A) [m^2]	Normal ($\vec{e}_n$)	Specularity (ρ)	Diffusivity (δ)	Rotation Sys.	Description
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2	1	5.720	[−1, 0, 0]	0.112	0.448		−X
3	1	7.010	[0, +1, 0]	0.112	0.448		+Y
4	1	7.010	[0, −1, 0]	0.112	0.448		−Y
5	1	5.400	[0, 0, +1]	0.112	0.448		+Z
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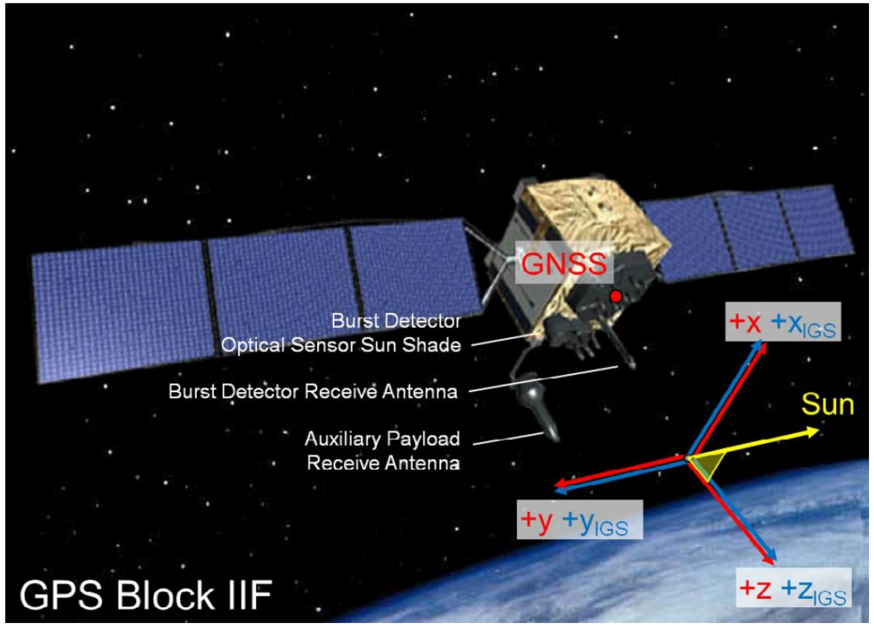


[Montenbruck et al, 2015. Adv. In Space Research]

Smartscale–3

Plate	Mod	Area (A) [m²]	Normal ($\vec{e}_n$)	Specularity (ρ)	Diffusivity (δ)	Rotation Sys.	Description
1	1	5.720	[+1, 0, 0]	0.112	0.448		+X
2	1	5.720	[–1, 0, 0]	0.112	0.448		–X
3	1	7.010	[0, +1, 0]	0.112	0.448		+Y
4	1	7.010	[0, –1, 0]	0.112	0.448		–Y
5	1	5.400	[0, 0, +1]	0.112	0.448		+Z
6	1	5.400	[0, 0, –1]	0.000	0.000		–Z
7	0	22.250	[+1, 0, 0]	0.195	0.035	+SUN: [0,+1, 0]	Solar panels front
8	0	22.250	[–1, 0, 0]	0.196	0.034	–SUN: [0,+1, 0]	Solar panels back

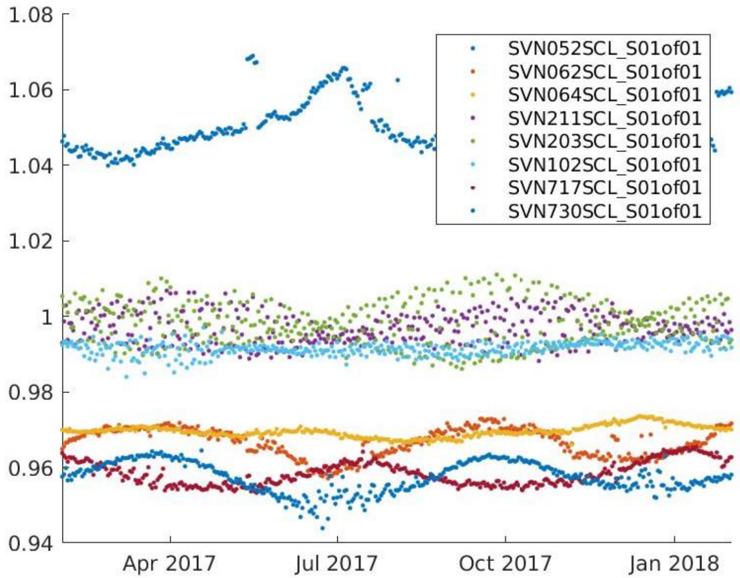
Discussion on Thermal re-radiation: Galileo

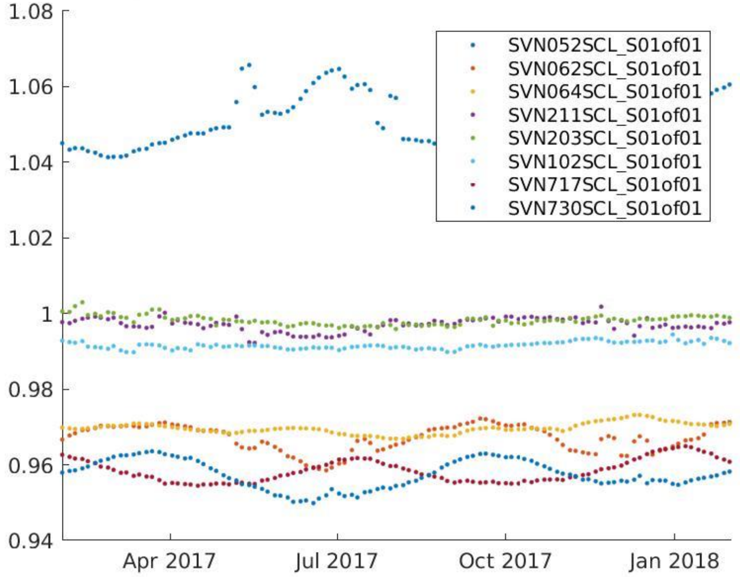
[https://www.esa.int/spaceinimages/Images/2014/07/Galileo_satellite]

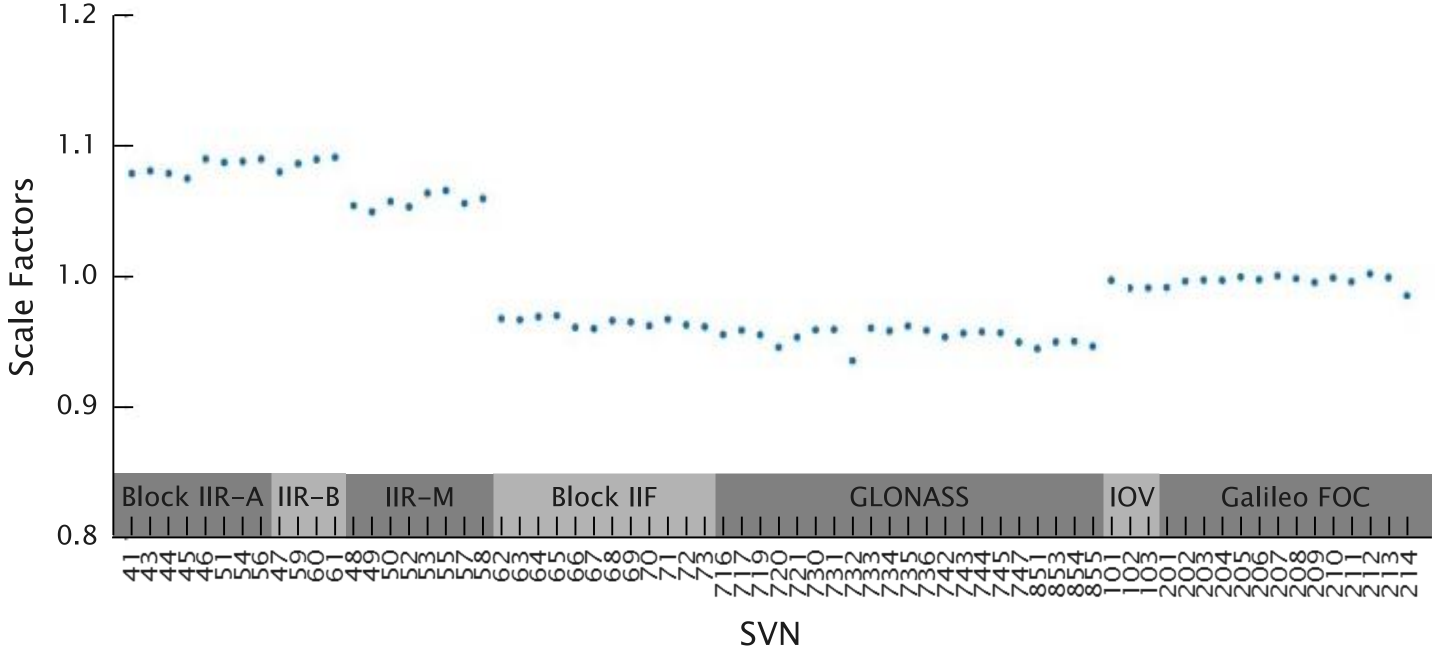
- Satellite geometry and optical properties given by GSA
- Front side of solar panel has two different "materials"
  - ~28% of solar panel surface area
  - With immediate thermal re-radiation yields scale factors closer to 1.

Plate	Mod	Area (A) [m²]	Normal ($\vec{e}_n$)	Specularity (ρ)	Diffusivity (δ)	Rotation Sys.	Description
1	1	1.320	[+1, 0, 0]	0.000	0.070		–X Material A
2	1	0.440	[–1, 0, 0]	0.000	0.070		+X Material A
3	1	0.880	[–1, 0, 0]	0.730	0.190		+X Material C
4	1	1.244	[0, +1, 0]	0.000	0.070		–Y Material A
5	1	1.539	[0, +1, 0]	0.730	0.190		–Y Material C
6	1	1.129	[0, –1, 0]	0.000	0.070		+Y Material A
7	1	1.654	[0, –1, 0]	0.730	0.190		+Y Material C
8	1	1.053	[0, 0, +1]	0.000	0.070		+Z Material A
9	1	1.969	[0, 0, +1]	0.220	0.210		+Z Material B
10	1	2.077	[0, 0, –1]	0.000	0.070		–Z Material A
11	1	0.959	[0, 0, –1]	0.730	0.190		–Z Material C
12	0	7.760	[+1, 0, 0]	0.080	0.000	+SUN: [0,+1, 0]	Solar Panels Material E
13	?	3.060	[+1, 0, 0]	0.100	0.000	+SUN: [0,+1, 0]	Solar Panels Material D
14	0	10.820	[–1, 0, 0]	0.196	0.034	–SUN: [0,+1, 0]	Solar Panels back

Long-term Trends in Scale Factors: Monoscale





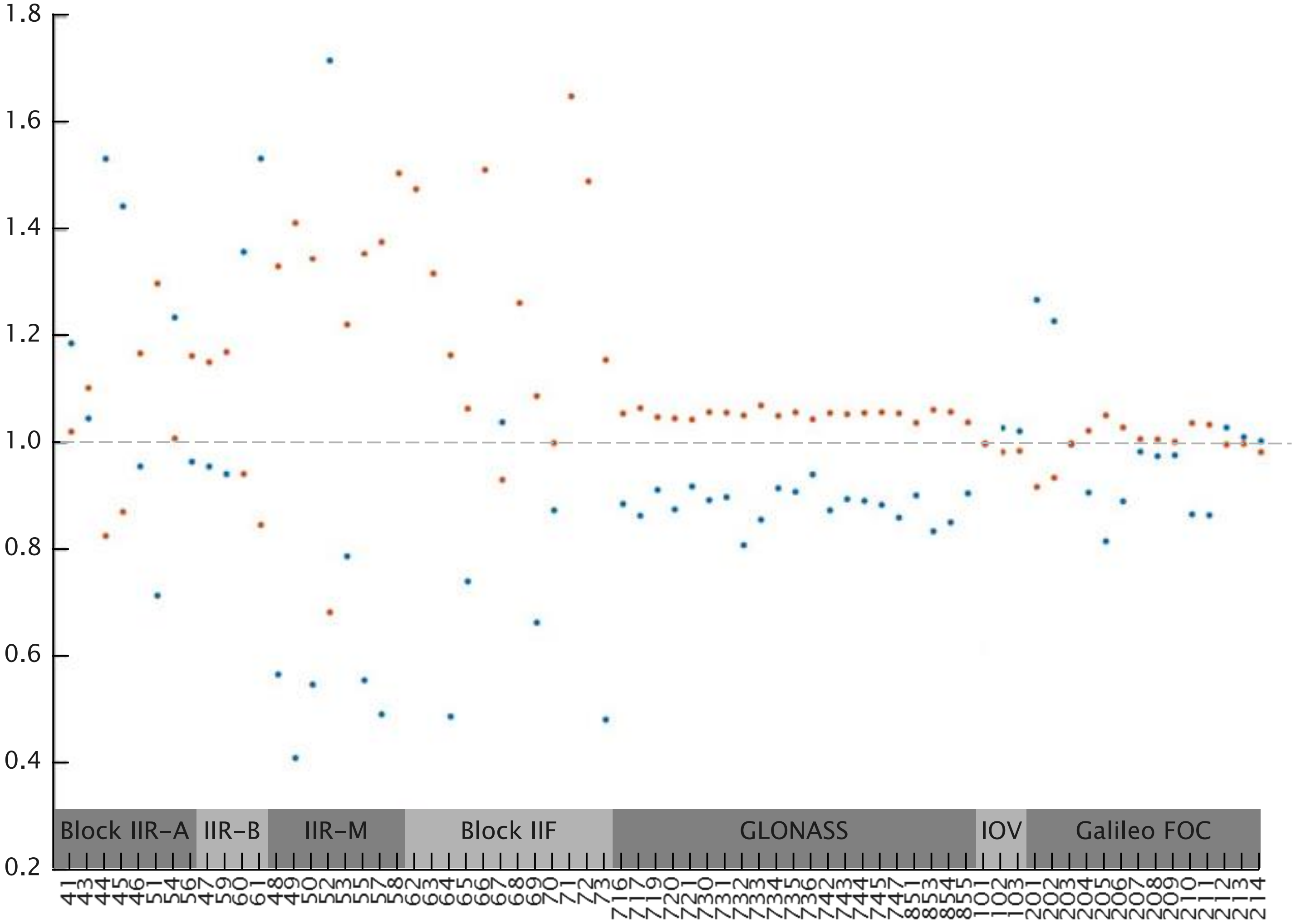


Top Left: Scale factors for selected satellites:
Monoscale model, daily solution, 1-year

Bottom Left: Scale factors for selected satellites:
Monoscale model, 7-day stack, 1-year

Top Right: Scale factors for all satellites:
Monoscale model, 1-year stack

Yearly Scale Factors: Smartscale-2



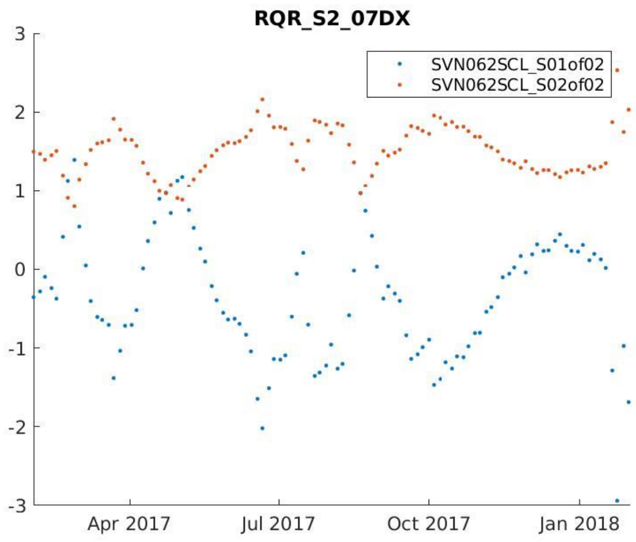
GLONASS & Galileo:
similar scale factors for all satellites in same block

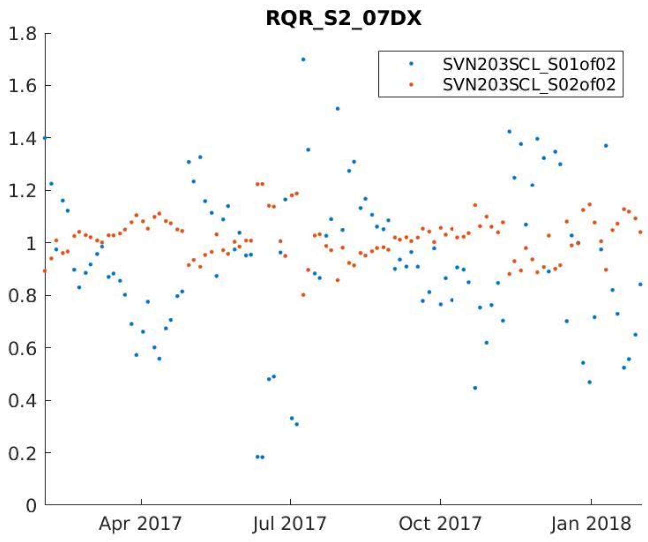
Scale factors close to 1.

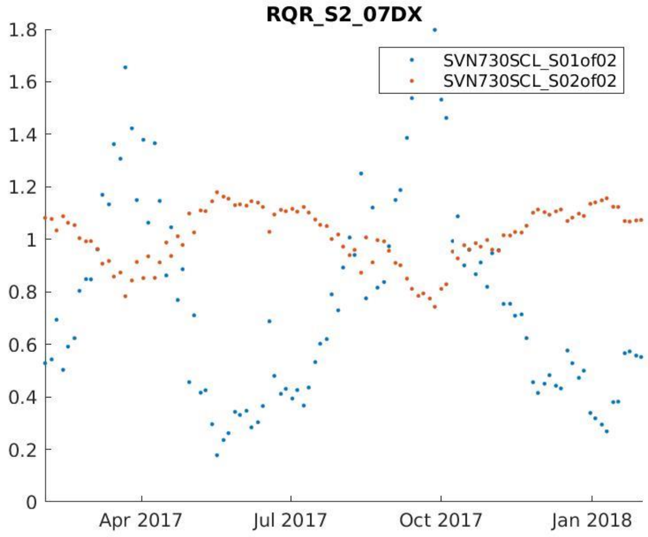
GPS:
more variation between satellites in same block

Scale factors farther away from 1.

Long-term Trends in Scale Factors: Smartscale-2







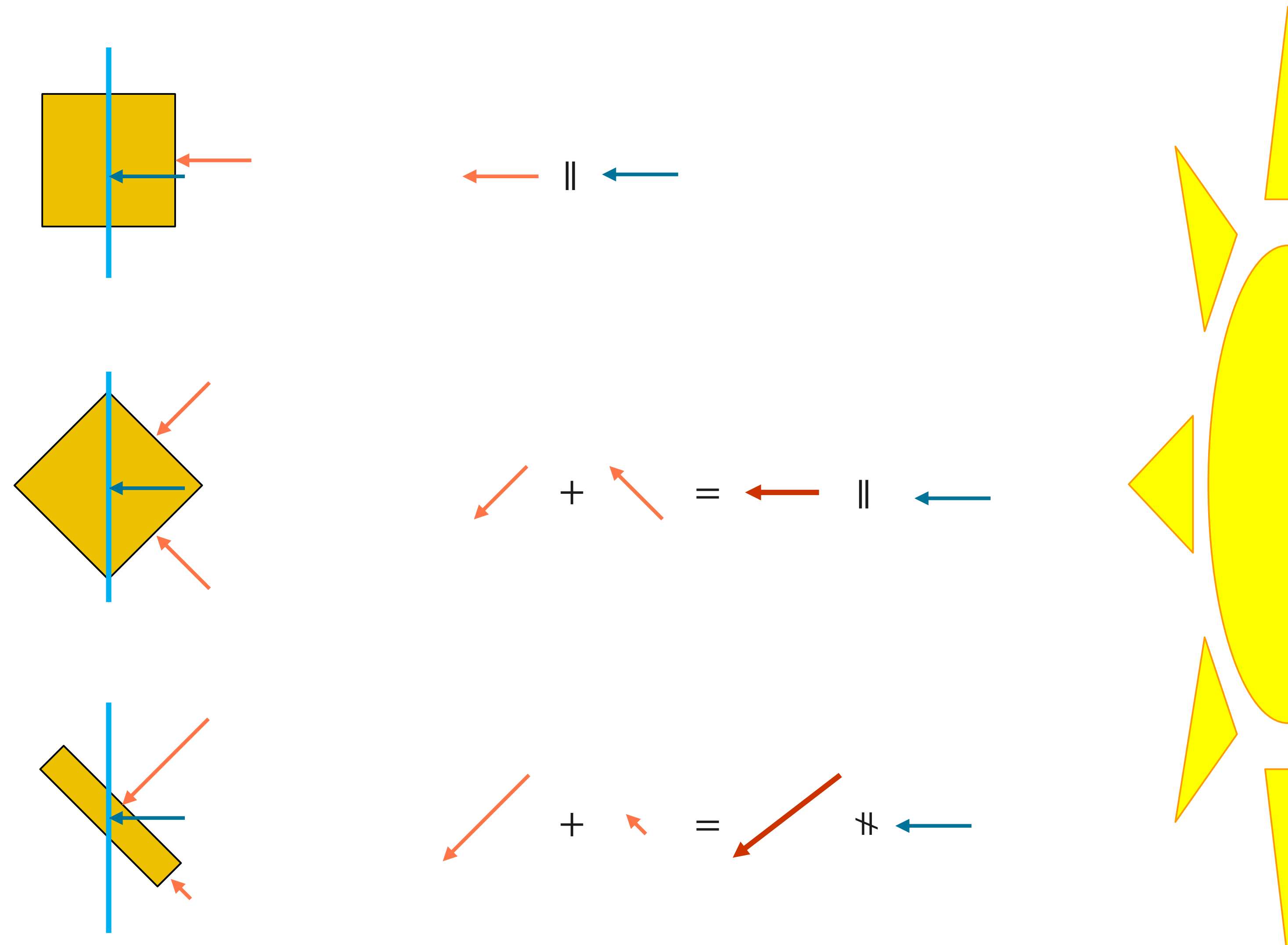
Scale factors for selected satellites:
Smartscale-2 model, 7-day stack, 1-year
Top Left: GPS SVN 62
Bottom Left: GLONASS SVN 730
Top Right: Galileo SVN 203

*Note different scale for GPS

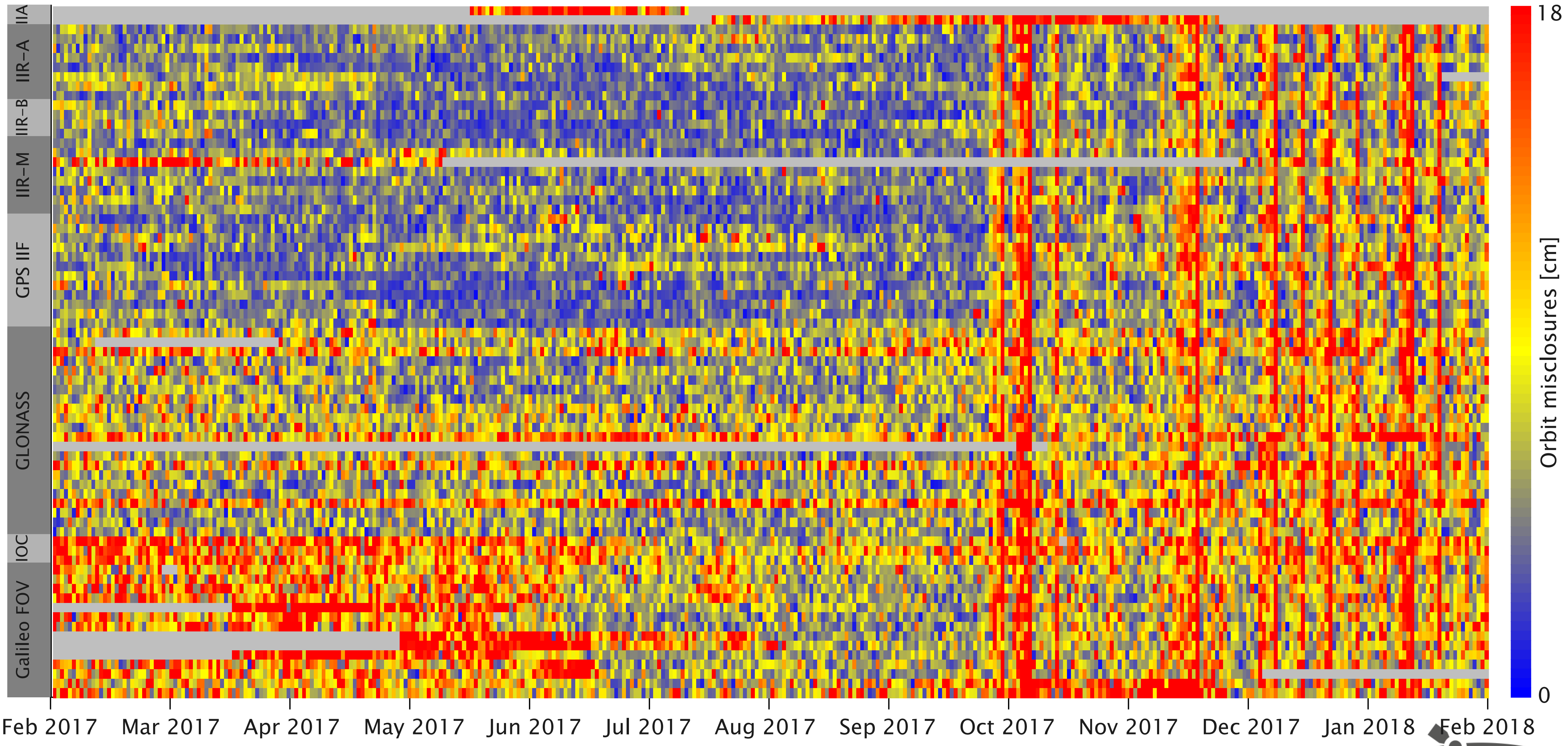
Monoscale vs. Smartscale/Multiscale

Co-variances between scale factors due to:

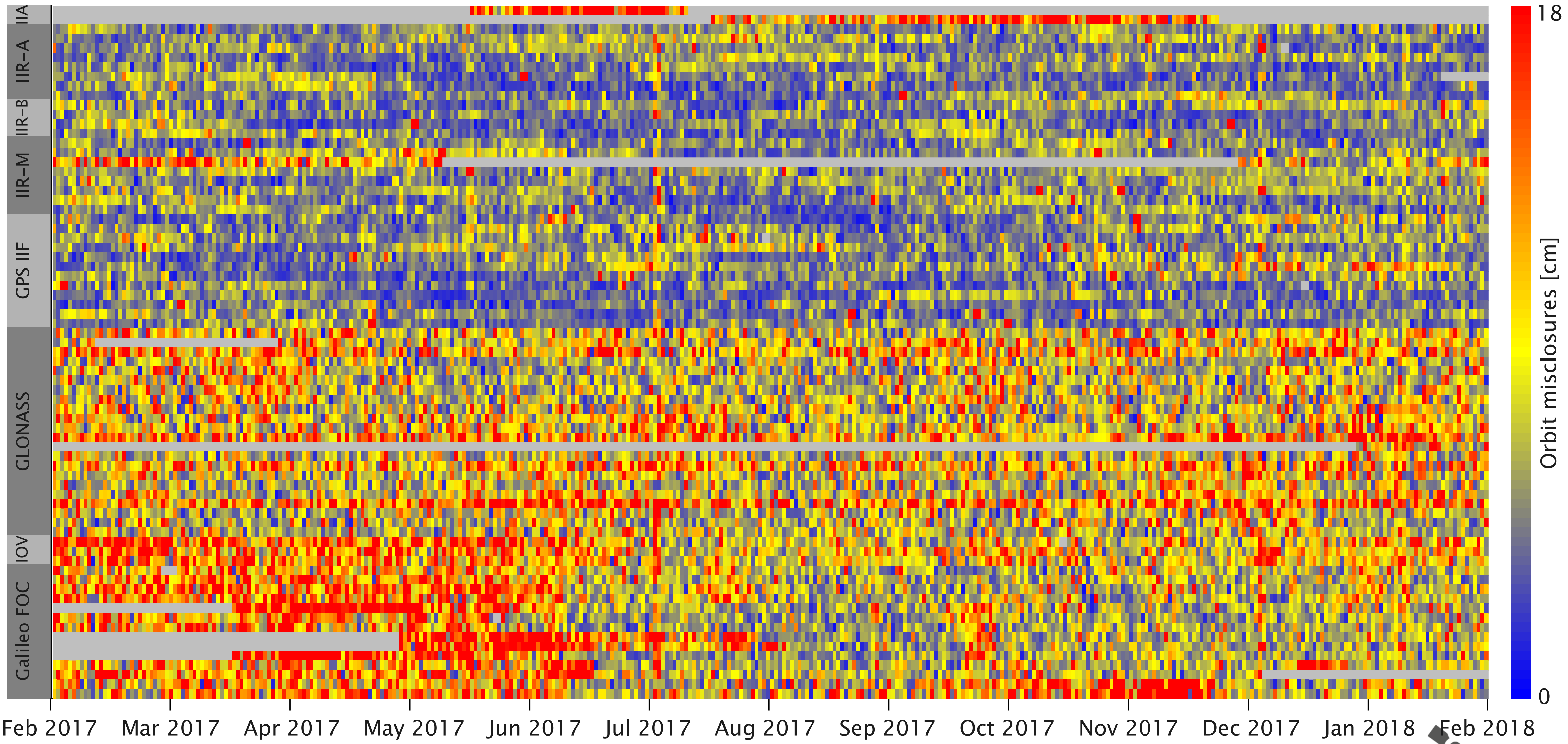
- Similar optical properties
- Parallel plates
- Attitude geometry
- Parallel resultant force



Orbit Misclosures: ECOM-only (1-day solutions)



Orbit Misclosures: ECOM-plus-boxwing (1-day solutions)



Orbit Misclosures: ECOM-plus-scaled-boxwing

Conclusions & Future Work

Conclusions

- Able to stack scale factors for long periods of time
- Able to distinguish/validate thermal re-radiation
- Number of scale factors per satellite depends on characteristics
- Improvements at the daily solution level

Forward Work

QUESTIONS?