GNSS Satellite Force Modeling: Unveiling the Origins of the Galileo Y-bias

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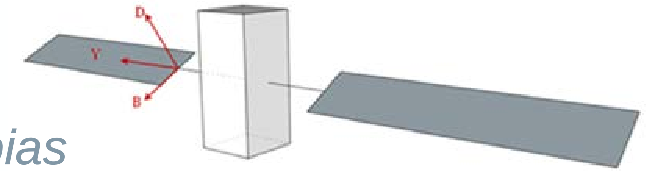
26/05/2022

Background

- Significant unpredicted acceleration observed along the solar panel (SP) axis of the GPS satellites (Lichten 1987, Fliegel 1992)
  - Because of Y-axis being aligned with SP axis, the effect became known as *Y-bias*



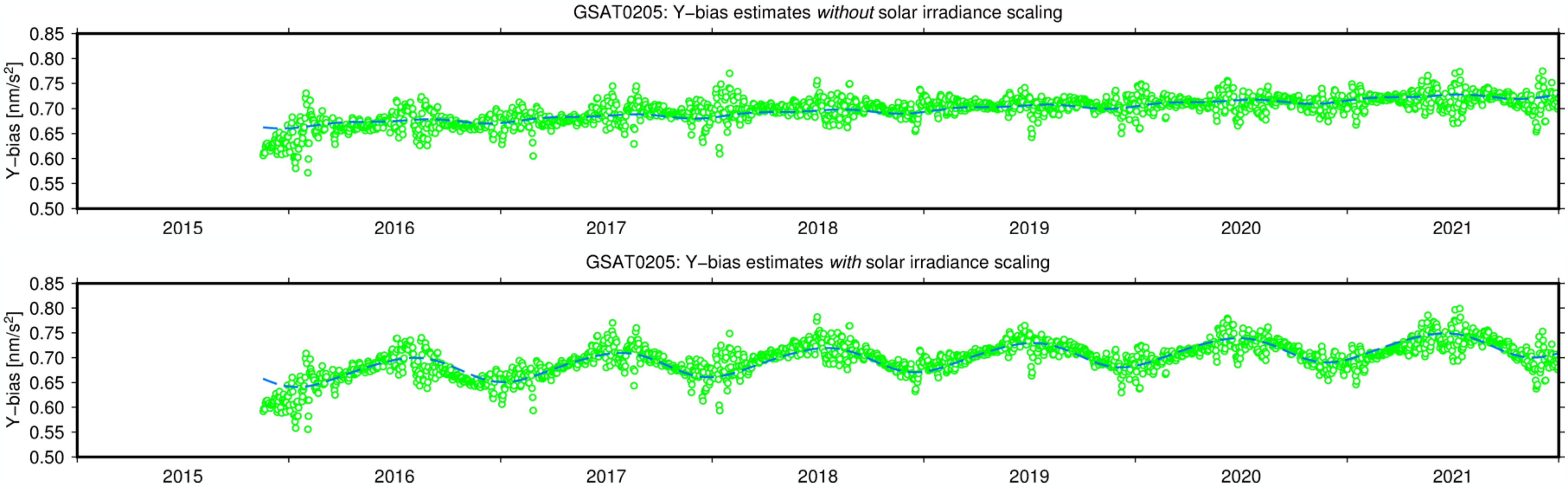
- Y-bias was found to be present on most GNSS spacecraft
- Y-bias vitally important for precise orbit determination, despite its low magnitude (< 1 nm/s^2)
  - One percent of the sum of all non-gravitational forces acting on a GNSS spacecraft
  - Exact value varies from satellite to satellite and over time
- Reasons for existence of Y-bias that have been suggested in GPS/Galileo literature are:
  - Mechanical misalignment of solar panels with respect to spacecraft body (Fliegel 1992)
  - Misalignment of solar panels with respect to the Sun due to a non-nominal attitude (Fliegel 1992)
  - Imbalance in radiated power between opposite ±Y radiators (Fliegel 1992)
  - Difference in timescale rates (Deines 1997)
  - Irregular shape of spacecraft bus (Li 2020)

Motivation & Approach

- Accurate knowledge about Y-bias and its temporal variability particularly relevant for Galileo system to fulfil its once-in-a-lifetime station-keeping maneuver requirements
- No consensus among GNSS experts on physical mechanism responsible for Galileo Y-bias
- Goal here is to characterize Galileo Y-bias and shed light on its origin
- Approach:
  - Use Galileo tracking data from daily set of 150 ground stations to produce 24-hour orbit SP3 files
  - Use orbit positions from daily SP3 as pseudo observations to estimate Y-bias in 5-day arc scenario
  - Use satellite laser ranging (SLR) normal points to estimate Y-bias in 20-day arc scenario
  - Calculate Y-bias based on surface properties and telemetry readings from payload (PL) and platform (PF) units

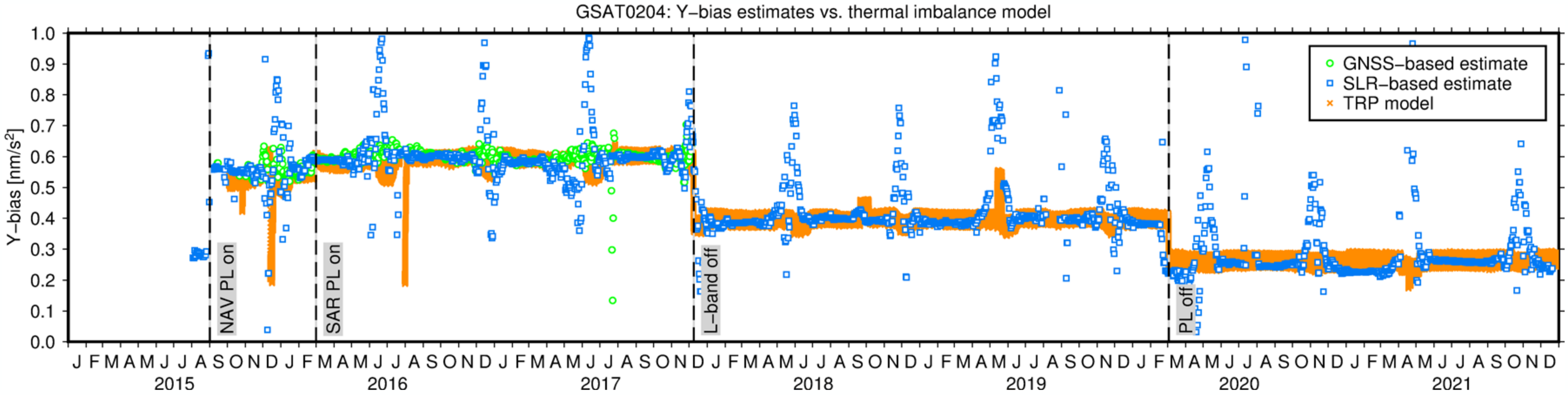
Origin & Characteristics of Galileo Y-bias

- Origin: Imbalance in radiated power between opposite ±Y radiators
  - Modular design on FOC – PL and PF units located on two panels on opposite sides of satellite body
  - Difference between +Y and -Y radiator of about 240 W (0.7 nm/s²) during normal mode operation
- Constant thermal force – no need to account for change in solar irradiance as Earth-Sun distance changes or satellite passes eclipse



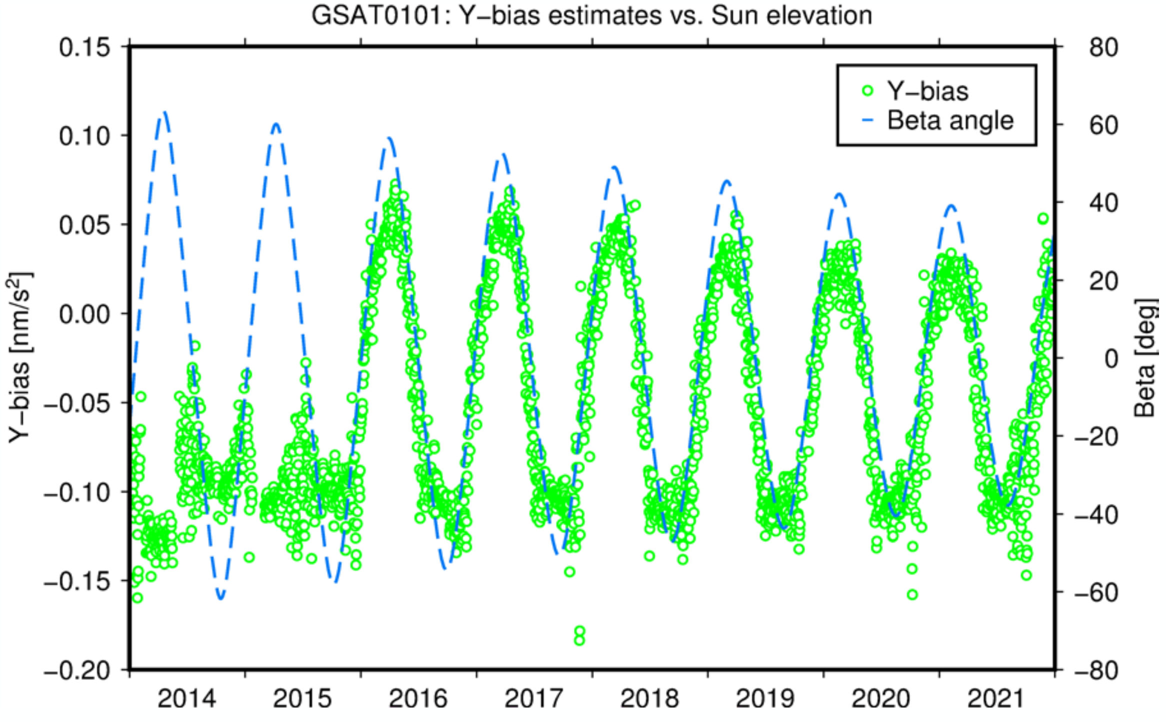
Origin & Characteristics of Galileo Y-bias (cont'd)

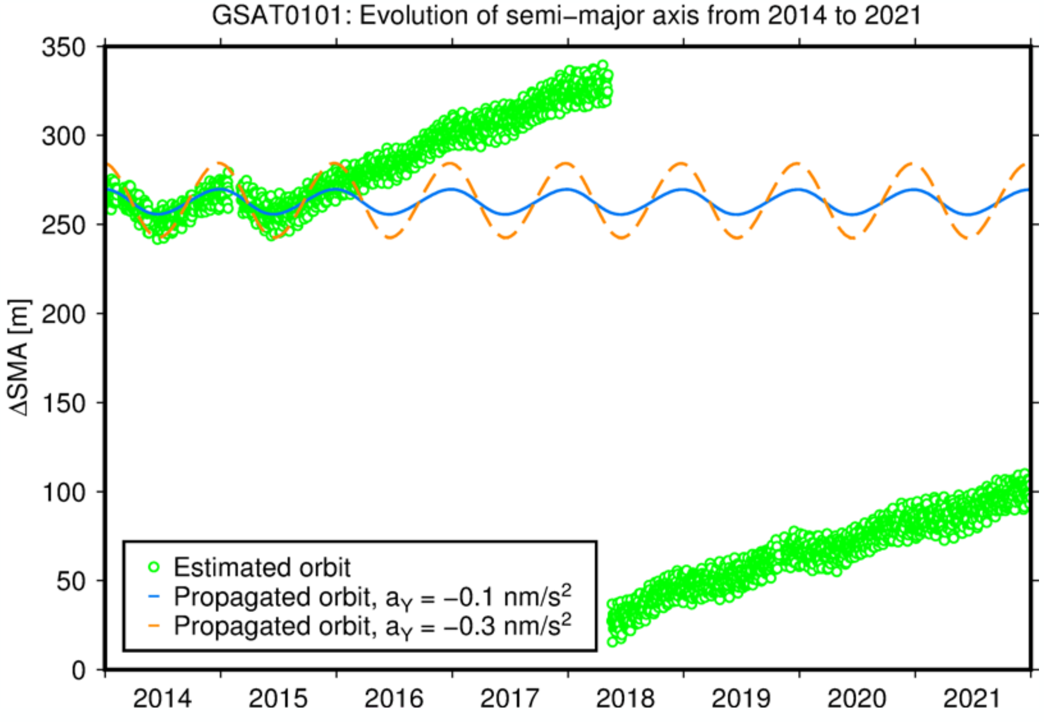
- Evaluation of Y-bias existing on Galileo spare vehicle GSAT0204
  - Comparison of thermal-derived Y-biases against estimates from GNSS/SLR long arc analyses
- Discontinuities due to changes in amount of dissipated heat after units being (de-)activated
  - Sep 2015: Navigation PL turned on ▸ +0.26 nm/s²
  - Mar 2016: Search-and-Rescue PL turned on ▸ +0.07 nm/s²
  - Dec 2017: L-band signal turned off ▸ -0.20 nm/s²
  - Mar 2020: All PL units turned off ▸ -0.13 nm/s²



Attitude-related Y-bias variations on GSAT0101

- Y-bias reasonably constant around -0.1 nm/s² until January 2016
  - Little effect on long-term orbit stability, sum of Y-bias accelerations averages out over one year
- Yearly variations between -0.10 and +0.05 nm/s² from January 2016 onwards
  - Effect leading to secular increase in semi-major axis of +25 m/year

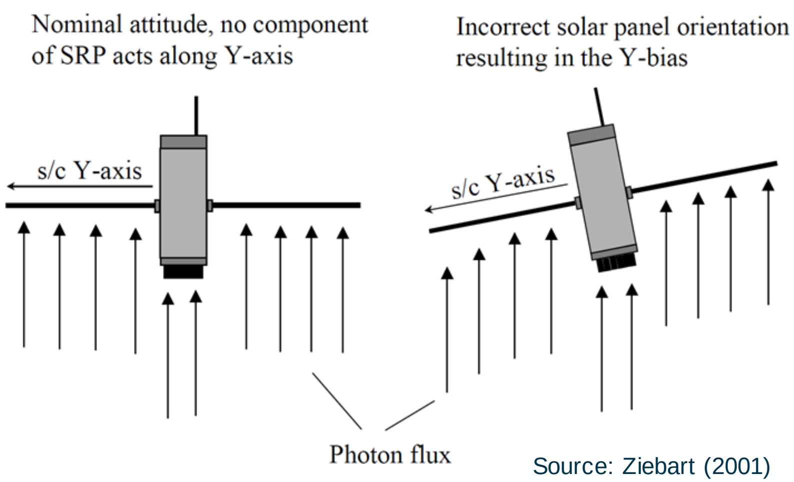




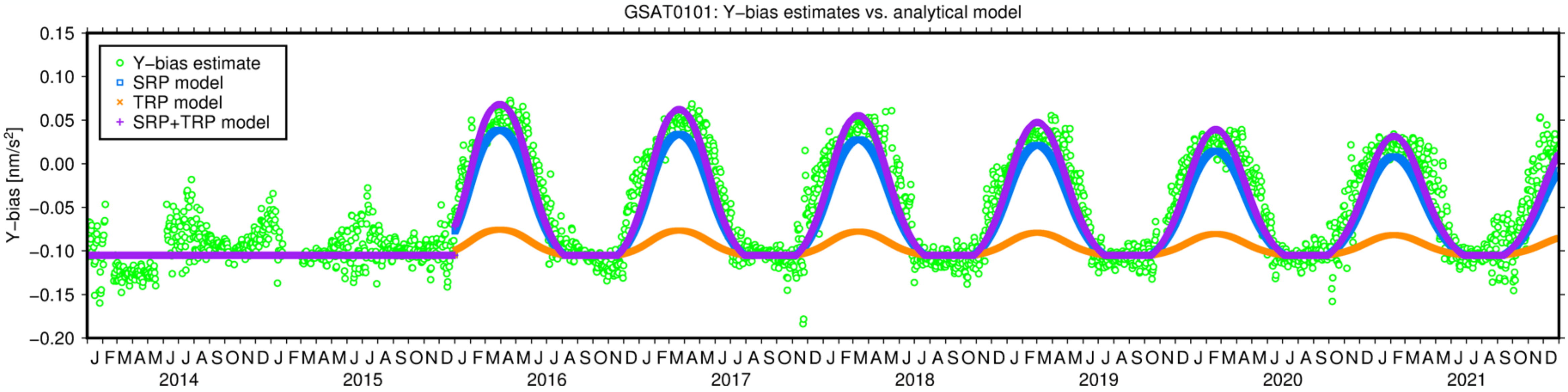
Analytical Y-bias model for GSAT0101

- Annual periodic signal in satellite yaw since January 2016
- Departure from nominal yaw resulting in inclination $\Delta\theta$ of Y-axis against solar ray direction of a few tenth of a degree
- Y-bias as sum of forces over SP areas, projected on Y-axis:

$$a_y(\Delta\theta) = \Delta\theta \cdot \sum_{i=1}^{5} \underbrace{\frac{2A_iE}{mc} \cdot \left(\frac{\delta_i}{3} + \rho_i\right)}_{\text{SRP}} + \underbrace{\frac{2A_i\sigma}{3mc} \cdot \left(\epsilon_{f,i}T_{f,i}^4 - \epsilon_{r,i}T_{r,i}^4\right)}_{\text{TRP}}$$



Source: Ziebart (2001)



Summary & Conclusions

- First hard evidence that Galileo satellite Y-bias is of thermal origin
  - Imbalance in radiated power on FOC spacecraft between opposite ±Y radiators of about 240 W
  - Solar panel orientation errors and the like only play a secondary role
  - Change in amount of heat followed by (de-)activation of electrical subsystems does directly impact Y-bias
- Implications for Galileo precise orbit determination:
  - Y-bias parameter has (still) to be determined as part of empirical force model
  - Direct estimation – no scaling with satellite-Sun distance as for other empirical radiation parameters
  - Y-bias force should be on all the time including during eclipse
- Attitude variations as present on GSAT0101 can give rise to Y-bias variations
  - Y-bias and solar panel orientation error are linearly related – another long-standing hypothesis in GNSS orbit dynamics that is now proven

References

- Fliegel, H. F., Gallini, T. E., Swift, E. R. (1992): "Global Positioning System Radiation Force Model for Geodetic Applications", Journal of Geophysical Research, Vol. 97, No. 1, pp. 559-568.
- Deines, S. (1997): "Apparent Correlation of the Global Positioning System Y-Bias to the Divergence Between Timescales", Proceedings of the 10th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GPS 1997), Kansas City, MO, September 1997, pp. 1107-1111.
- Lichten, S. M. and Border, J. S. (1987): "Strategies for High Precision Global Positioning System Orbit Determination", Journal of Geophysical Research, Vol. 92, No. B12, pp. 12751-12762.
- Li, Z. and Ziebart, M. (2020): “Uncertainty analysis on direct solar radiation pressure modelling for GPS IIR and Galileo FOC satellites”. Advances in Space Research, Vol. 66, No. 4.
- Ziebart, M. (2001): “High precision analytical solar radiation pressure modelling for GNSS spacecraft”. Ph.D. Thesis, University of East London.