Comparison and generalization of GNSS satellite attitude models

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EGU General Assembly 2021 (vEGU21: Gather Online)

2021-04-28

DOI: 10.5194/egusphere-egu21-7825

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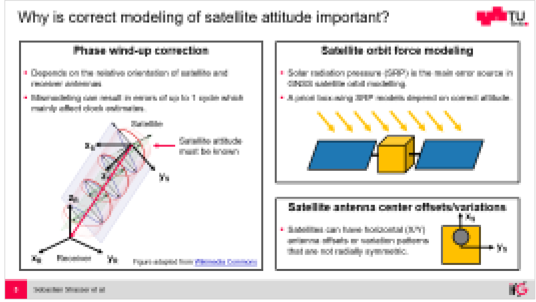
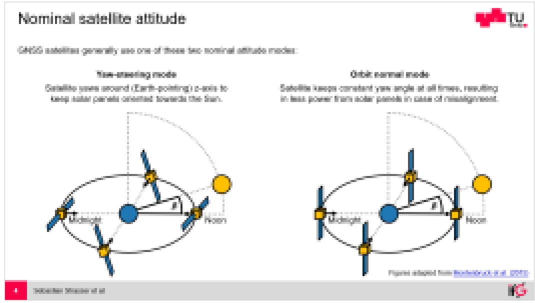
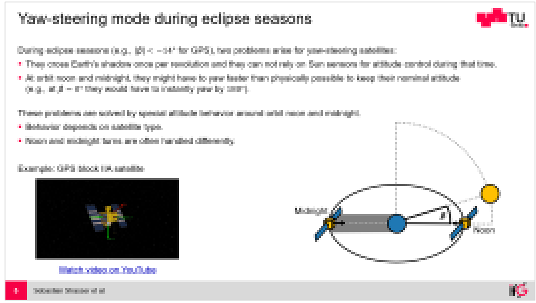
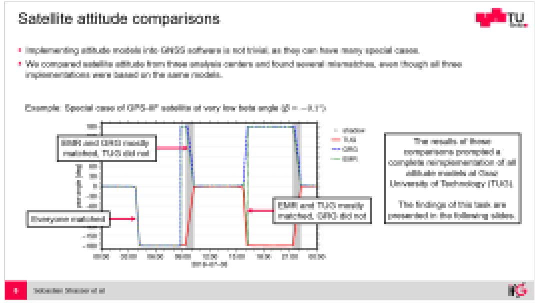
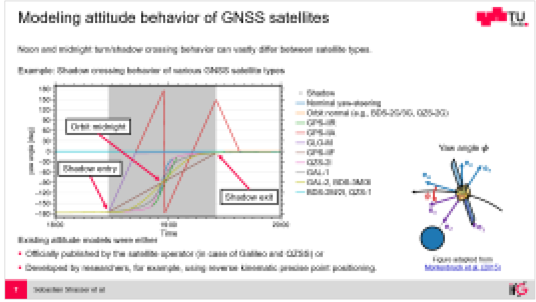


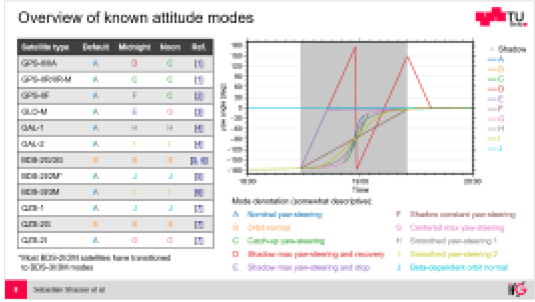


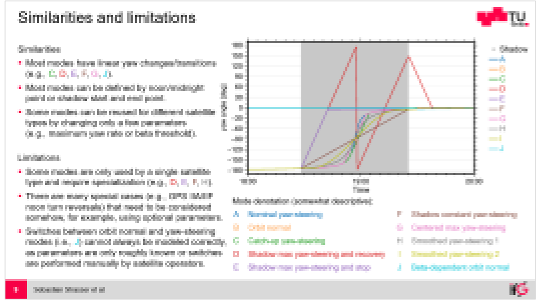




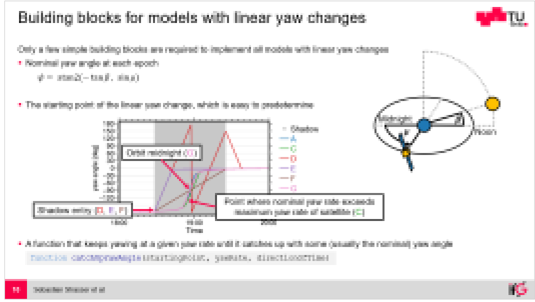
2) Overview and comparison of attitude modes

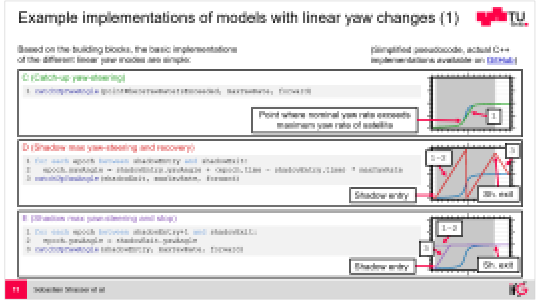


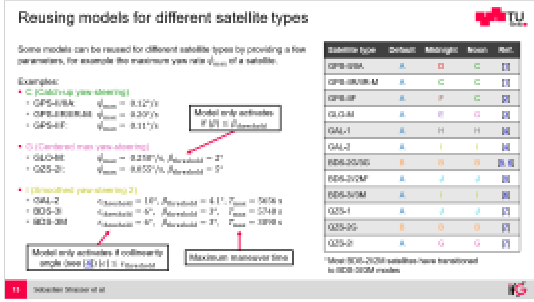


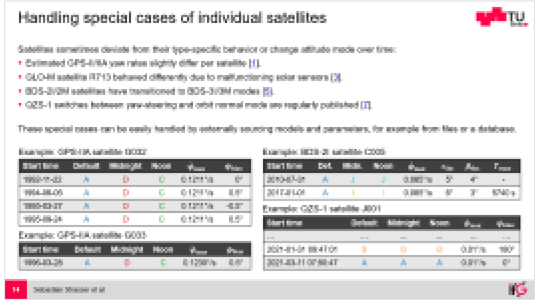


3) Implementation, model parameters, and special cases









Why is correct modeling of satellite attitude important?

Phase wind-up correction

- Depends on the relative orientation of satellite and receiver antennas
- Mismodeling can result in errors of up to 1 cycle which mainly affect clock estimates.

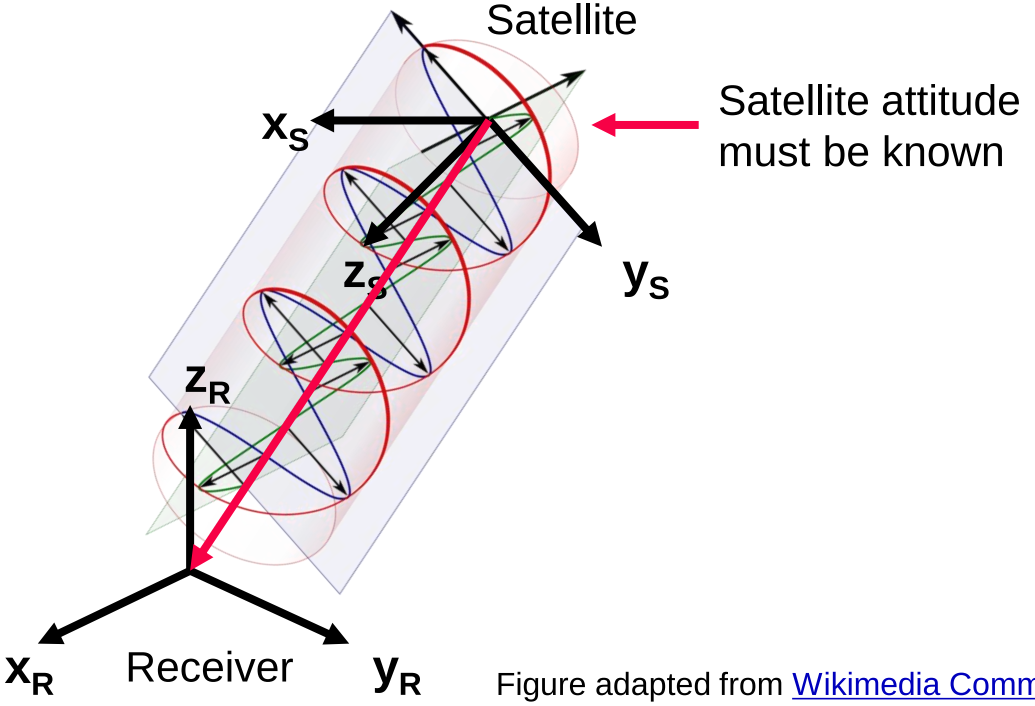
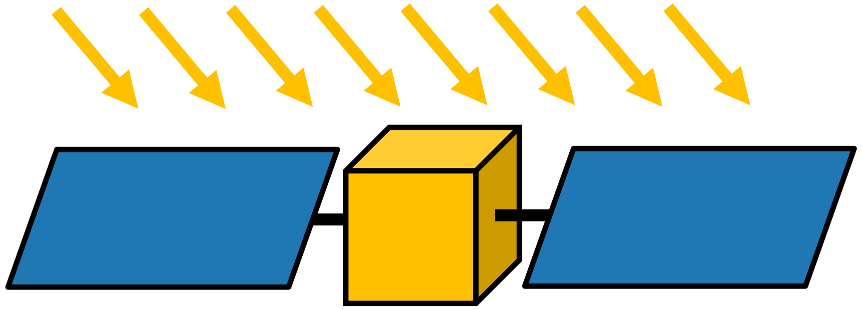


Figure adapted from Wikimedia Commons

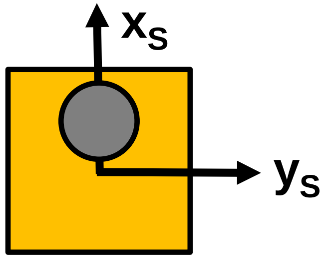
Satellite orbit force modeling

- Solar radiation pressure (SRP) is the main error source in GNSS satellite orbit modelling.
- A priori box-wing SRP models depend on correct attitude.



Satellite antenna center offsets/variations

- Satellites can have horizontal (X/Y) antenna offsets or variation patterns that are not radially symmetric.

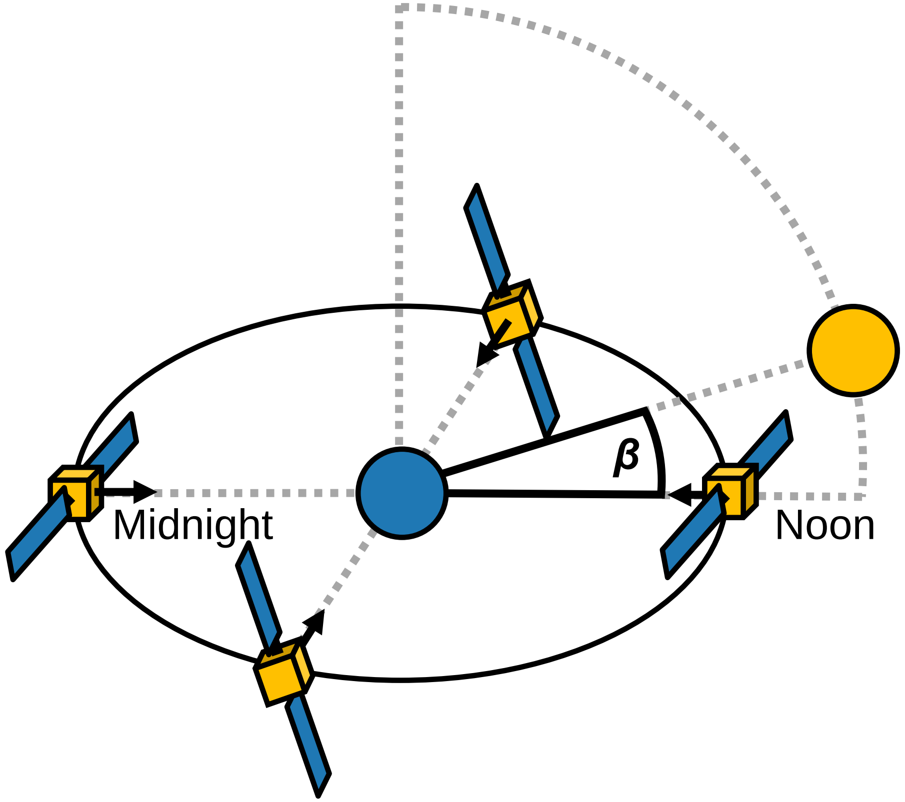


Nominal satellite attitude

GNSS satellites generally use one of these two nominal attitude modes:

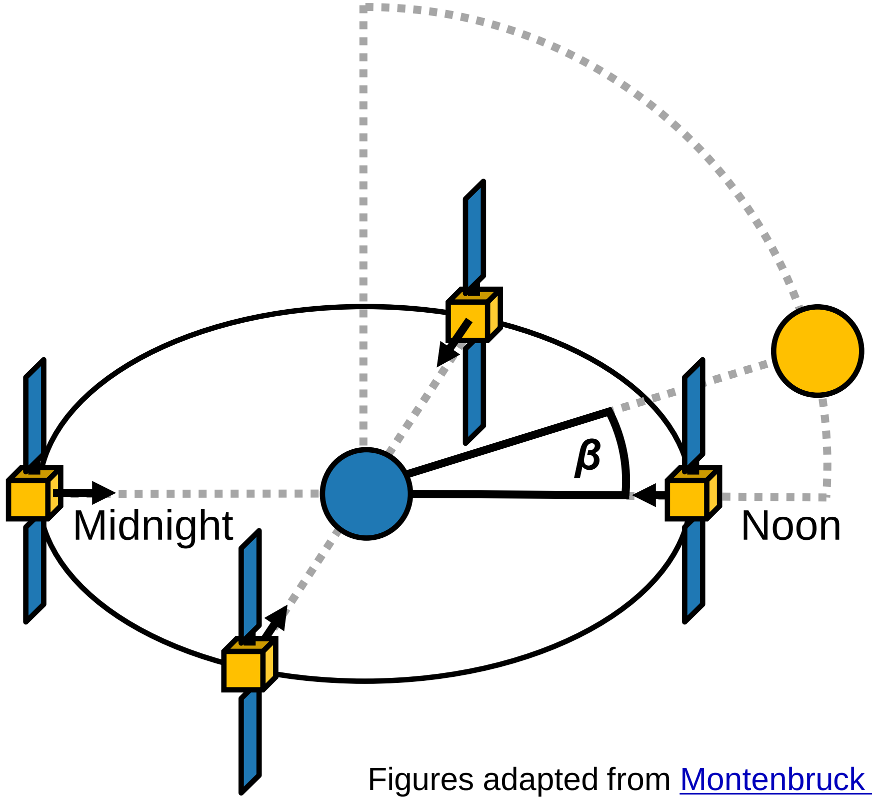
Yaw-steering mode

Satellite yaws around (Earth-pointing) z-axis to keep solar panels oriented towards the Sun.



Orbit normal mode

Satellite keeps constant yaw angle at all times, resulting in less power from solar panels in case of misalignment.



Figures adapted from Montenbruck et al. (2015)

Yaw-steering mode during eclipse seasons

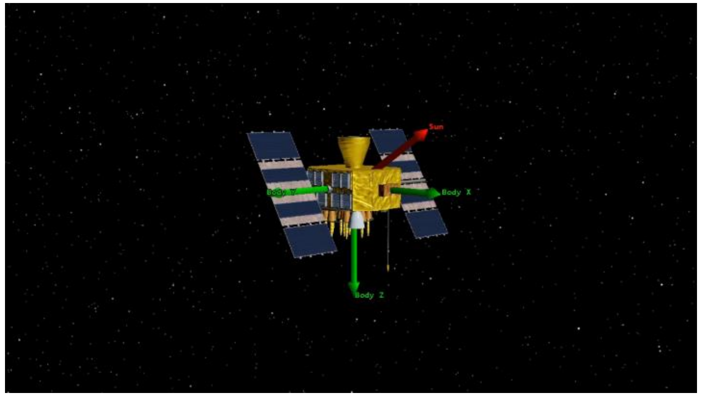
During eclipse seasons (e.g., $|\beta| < {\sim}14°$ for GPS), two problems arise for yaw-steering satellites:

- They cross Earth's shadow once per revolution and they can not rely on Sun sensors for attitude control during that time.
- At orbit noon and midnight, they might have to yaw faster than physically possible to keep their nominal attitude (e.g., at $\beta = 0°$ they would have to instantly yaw by $180°$).

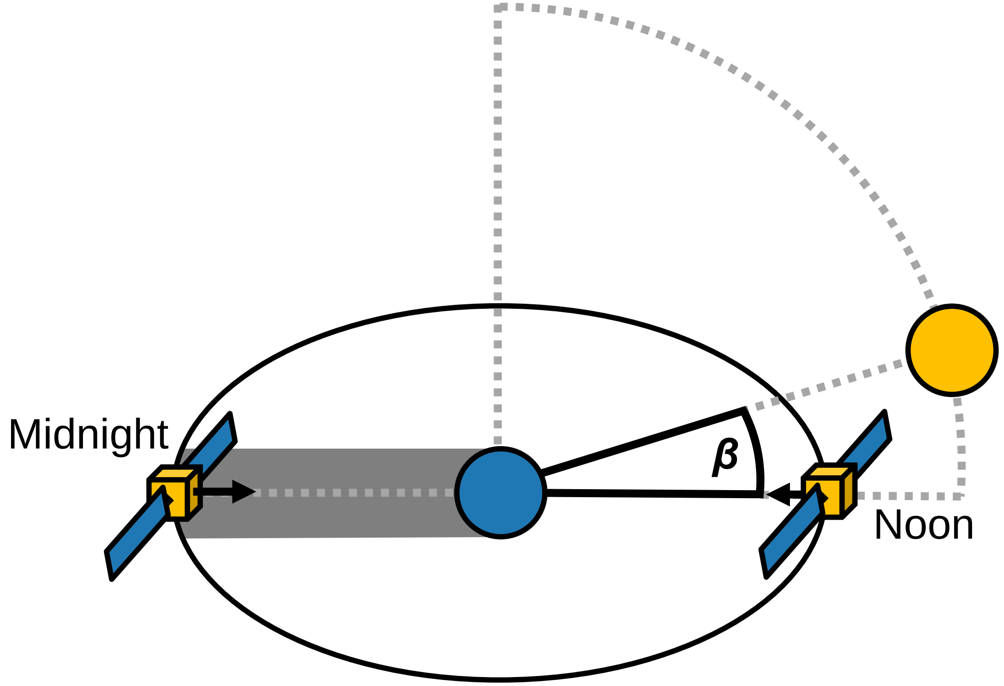
These problems are solved by special attitude behavior around orbit noon and midnight.

- Behavior depends on satellite type.
- Noon and midnight turns are often handled differently.

Example: GPS block IIA satellite



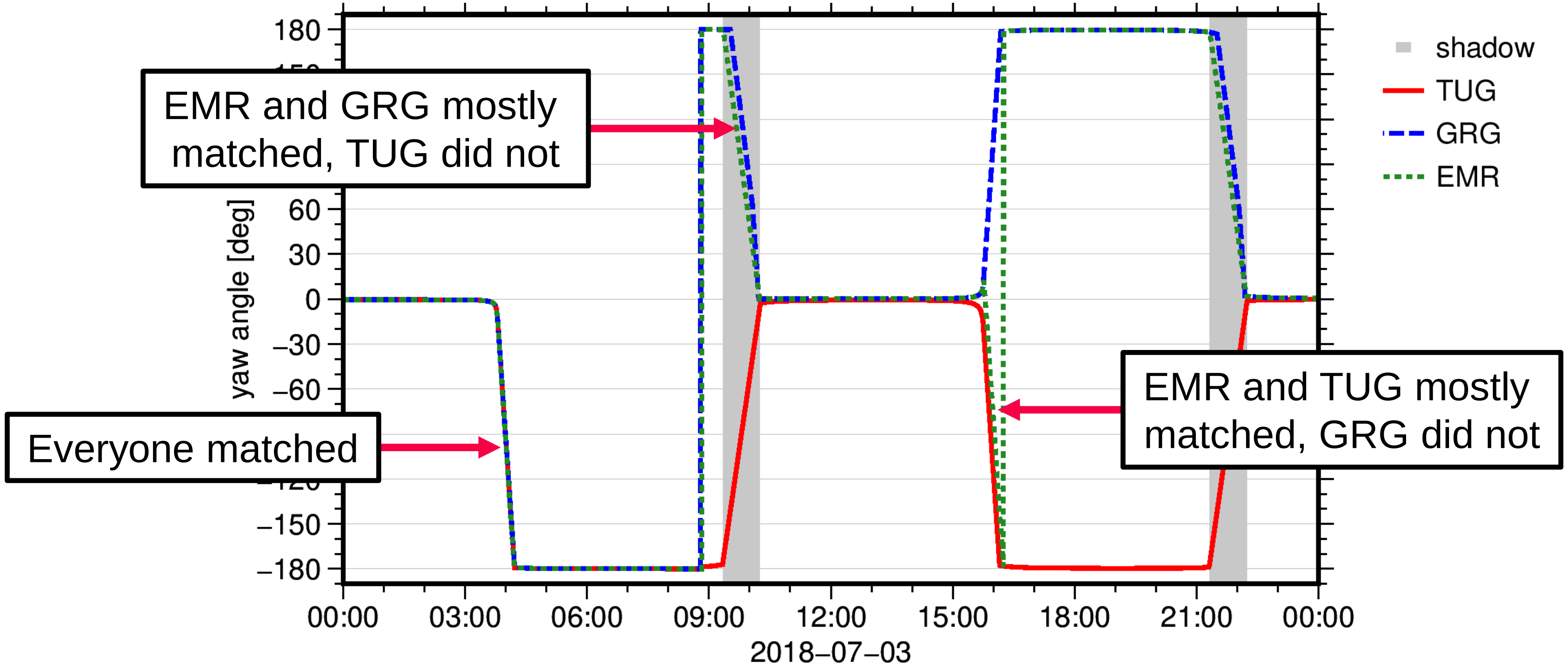
Watch video on YouTube



Satellite attitude comparisons

- Implementing attitude models into GNSS software is not trivial, as they can have many special cases.
- We compared satellite attitude from three analysis centers and found several mismatches, even though all three implementations were based on the same models.

Example: Special case of GPS-IIF satellite at very low beta angle ($\beta \approx -0.1°$)



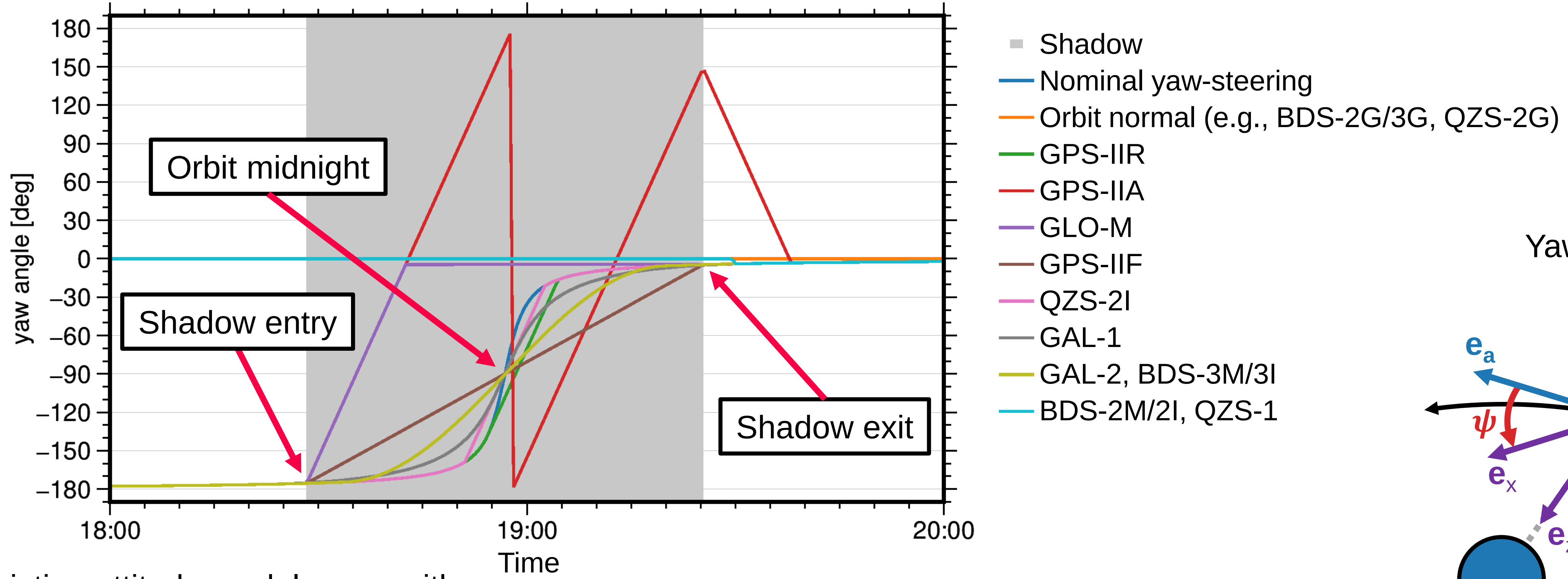
The results of these comparisons prompted a complete reimplementation of all attitude models at Graz University of Technology (TUG).

The findings of this task are presented in the following slides.

Modeling attitude behavior of GNSS satellites

Noon and midnight turn/shadow crossing behavior can vastly differ between satellite types.

Example: Shadow crossing behavior of various GNSS satellite types



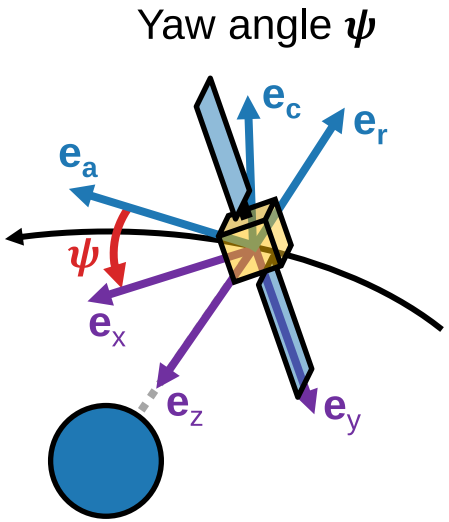


Figure adapted from
Montenbruck et al. (2015)

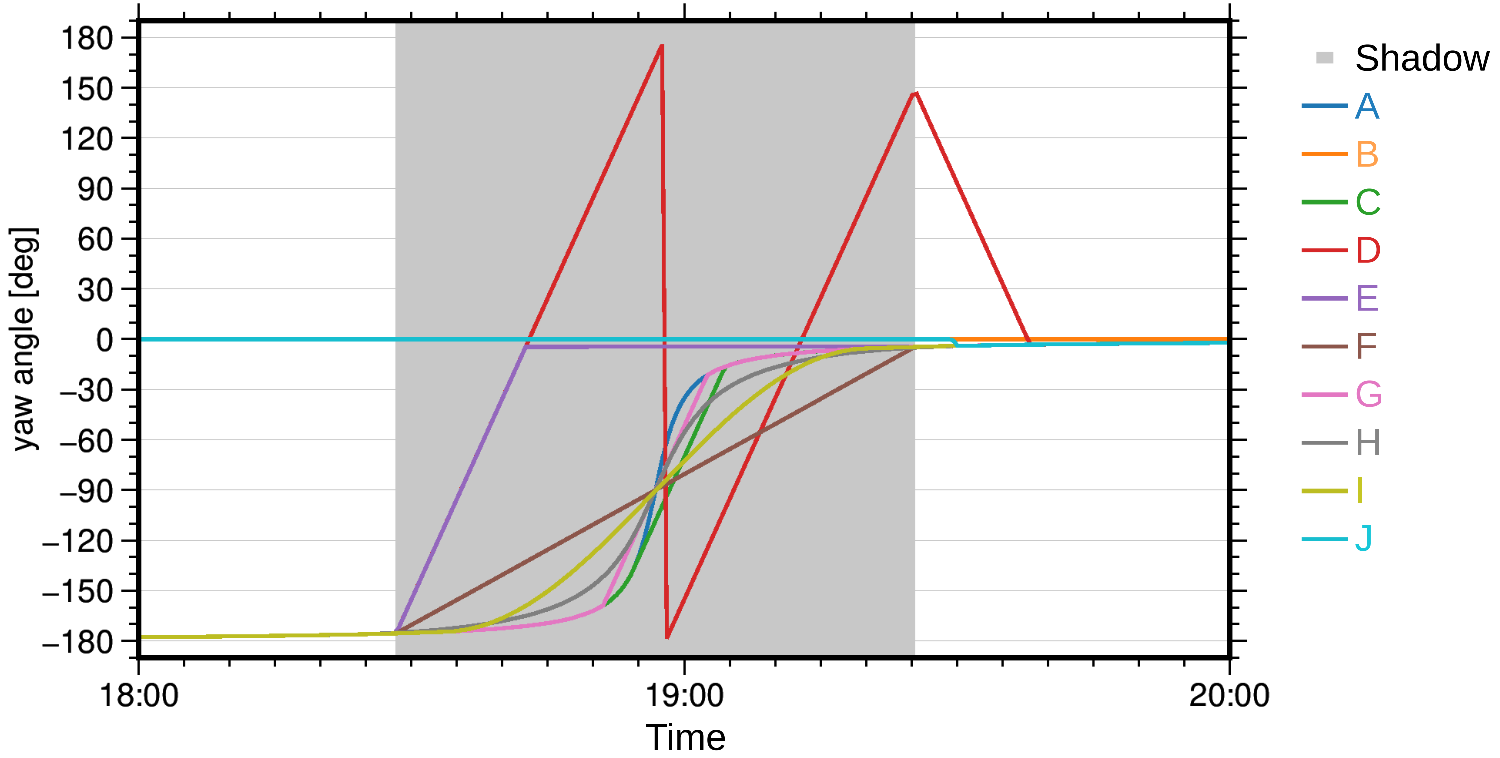
Existing attitude models were either

- Officially published by the satellite operator (in case of Galileo and QZSS) or
- Developed by researchers, for example, using reverse kinematic precise point positioning.

Overview of known attitude modes

Satellite type	Default	Midnight	Noon	Ref.
GPS-II/IIA	A	D	C	[1]
GPS-IIR/IIR-M	A	C	C	[1]
GPS-IIF	A	F	C	[2]
GLO-M	A	E	G	[3]
GAL-1	A	H	H	[4]
GAL-2	A	I	I	[4]
BDS-2G/3G	B	B	B	[5, 6]
BDS-2I/2M*	A	J	J	[5]
BDS-3I/3M	A	I	I	[6]
QZS-1	A	J	J	[7]
QZS-2G	B	B	B	[7]
QZS-2I	A	G	G	[7]

*Most BDS-2I/2M satellites have transitioned to BDS-3I/3M modes



Mode denotation (somewhat descriptive):

- A Nominal yaw-steering
- B Orbit normal
- C Catch-up yaw-steering
- D Shadow max yaw-steering and recovery
- E Shadow max yaw-steering and stop
- F Shadow constant yaw-steering
- G Centered max yaw-steering
- H Smoothed yaw-steering 1
- I Smoothed yaw-steering 2
- J Beta-dependent orbit normal

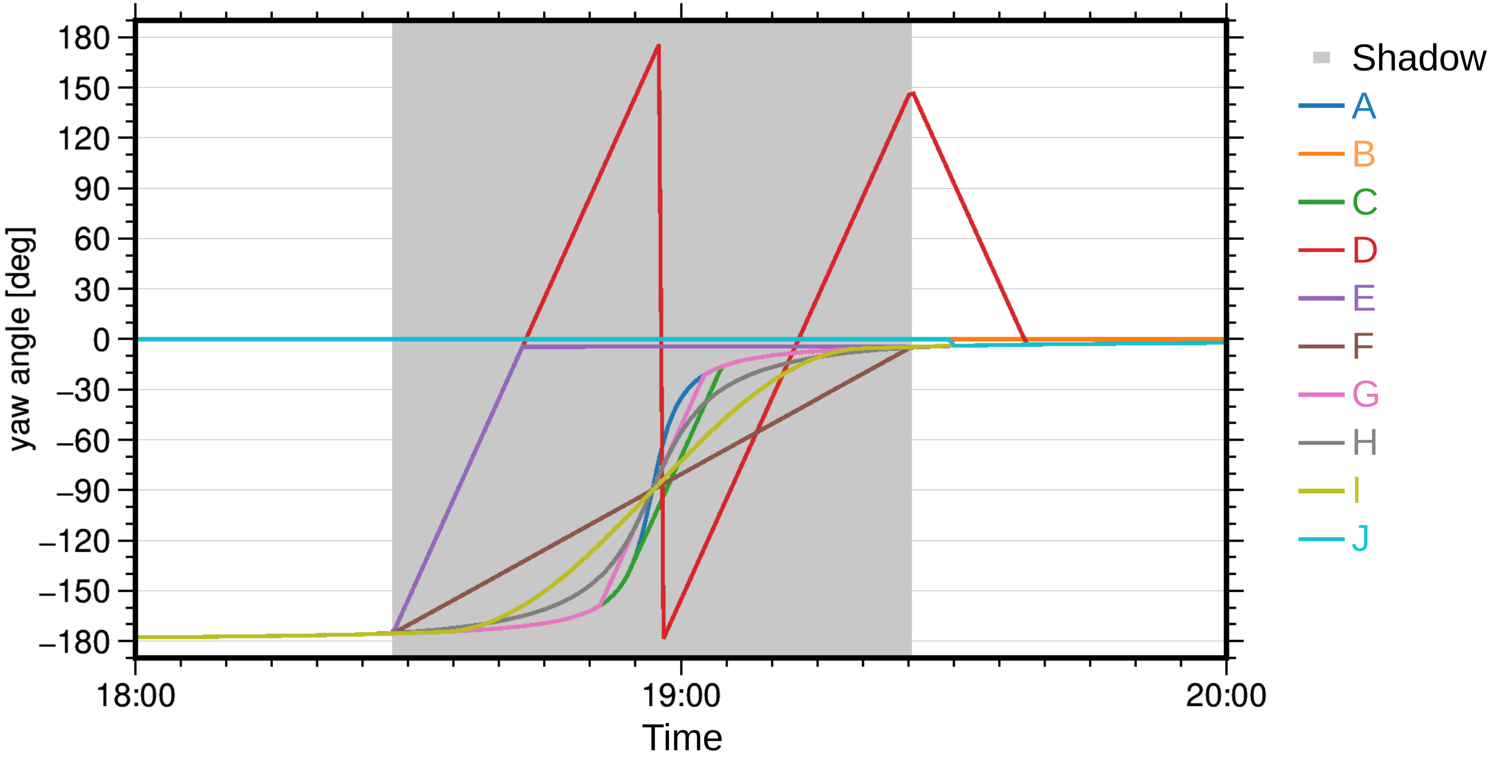
Similarities and limitations

Similarities

- Most modes have linear yaw changes/transitions (e.g., C, D, E, F, G, J).
- Most modes can be defined by noon/midnight point or shadow start and end point.
- Some modes can be reused for different satellite types by changing only a few parameters (e.g., maximum yaw rate or beta threshold).

Limitations

- Some modes are only used by a single satellite type and require specialization (e.g., D, E, F, H).
- There are many special cases (e.g., GPS IIA/IIF noon turn reversals) that need to be considered somehow, for example, using optional parameters.
- Switches between orbit normal and yaw-steering modes (i.e., J) cannot always be modeled correctly, as parameters are only roughly known or switches are performed manually by satellite operators.



Mode denotation (somewhat descriptive):

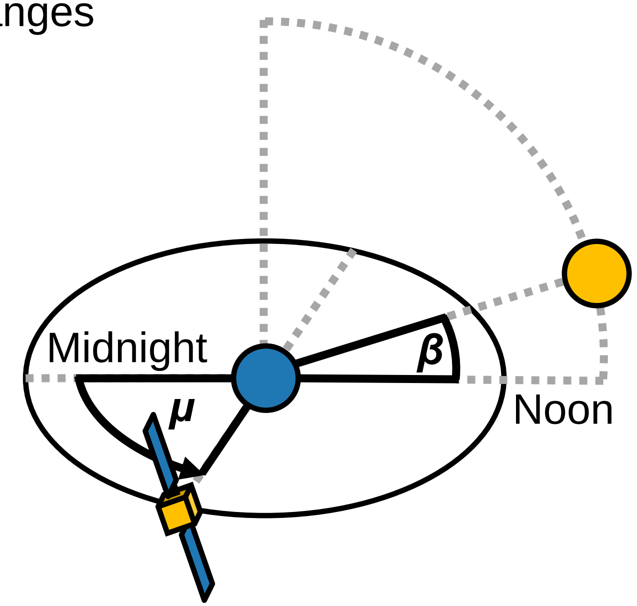
A	Nominal yaw-steering	F	Shadow constant yaw-steering
B	Orbit normal	G	Centered max yaw-steering
C	Catch-up yaw-steering	H	Smoothed yaw-steering 1
D	Shadow max yaw-steering and recovery	I	Smoothed yaw-steering 2
E	Shadow max yaw-steering and stop	J	Beta-dependent orbit normal

Building blocks for models with linear yaw changes

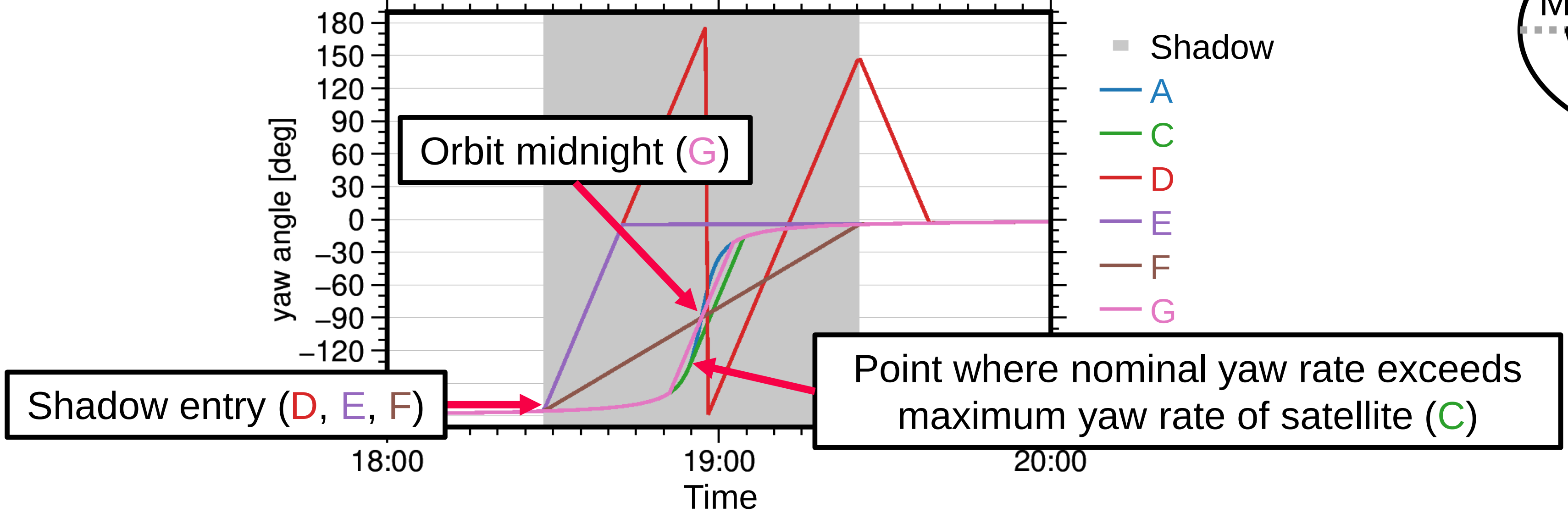
Only a few simple building blocks are required to implement all models with linear yaw changes

- Nominal yaw angle at each epoch

$$\psi = \operatorname{atan2}(-\tan\beta\,,\ \sin\mu)$$



- The starting point of the linear yaw change, which is easy to predetermine



- A function that keeps yawing at a given yaw rate until it catches up with some (usually the nominal) yaw angle

```
function catchUpYawAngle(startingPoint, yawRate, directionOfTime)
```

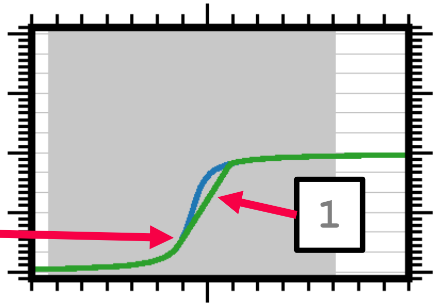
Example implementations of models with linear yaw changes (1)

Based on the building blocks, the basic implementations of the different linear yaw modes are simple:

(Simplified pseudocode, actual C++ implementations available on GitHub)

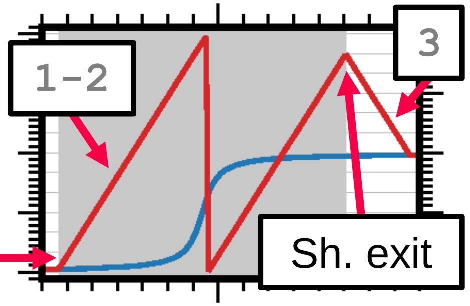
C (Catch-up yaw-steering)

```
1 catchUpYawAngle(pointWhereYawRateIsExceeded, maxYawRate, forward)
```



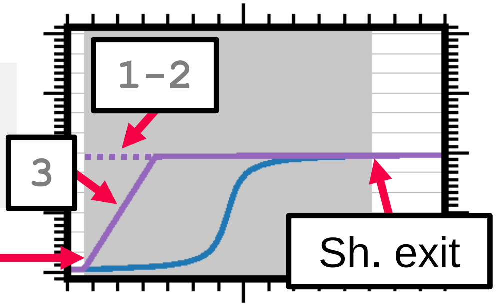
D (Shadow max yaw-steering and recovery)

```
1 for each epoch between shadowEntry and shadowExit:
2   epoch.yawAngle = shadowEntry.yawAngle + (epoch.time - shadowEntry.time) * maxYawRate
3 catchUpYawAngle(shadowExit, maxYawRate, forward)
```



E (Shadow max yaw-steering and stop)

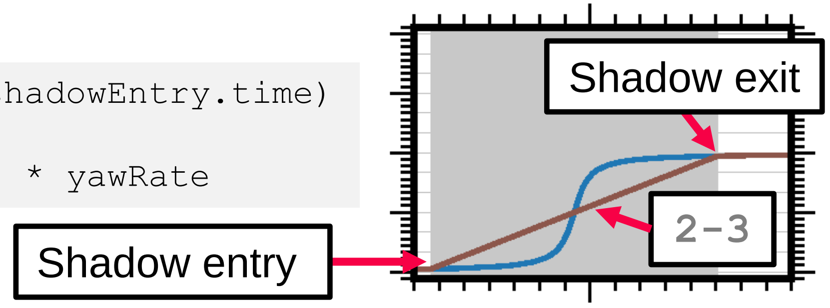
```
1 for each epoch between shadowEntry+1 and shadowExit:
2   epoch.yawAngle = shadowExit.yawAngle
3 catchUpYawAngle(shadowEntry, maxYawRate, forward)
```



Example implementations of models with linear yaw changes (2)

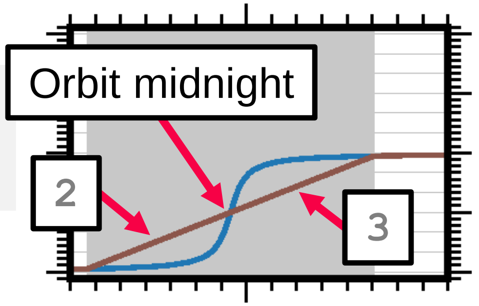
F (Shadow constant yaw-steering)

```
yawRate = (shadowExit.yawAngle-shadowEntry.yawAngle) / (shadowExit.time-shadowEntry.time)
for each epoch between shadowEntry and shadowExit:
  epoch.yawAngle = shadowEntry.yawAngle + (epoch.time - shadowEntry.time) * yawRate
```



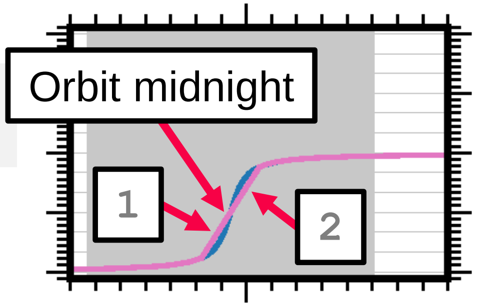
Alternatively (similar to G):

```
yawRate = (shadowExit.yawAngle-shadowEntry.yawAngle) / (shadowExit.time-shadowEntry.time)
catchUpYawAngle(orbitMidnight, yawRate, backward)
catchUpYawAngle(orbitMidnight, yawRate, forward)
```



G (Centered max yaw-steering)

```
catchUpYawAngle(orbitMidnight, maxYawRate, backward)
catchUpYawAngle(orbitMidnight, maxYawRate, forward)
```



Reusing models for different satellite types

Some models can be reused for different satellite types by providing a few parameters, for example the maximum yaw rate $\dot{\psi}_{\text{max}}$ of a satellite.

Examples:

- C (Catch-up yaw-steering)
  - GPS-II/IIA: $\dot{\psi}_{\text{max}} = 0.12°/\text{s}$
  - GPS-IIR/IIR-M: $\dot{\psi}_{\text{max}} = 0.20°/\text{s}$
  - GPS-IIF: $\dot{\psi}_{\text{max}} = 0.11°/\text{s}$
- G (Centered max yaw-steering)
  - GLO-M: $\dot{\psi}_{\text{max}} = 0.250°/\text{s},\ \beta_{\text{threshold}} = 2°$
  - QZS-2I: $\dot{\psi}_{\text{max}} = 0.055°/\text{s},\ \beta_{\text{threshold}} = 5°$
- I (Smoothed yaw-steering 2)
  - GAL-2 $\epsilon_{\text{threshold}} = 10°,\ \beta_{\text{threshold}} = 4.1°,\ T_{\text{max}} = 5656\ \text{s}$
  - BDS-3I $\epsilon_{\text{threshold}} = 6°,\ \beta_{\text{threshold}} = 3°,\ T_{\text{max}} = 5740\ \text{s}$
  - BDS-3M $\epsilon_{\text{threshold}} = 6°,\ \beta_{\text{threshold}} = 3°,\ T_{\text{max}} = 3090\ \text{s}$

Model only activates if $|\beta| \le \beta_{\text{threshold}}$

Model only activates if collinearity angle (see [4]) $|\epsilon| \le \epsilon_{\text{threshold}}$

Maximum maneuver time

Satellite type	Default	Midnight	Noon	Ref.
GPS-II/IIA	A	D	C	[1]
GPS-IIR/IIR-M	A	C	C	[1]
GPS-IIF	A	F	C	[2]
GLO-M	A	E	G	[3]
GAL-1	A	H	H	[4]
GAL-2	A	I	I	[4]
BDS-2G/3G	B	B	B	[5, 6]
BDS-2I/2M*	A	J	J	[5]
BDS-3I/3M	A	I	I	[6]
QZS-1	A	J	J	[7]
QZS-2G	B	B	B	[7]
QZS-2I	A	G	G	[7]

*Most BDS-2I/2M satellites have transitioned to BDS-3I/3M modes

Handling special cases of individual satellites

Satellites sometimes deviate from their type-specific behavior or change attitude mode over time:

- Estimated GPS-II/IIA yaw rates slightly differ per satellite [1].
- GLO-M satellite R713 behaved differently due to malfunctioning solar sensors [3].
- BDS-2I/2M satellites have transitioned to BDS-3I/3M modes [5].
- QZS-1 switches between yaw-steering and orbit normal mode are regularly published [7].

These special cases can be easily handled by externally sourcing models and parameters, for example from files or a database.

Example: GPS-IIA satellite G032

Start time	Default	Midnight	Noon	$\dot{\psi}_{max}$	ψ_{bias}
1992-11-22	A	D	C	0.1211°/s	0°
1994-06-05	A	D	C	0.1211°/s	0.5°
1995-03-27	A	D	C	0.1211°/s	-0.5°
1995-09-24	A	D	C	0.1211°/s	0.5°

Example: GPS-IIA satellite G033

Start time	Default	Midnight	Noon	$\dot{\psi}_{max}$	ψ_{bias}
1996-03-28	A	D	C	0.1230°/s	0.5°

Example: BDS-2I satellite C005

Start time	Def.	Midn.	Noon	$\dot{\psi}_{max}$	$\epsilon_{thr.}$	$\beta_{thr.}$	T_{max}
2010-07-31	A	J	J	0.085°/s	5°	4°	-
2017-01-01	A	I	I	0.085°/s	6°	3°	5740 s

Example: QZS-1 satellite J001

Start time	Default	Midnight	Noon	$\dot{\psi}_{max}$	ψ_{bias}
…	…	…	…	…	…
2021-01-31 09:47:01	B	B	B	0.01°/s	180°
2021-03-11 07:50:47	A	A	A	0.01°/s	0°

Summary

GNSS satellites use various attitude modes that are not always trivial to implement into software packages.

We presented:

- An overview and comparison of known GNSS satellite attitude modes
- Ways to generalize the models, leading to less special code and (hopefully) less potential implementation errors
- A possible way to handle special cases without sacrificing generality

All attitude models have been implemented in TUG's open-source software GROOPS. The C++ source code, documentation, and an overview of model parameters are available on GitHub. A data set containing test output for all models is also available.

GROOPS is a software toolkit for tasks such as:

- Gravity field recovery
- GNSS network processing and PPP
- Satellite orbit determination
- Statistical analysis and visualization

You can learn more about the software in our EGU 2021 contribution on GROOPS:

Kvas et al. (2021) GROOPS: An open-source software package for GNSS processing and gravity field recovery. DOI: 10.5194/egusphere-egu21-10574

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