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Horizontal and vertical wind measurements from GOCE angular accelerations

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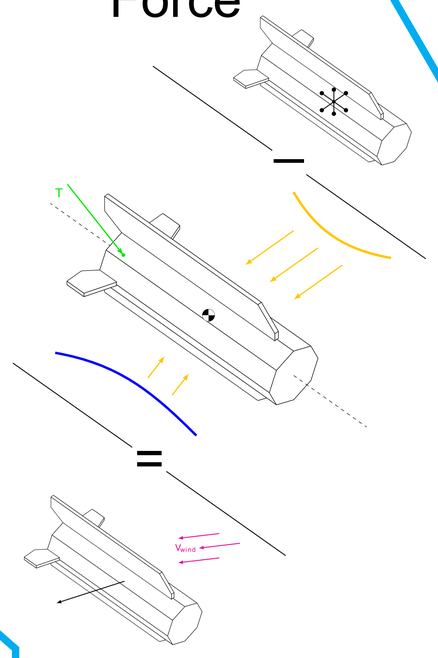
In the past the linear accelerations measured by GOCE have been used to derive the neutral density and cross-wind in the thermosphere [1]. On this poster the result of a similar effort is presented, in which the angular accelerations were used for the same purpose. Although modeling the disturbance torque requires a greater effort than modeling the force (compare the left and right wing), a similar level of detail can be obtained from both sources. Combining the forces and torques will in the future allow for estimating more aerodynamic parameters.
All time series are taken on May 28, 2011; the results section uses data from the whole month of May, 2011.

Force

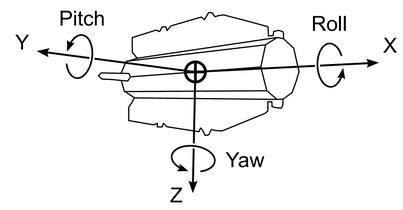
The **'measured'** force is derived from the measured linear acceleration.



The **thruster** in controlled to counteract the drag, primarily in the in-flight direction.

Radiation pressure is modeled for sunlight, Earth infrared and Earth albedo.

The resultant force is assumed to be **aerodynamic**.



All axes used on this poster are defined in the body frame displayed here. The **x** axis points in the direction of flight, **z** points down and **y** completes the right hand frame. **Roll**, **pitch**, and **yaw** are defined poisitive as shown, around the x, y, and z axis respectively.

Below the **individual model outputs** are compared to the **measured force**.

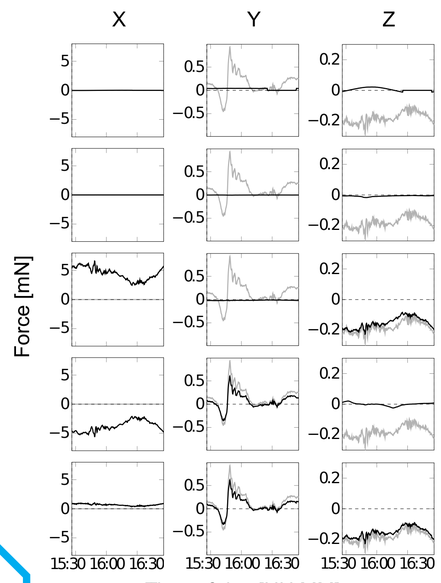
Solar radiation pressure causes a small, constant force in the cross-track direction due to the sun-synchronous nature of the orbit.

The **Earth radiation** is a combination of albedo and Earth infrared. It has a significant influence in the vertical direction.

The **thrust** counteracts the drag, and is therefore dominant in the in-flight direction. Other components are due to misalignment.

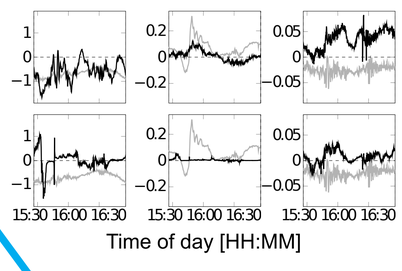
This **aerodynamic** model is used as a reference. It uses ANGARA* force coefficients and cross-wind and density derived from GOCE linear accelerations in the past [1].

The **total modeled force** (including the reference aerodynamic model) closely approximates the measured force.



The **residual force** is reduced to zero if the winds are estimated based on the forces. With winds **from the torque** the solution is more erratic than with the **reference wind**.

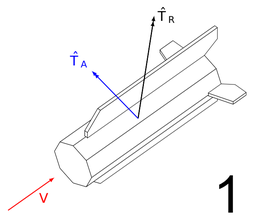
If the wind is derived **from forces and torques** combined, we find an intermediate solution after a fixed number of iterations that favors force in the cross-wind estimation.



Using only the torque to derive the wind and density (vertical axis) we find reasonable consistency with the force-derived cross-wind. Because the roll torque hardly depends on wind, the density cannot be estimated in this case, and remains at the NRLMSISE-00 value used in the initialization.

Algorithm

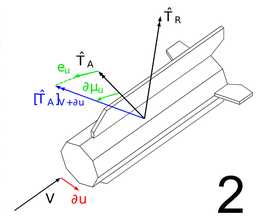
An iterative algorithm was implemented to obtain the wind and neutral density at the satellite's location from the force and/or torque. The algorithm is initialized by finding the residual force and torque as indicated on the left and right respectively.



1

The **aerodynamic velocity** is initialized as the sum of the orbital velocity and the corotation of the atmosphere. Both the **aerodynamic** and **residual** torque are normalized to unit vectors.

The velocity is **changed** perpendicular to its original direction, leading to a **new aerodynamic torque**. The **angle** between the two normalized torques and the **direction** along the arc connecting them are stored.



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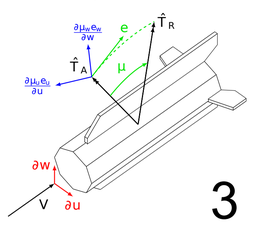
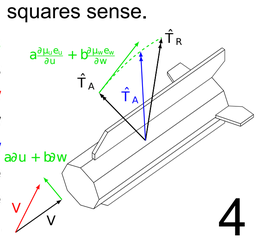


3

The same process in a **second direction** yields another **tangent derivative** (product of the unit vector and the angle). Together they form the Jacobian used to approximate the **required change** in a least squares sense.

The **least squares solution** found above is applied to find the **new velocity**. Both the new velocity and the **new aerodynamic torque** are normalized, and the algorithm is repeated.



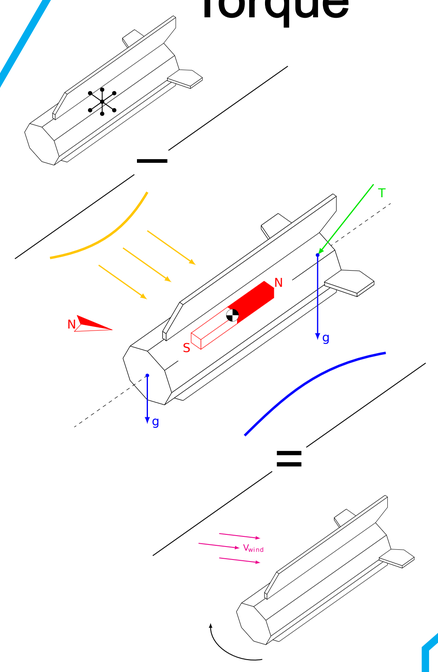
4

Finally, when the error angle is below 10^{-4} degrees, the aerodynamic torque is scaled to best fit the residual by estimating the neutral density.

It was found that although this algorithm works for forces, the Jacobian in step 3 is not full rank using only torques. The roll torque is very small and hardly depends on the wind direction. Because the aerodynamic torque is almost purely yaw, the two derivatives in step three are parallel.
To circumvent this problem, a large constant offset is added in roll to both the residual and the aerodynamic torque in all above steps.

Torque

The **'measured'** torque is derived from the measured angular rate and acceleration.



Magnetic torque is caused by control from magnetic torquers, the ion thruster magnet, and residual magnetic dipoles. The residual dipole of the payload and scale factors for the control dipoles were estimated, reducing the residual torque in a least-squares sense.

Solar radiation pressure causes a small torque when not in eclipse.

Gravity gradient torque effects the pitch attitude when the pitch angle is large.

The thrust does not point through the center of mass, causing a **misalignment** torque.

The resultant, unmodeled torque is assumed to be **aerodynamic**.

Below the **individual model outputs** are compared to the **measured torque**.

The **magnetic control** torque is dominant in the tightly controlled roll and pitch axes. Estimated scale factors are included.

The magnetic torque due to **residual dipoles** is the primary torque to counteract for the torquers. Estimated dipoles are included.

The **ion propulsion system** uses a magnet, which causes a significant torque in pitch.

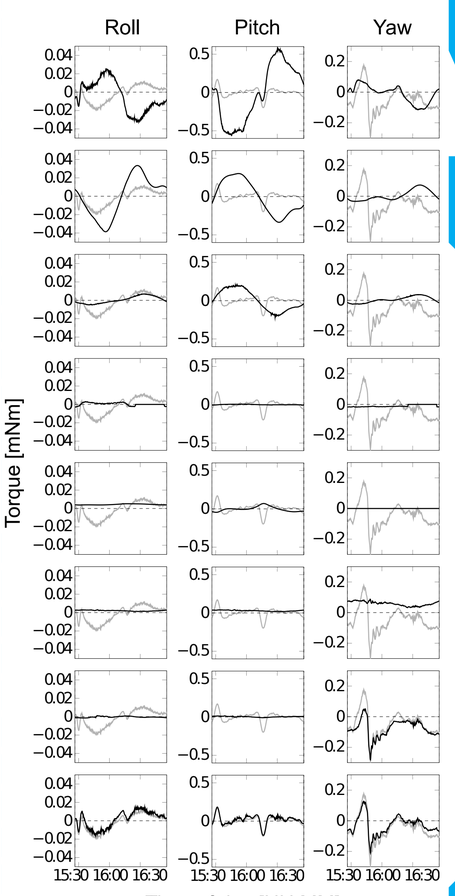
Solar radiation pressure causes a minor offset in the yaw torque, but is most significant in the roll torque, which is small overall.

The **gravity gradient** over the satellite body is largest during maneuvers, that generally occur over the equator. J2 effects are observed in the same region, in the pitch torque.

Correcting the **thrust** direction based on jumps in torque at orbit lowering maneuvers, the yaw torque is affected strongly by the thrust level.

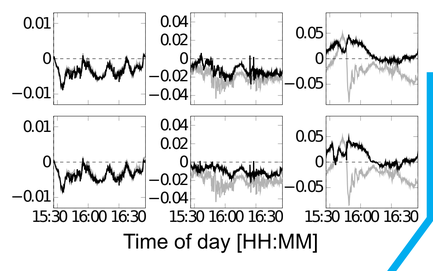
The **aerodynamic** model is used in residual dipole estimations. It uses ANGARA* coefficients and GOCE derived wind and density data [1].

The **total modeled torque** (including reference aerodynamics) closely approximates the measured torque.



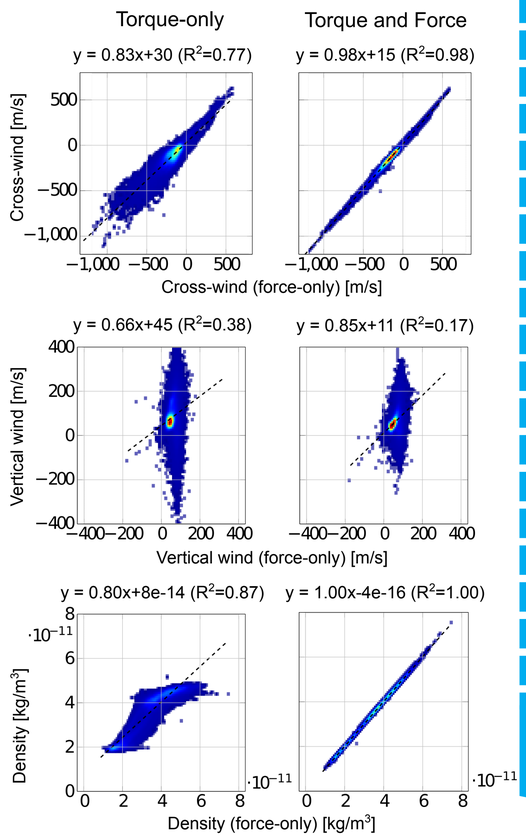
The **residual torque** is reduced to zero when torque is used to derive the wind. With wind **from forces** the residual is clearly different from that obtained using the **reference wind data**.

The solution **from forces and torques** especially improves the pitch residual, implying that the torques significantly influence the vertical wind.



Using both the torque and force to derive the wind and density (vertical axis) we observe that the cross-wind closely follows the force-derived wind, whereas the vertical wind is more driven by the pitch torque. Density can now be derived from the X-force, as in the forces-only case.

Results



Future work

The results show that the wind and density from forces are inconsistent with those derived from the torques. As these discrepancies also stem from errors in the yaw torque and side force where aerodynamic effects are dominant, this implies errors still remain in the aerodynamic model. In our future work we will attempt to correct these inconsistencies by estimating more parameters, such as the accommodation coefficient.

References:
[1] E.N. Doornbos. *GOCE+ Theme 3: Air density and wind retrieval using GOCE data: Data Set User Manual*, July 2016

*ANGARA is a Monte-Carlo simulator developed by HTG, Göttingen.

Fourth Swarm Science Meeting & Geodetic Missions Workshop, Banff (AL), Canada, March 2017
Thermosphere session, Poster ID 18