Three-axis magnetic control for a nanosatellite: practical limitations due to a residual dipole moment

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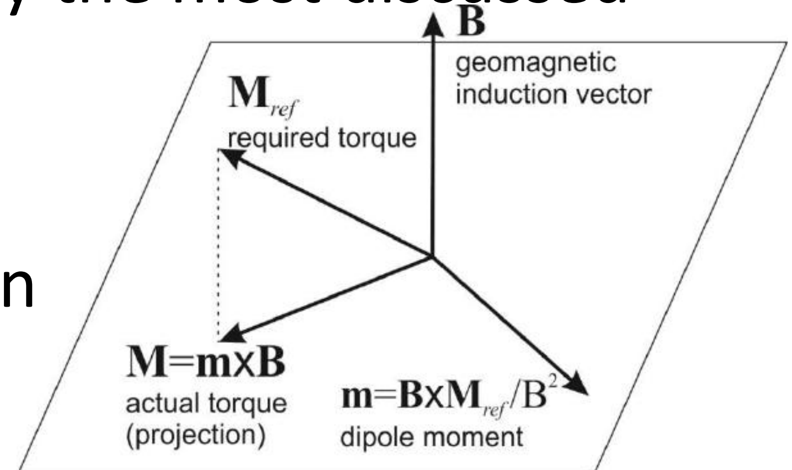
Features of magnetic control for a CubeSat and NanoSat

- Magnetorquers comply with the true spirit of a CubeSat: they are small, lightweight, cheap and reliable
- The trade-off is the restriction in direction (“almost” underactuated system)
  - Large field for fundamental research in control theory (system is ultimately controllable)
  - Practical considerations in control gains adjustment
  - Specific engineering issues relevant for very small satellites

Issues with the magnetic control

- Lyapunov control is currently the most discussed candidate for the task
- Control value is severely limited due to the restriction in direction



- Control drives the satellite more or less to the necessary attitude. The attitude error may increase after the control implementation iteration if the torque is too strong

Problems for small satellites

- Small control torque reduces the capability of disturbance rejection (on top of the direction restriction)
- Both control and disturbance torques values scale with the satellite inertia
- The scaling factor is different. It is governed by the physical nature of the disturbance sources

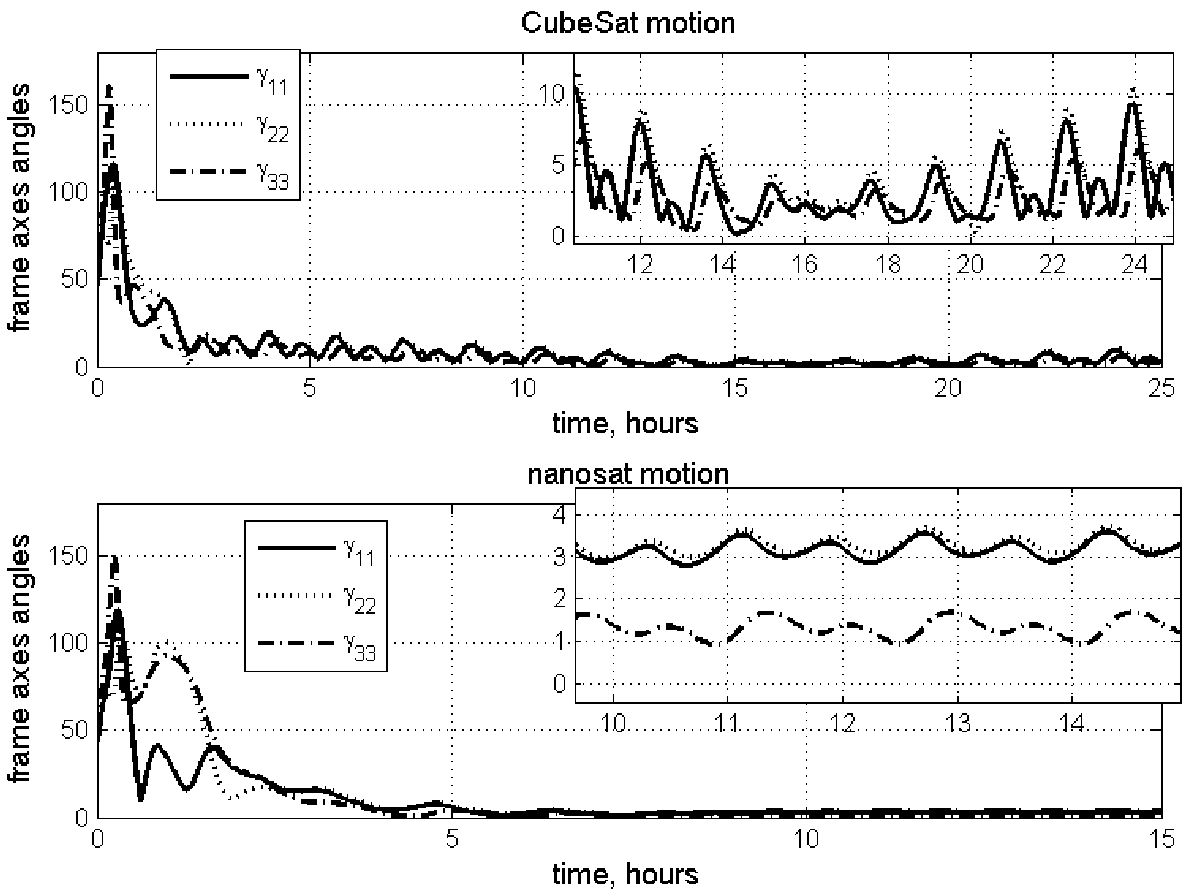
Control gains adjustment

- Orbit parameters: circular, inclination 97 degrees, altitude 550 km (SSO)
- Inertia moments
  - 0.0034, 0.0032, 0.0036 kg·m^2 (typical 1U CubeSat)
  - 0.15, 0.13, 0.11 kg·m^2 (typical 10 kg NanoSat)
- Typical dipole control moments are
  - for 1U CubeSat 10^{-5}- 10^{-4} A·m^2
  - for NanoSat 10^{-3}-10^{-2} A·m^2
- CubeSat dipole is too small for the implementation by available magnetorquers

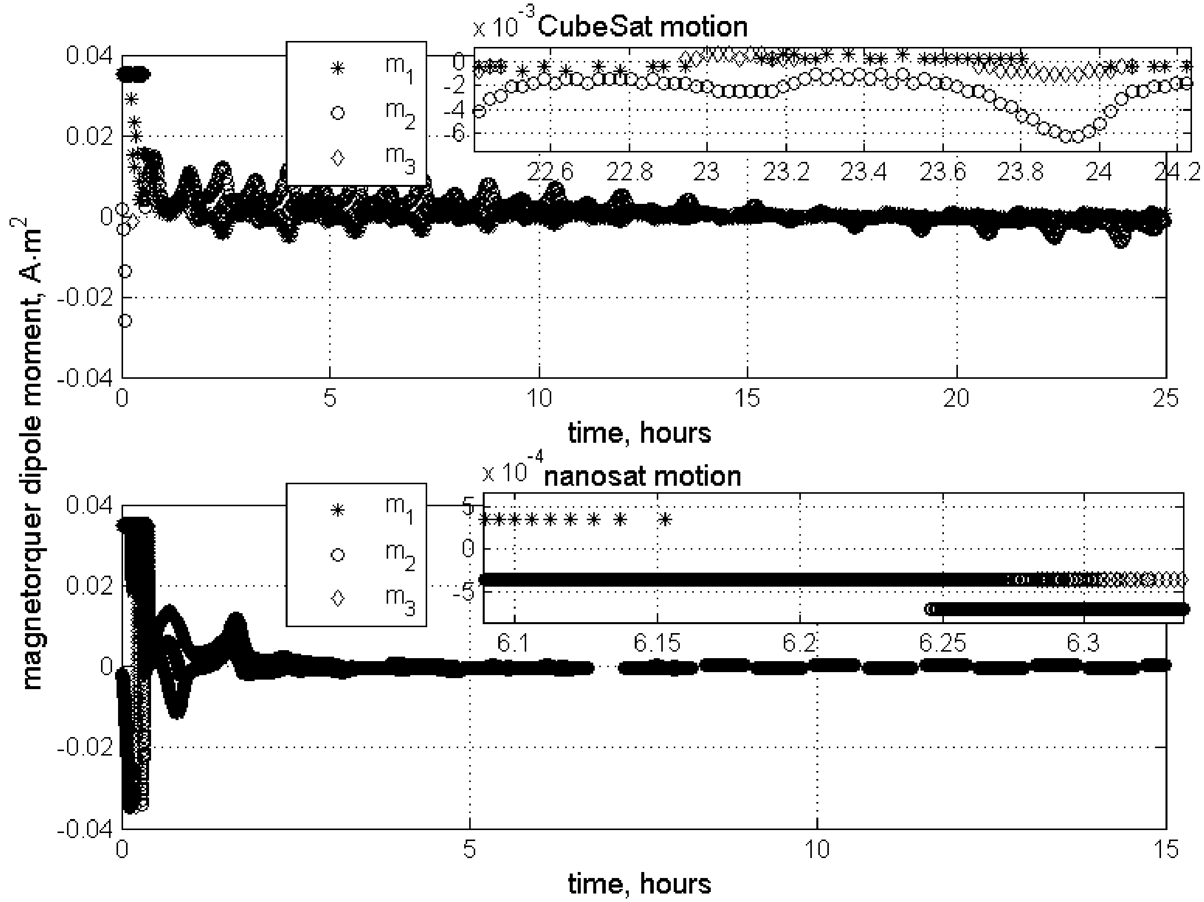
Control implementation

- CubeSat requires artificial control value increase: 100 times higher control is commanded once every 100 seconds
- PWM simulation is introduced:
  - Maximum magnetorquer dipole moment is $3.5 \cdot 10^{-2}$ A·m^2 (Gomspace P100 solar panel embedded magnetorquers)
  - Implementation step and minimum control dipole value is $3.5 \cdot 10^{-4}$ A·m^2

Stabilization accuracy (gravity and aerodynamic, no attitude determination)



Control dipole value



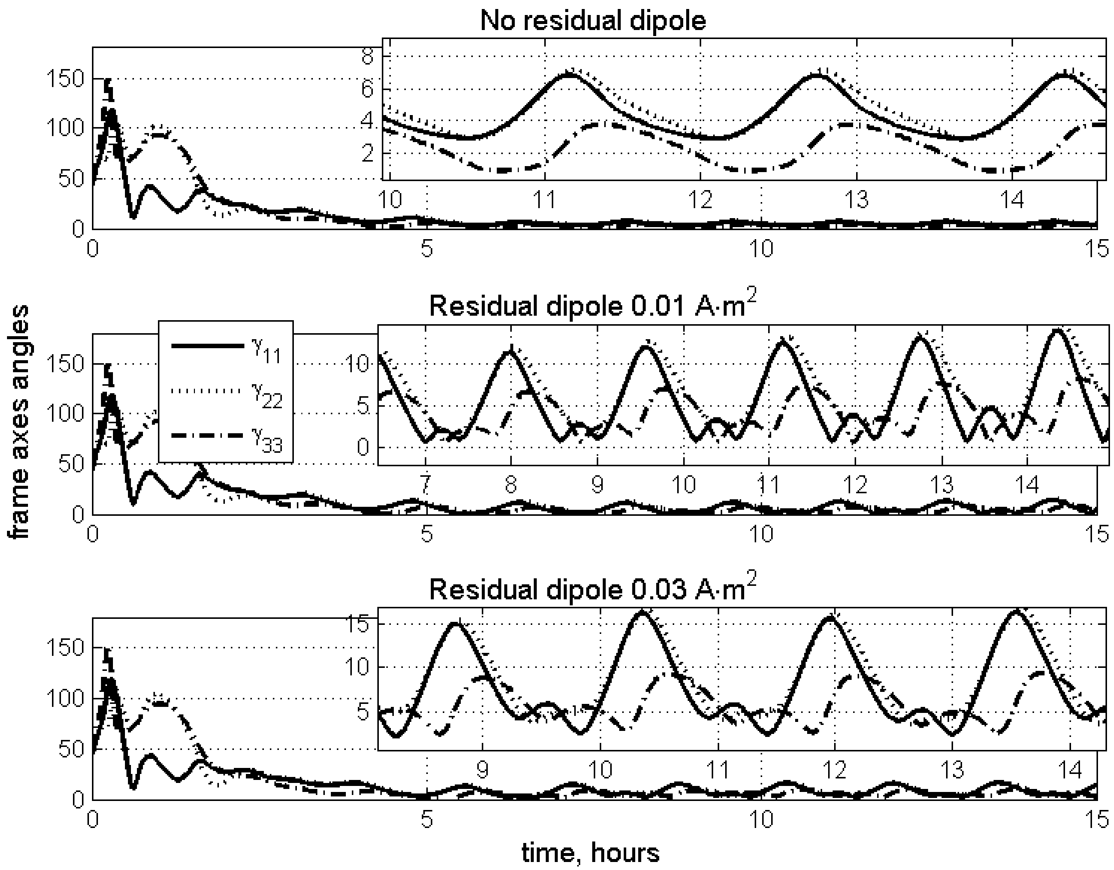
Control and disturbances values comparison

	CubeSat	**NanoSat**
Control (in the vicinity of necessary attitude)	10^{-9} N·m 10^{-5} A·m^2	10^{-8} N·m 10^{-4} A·m^2
Gravity	10^{-10} N·m	10^{-8} N·m
Aerodynamic (mediocre activity)	10^{-10} N·m	10^{-9} N·m
Residual dipole value and estimation accuracy	(1-4)·10^{-2} A·m^2 10^{-3} A·m^2	

Residual dipole effect

- Residual dipole must be compensated
- Even the ideal residual dipole knowledge is prone to the error from the PWM implementation
- CubeSat control is impossible: practically available PWM discreteness is larger than the control dipole value
- NanoSat is on the edge

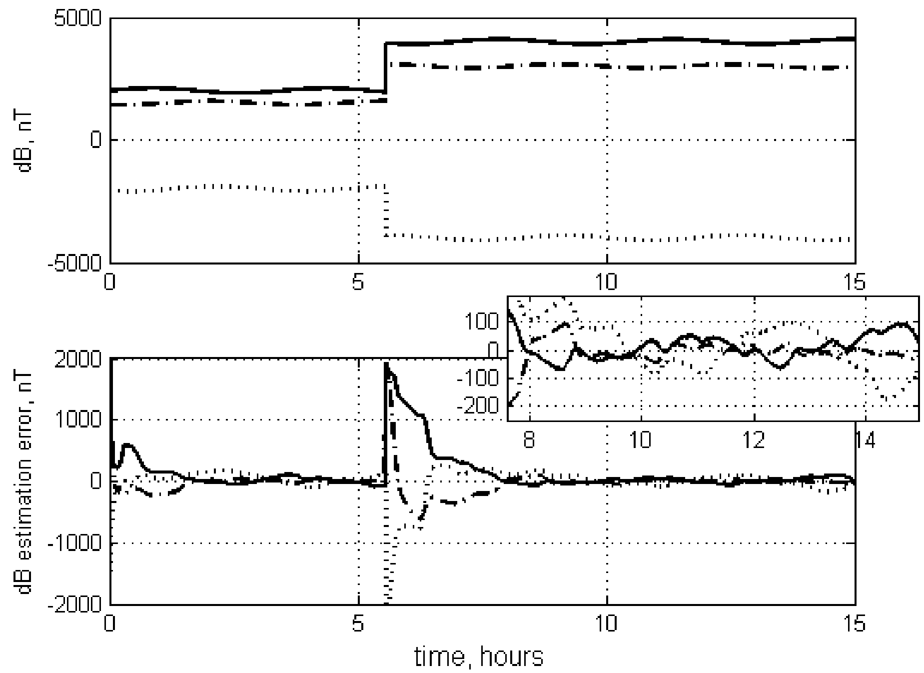
Residual dipole effect simulation

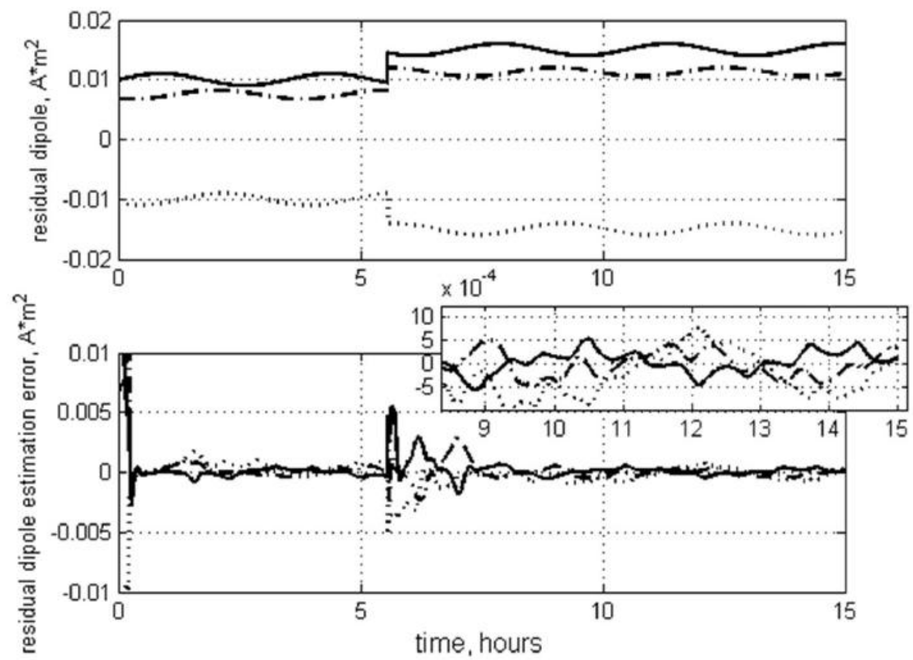


Extended Kalman filter implementation

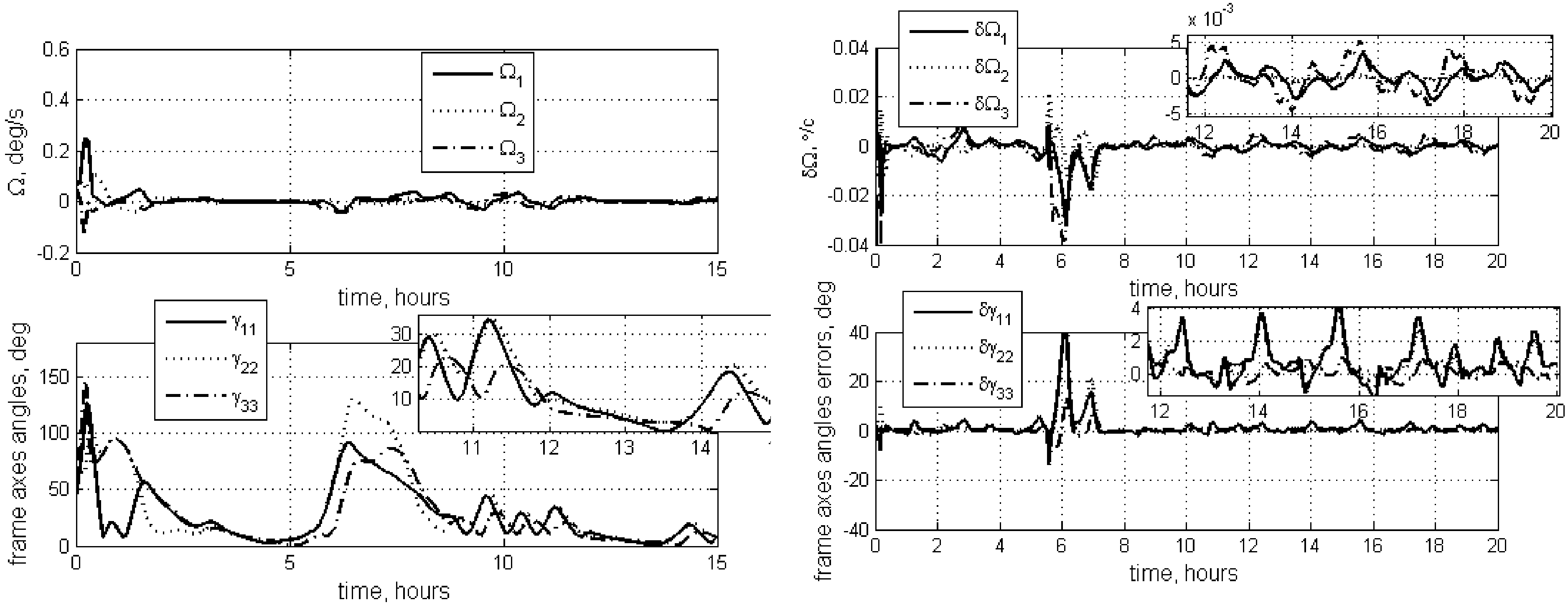
- Magnetometer measurements are used
- State vector consists of the attitude motion parameters, residual dipole and magnetometer bias
- 1s is allocated for the state vector estimation (1 Hz sampling rate) and 5 s for the control implementation
- Residual dipole compensation is required on the attitude determination step
- Constant and periodic residual dipole and magnetometer bias are simulated

Magnetometer bias and residual dipole estimation





Kalman filter implementation simulation



Conclusion

- Residual dipole doesn't allow three axis magnetic control on a CubeSat
- Nanosatellite may be controlled with low accuracy
  - All possible measures to reduce and estimate the residual dipole are necessary
  - The availability and quality of these measures are questionable

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