Comparison of Acoustic Models and Trajectory Generation Methods for an Acoustically-Aware Aircraft

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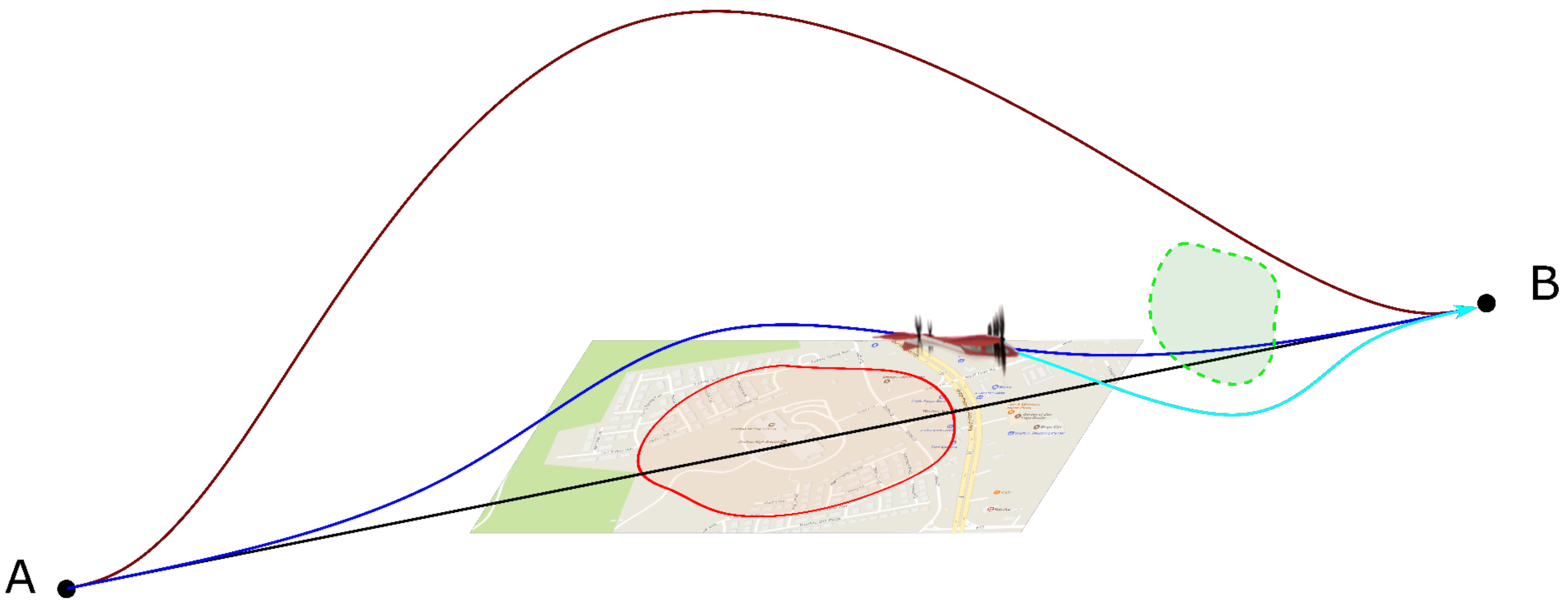
AIAA SciTech Forum

National Harbor, MD

January 2023

Motivation

- Noise management is one of the major barriers to Urban Air Mobility
- Approaches to noise mitigation (non-exhaustive)
  - Vehicle configuration
  - Directivity control via propeller phase synchronization
  - *Trajectory optimization*



Objective

- Create framework for trajectory generation integrating location-based acoustic metrics and vehicle performance limitations
  - Multiple trajectory optimization methods and acoustic noise models
  - Mission-relevant constraints
    - Mission duration, airspace restrictions, …
  - Vehicle dynamic constraints
    - Aircraft structural limitations, min/max airspeed, …
  - Vehicle separation/obstacle avoidance
  - Acoustic constraints at a number of discrete observer locations

Comparison of Models and Methods

- Two acoustic source noise models
  - Omni-directional model based on propeller tip Mach Number
  - Directional hemisphere-based model
- Two trajectory planning methods
  - Pre-mission full-trajectory planner using polynomial parameterization
  - Receding horizon (near) real-time nonlinear model predictive control (MPC) trajectory planner
- Compare trajectory planning performance using both noise models and trajectory generation methods

Vehicle Dynamics

- Fixed-wing distributed propulsion aircraft
  - Can represent tilt-wing or split-propulsion vehicle in forward flight
  - Coordinated flight aircraft model*
    - Basic aerodynamic model
    - Simplified motor/propeller model
    - Assumes underlying tracking controller
- Parameter values taken from model of NASA's GL-10 aircraft

Figure credit: NASA

*Adapted from J Hauser, R Hindman, "Aggressive Flight Maneuvers," IEEE Conference on Decision and Control, 1997.

Omni-Directional Acoustic Model

- Metric is *sound pressure level (SPL)*
- Model data fit from the Propeller Analysis System of the Aircraft Noise Prediction Program (PAS-ANOPP)
- Based on effective propeller tip Mach number
- Optional frequency weighting

$$M_{\mathrm{eff}} = \frac{M_t}{1 + J(1 - M_t)}$$

$$M_t = \omega_p d_p / 2c$$

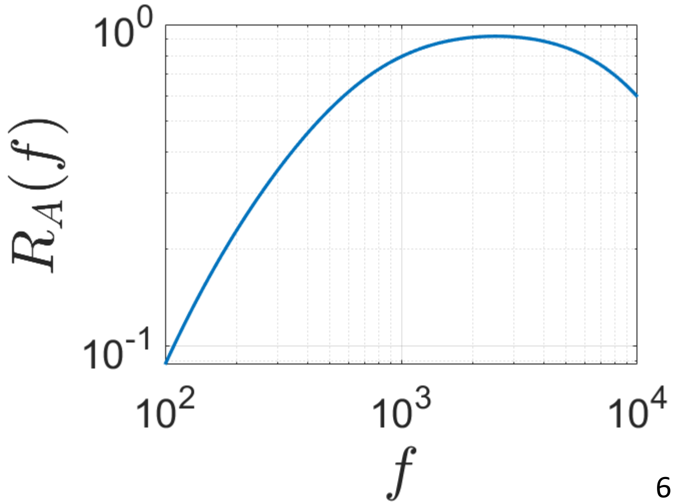
Frequency weighting

Number of propellers

$$SPL = 10\log_{10}\left(\frac{1}{\hat{p}^2}\sum_{k=0}^{N_f}\left[\hat{p}^2_{\mathrm{rms},k}\left(\frac{M_{\mathrm{eff}}}{\hat{M}_{\mathrm{eff}}}\right)^{\xi_k} R_A(f_k)\right]\left(\frac{\hat{r}}{r}\right)^2 N_p\right)$$

Propeller speed

Distance to observer



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Hemisphere Acoustic Model

- Metric is *sound pressure level (SPL)*
- Model data from the Propeller Analysis System of the Aircraft Noise Prediction Program (PAS-ANOPP)
- Directional noise emission
- Interpolation over airspeed, angle of attack, propeller speed, direction to observer

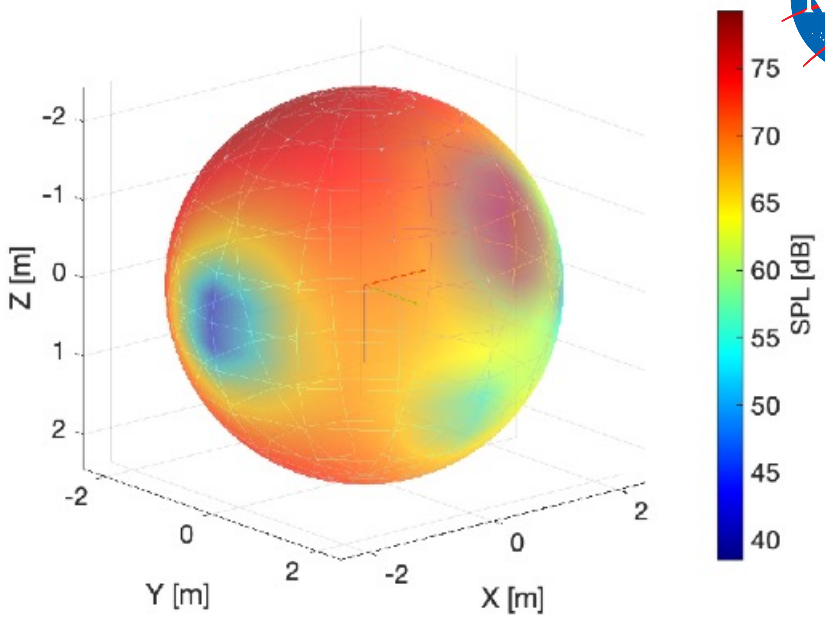
Pressure doubling

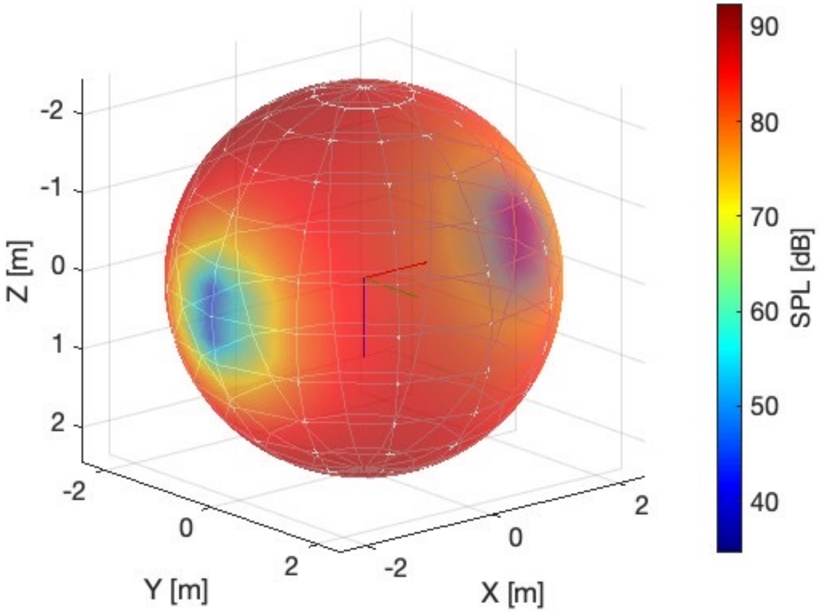
Frequency weighting

$$SPL_{obs} = SPL + 20\log_{10}\left(\frac{\hat{r}}{r}\right) + 6 + R_A(f) + 10\log_{10}(N_p)$$

Distance to observer

Number of propellers





Pre-Mission Trajectory Planner*

- Full trajectory optimization with polynomial parameterization
  - Simplified (differentially flat) vehicle dynamics, acoustic source model, and propagation model
  - Implemented as a 2nd order Hermite interpolation problem
  - Bézier polynomial representation of spatial path and parametric speed
  - Numeric (discrete) evaluation of mid- to high-fidelity acoustic source and propagation models

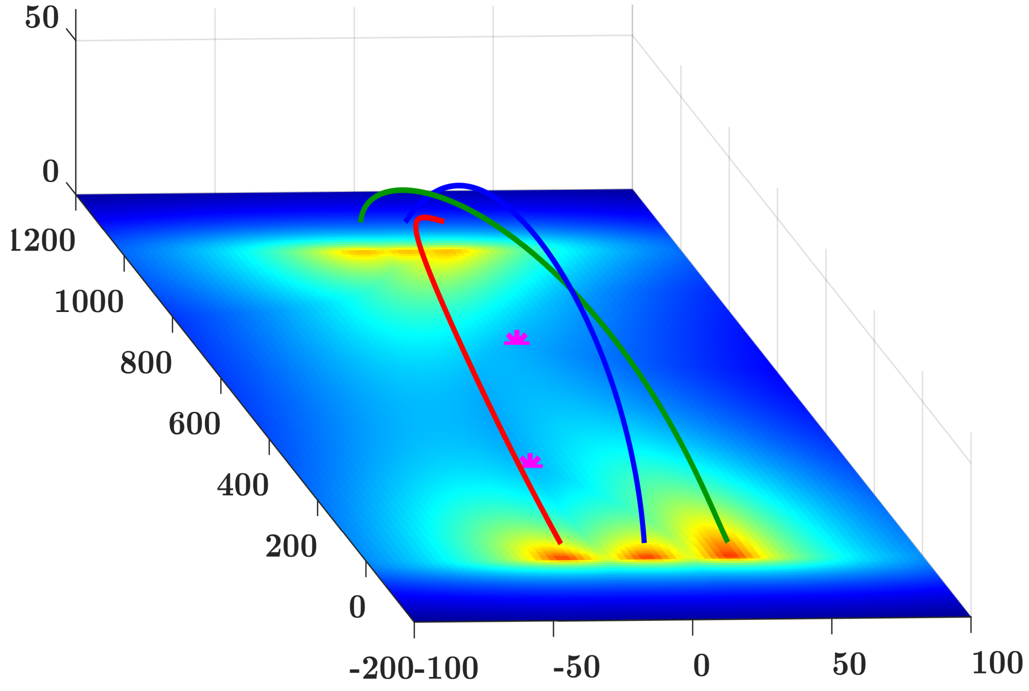
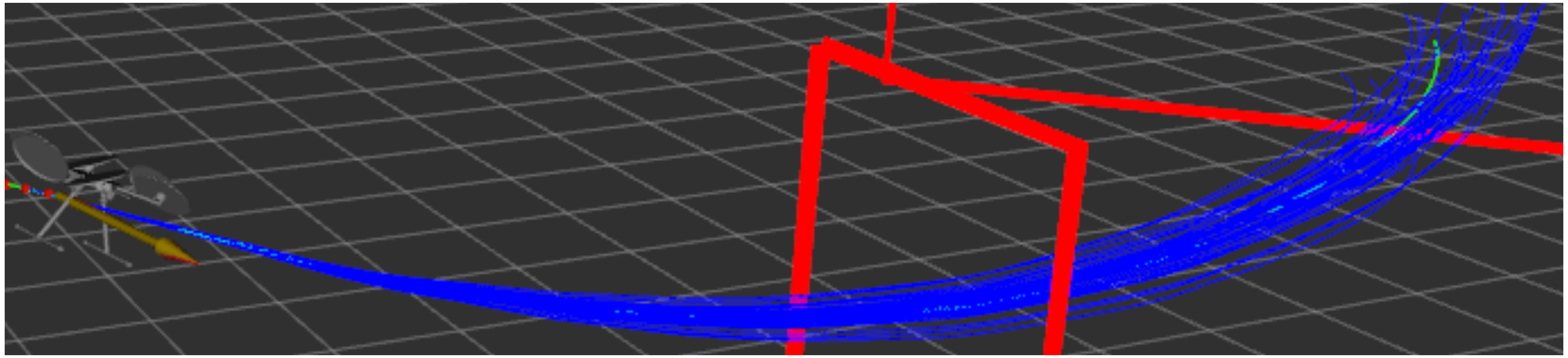


Figure Credit: *KA Ackerman and IM Gregory, "Trajectory Generation for Noise-Constrained Autonomous Flight Operations," AIAA SciTech Forum, Jan 2020. AIAA-2020-0978

MPC Motion planner*

- Model Predictive Path Integral Control (MPPI)**
  - Stochastic optimization technique used as nonlinear MPC
  - Framework to efficiently solve a finite horizon nonlinear optimal control problems
  - State cost function can be arbitrarily complex
  - Sampling-based optimization leverages GPU for efficient computation



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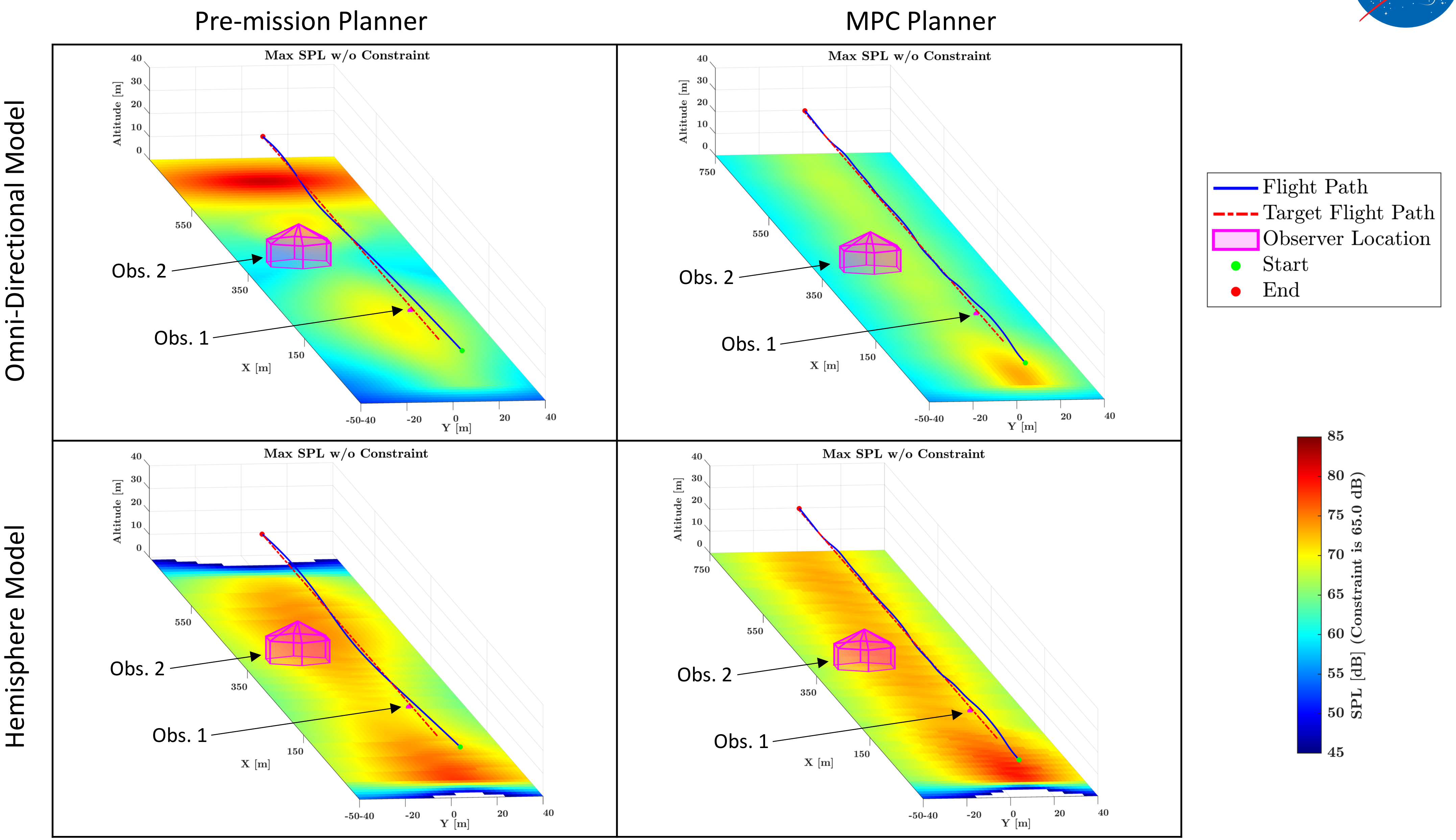
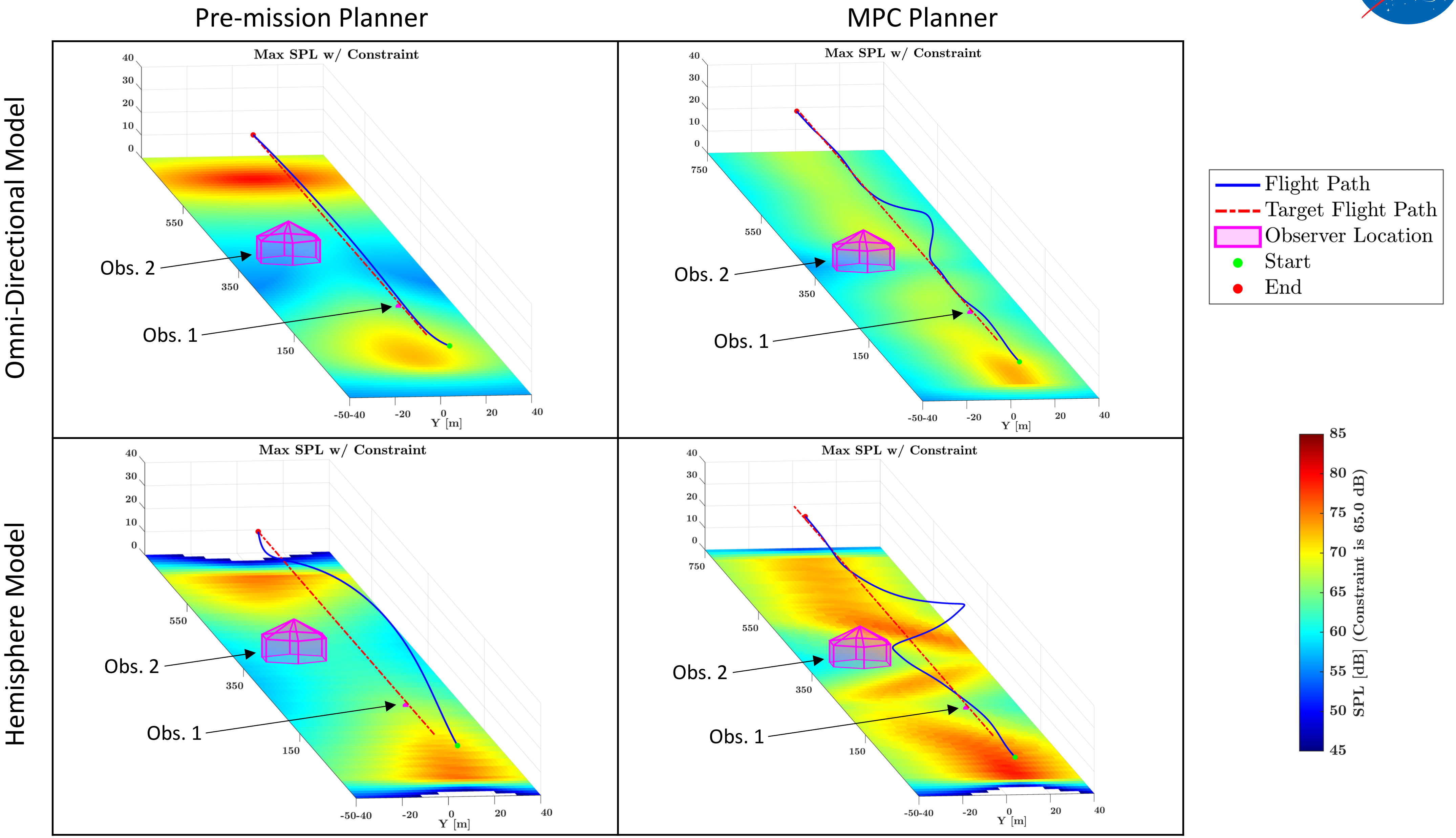
**G Williams, P Drews, B Goldfain, JM Rehg, EA Theodorou, "Information Theoretic Model Predictive Control: Theory and Applications to Autonomous Driving," IEEE Transactions on Robotics, 2018.

Comparison – Acoustic Constraint Inactive



Comparison – Acoustic Constraint Active



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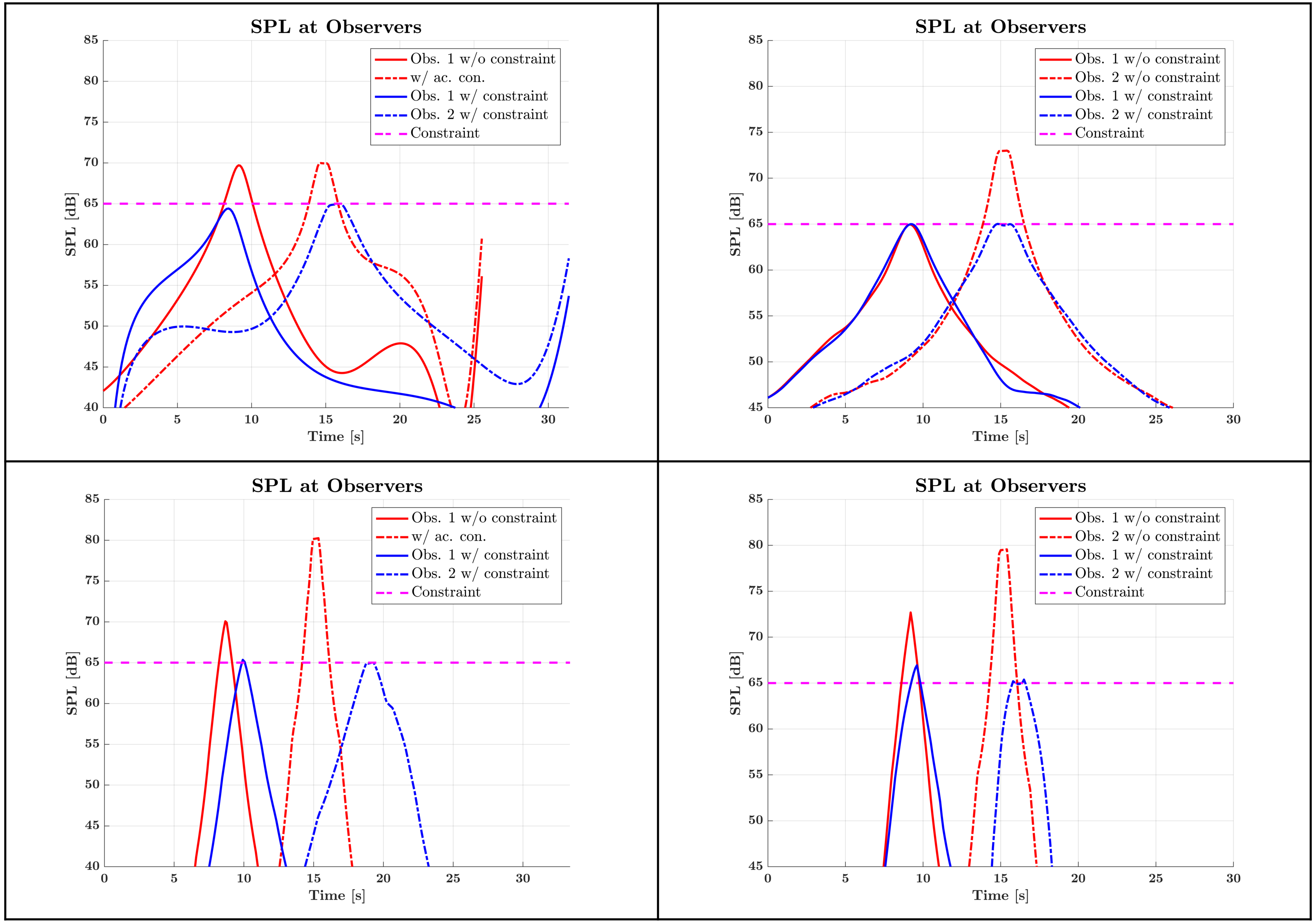
Comparison – Sound Pressure Level

Pre-mission Planner

MPC Planner

Omni-Directional Model

Hemisphere Model



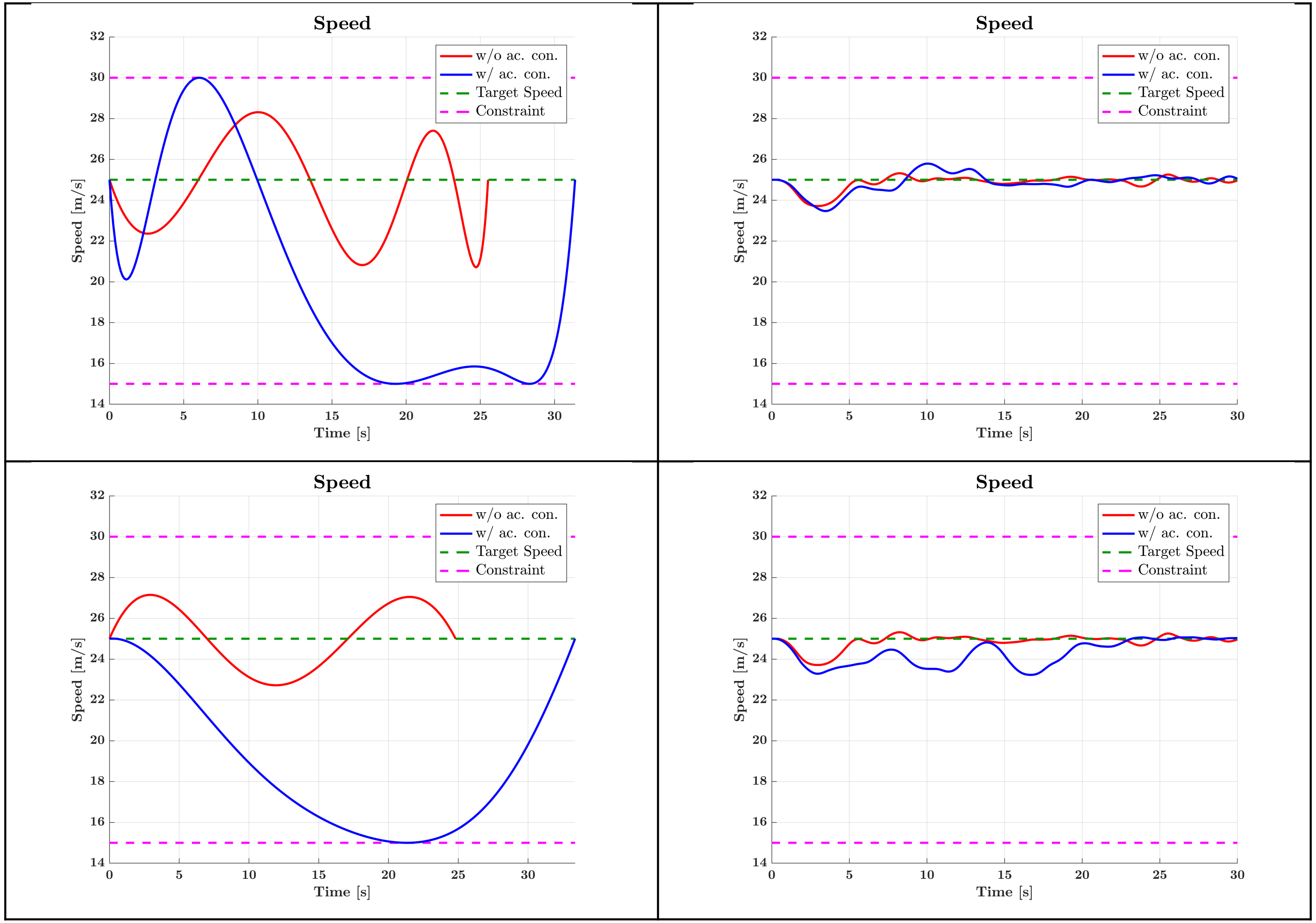
Comparison – Vehicle Speed

Pre-mission Planner

MPC Planner

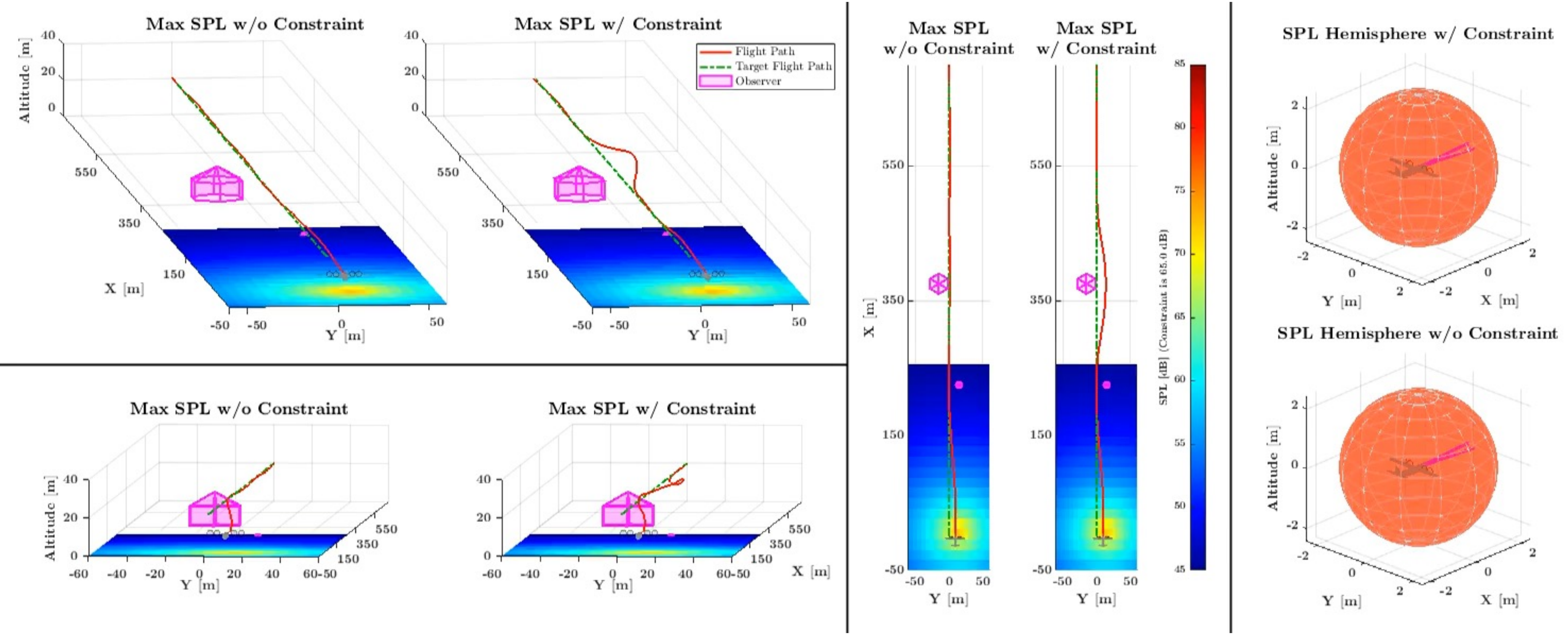
Omni-Directional Model

Hemisphere Model



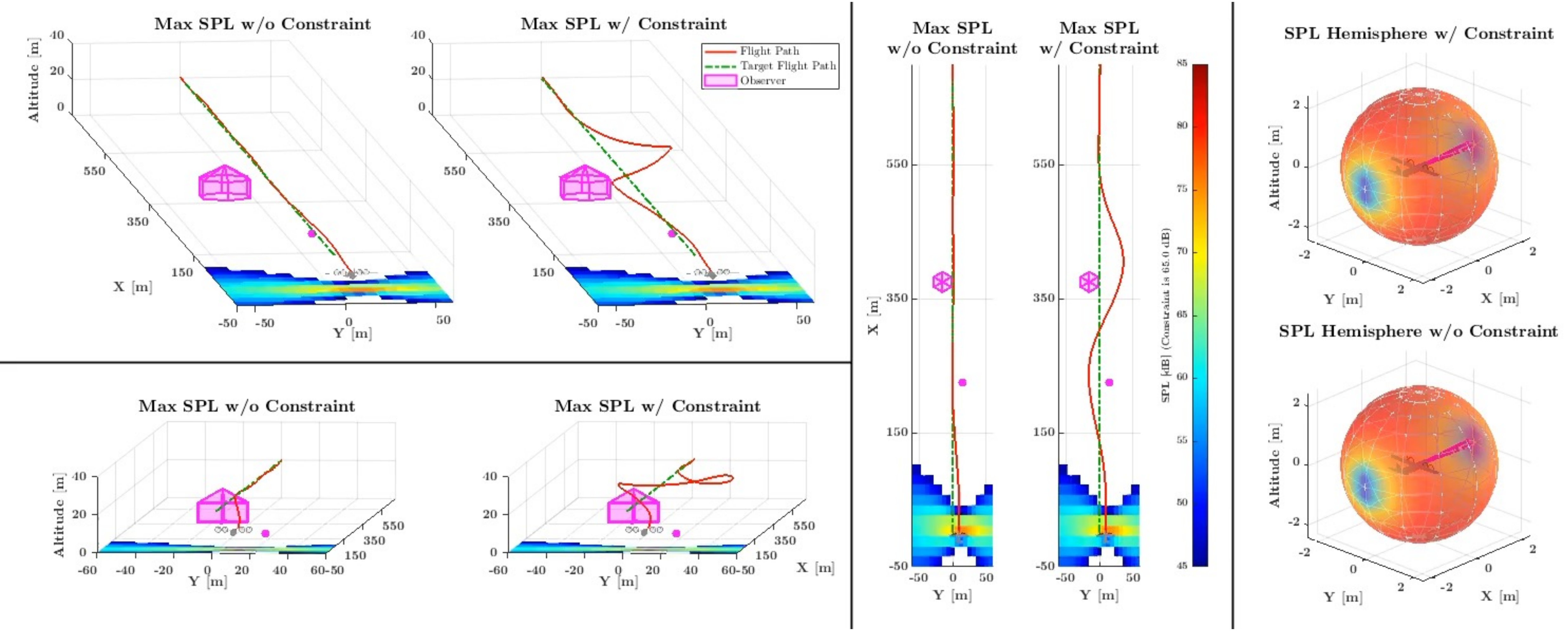
Noise Model Comparison

- Omni-directional propeller speed model



Noise Model Comparison

- Hemisphere model



Summary

- Compared two different trajectory planning methods and two acoustic noise models
  - Full trajectory planning with guaranteed constraint satisfaction
  - Finite horizon planning has greater freedom in trajectory planning
    - Better able to exploit directionality of hemisphere model
  - Directionality of noise emission makes difference in maximum noise levels seen on ground
    - Higher peak noise, but shorter duration with hemisphere model
- Future efforts focused on combining planner methods to leverage advantages of each
- Acknowledgements

  - NASA’s Revolutionary Vertical Lift Technology Project
  - Dr. Kyle Pascioni (NASA Langley Research Center)
  - Dr. Javier Puig Navarro (National Institute of Aerospace)

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Background Material

Vehicle Dynamics

- Fixed-wing distributed propulsion aircraft
  - Can represent tilt-wing or split-propulsion vehicle in forward flight
  - Coordinated flight aircraft model*
    - Includes basic aerodynamic model
    - Assumes underlying tracking controller
  - Dynamics:

$$\dot{\boldsymbol{x}} = \boldsymbol{v}$$

$$\dot{\boldsymbol{v}} = \boldsymbol{g} + \boldsymbol{R}\boldsymbol{a}_v$$

$$\dot{\boldsymbol{q}} = \frac{1}{2}\boldsymbol{q} \otimes \begin{bmatrix} 0 \\ \boldsymbol{\omega}_v \end{bmatrix}$$

$$\boldsymbol{\omega}_v = \begin{bmatrix} p_s & -\boldsymbol{e}_3\left(\boldsymbol{a}_v + \boldsymbol{g}\right)/V & \boldsymbol{e}_3\boldsymbol{g}/V \end{bmatrix}^\mathsf{T}$$

$$\begin{bmatrix} T & \alpha & p_s \end{bmatrix}^\mathsf{T} = \boldsymbol{u}$$

Coordinated flight constraint

$$\boldsymbol{e}_3 = \begin{bmatrix} 0 & 0 & 1 \end{bmatrix}^\mathsf{T}$$

*Adapted from J Hauser, R Hindman, “Aggressive Flight Maneuvers,” IEEE Conference on Decision and Control, 1997.

Vehicle Dynamics

- Aerodynamic model:

$$\boldsymbol{a}_v = \begin{bmatrix} \frac{T}{m}\cos\alpha - \frac{\rho V^2 S}{2m}\left(\sin\alpha\left(C_{N_0} + C_{N_\alpha}\alpha\right) + \cos\alpha\left(C_{A_0} + C_{A_{\alpha^2}}\alpha^2\right)\right) \\ 0 \\ -\frac{T}{m}\sin\alpha - \frac{\rho V^2 S}{2m}\left(\cos\alpha\left(C_{N_0} + C_{N_\alpha}\alpha\right) - \sin\alpha\left(C_{A_0} + C_{A_{\alpha^2}}\alpha^2\right)\right) \end{bmatrix}$$

Highlighted variables:
Thrust – blue
AoA – red
Aero Coeff - green

- Propeller/motor model:

$$T = c_2(J)\omega_p^2 + c_1(J)\omega_p + c_0(J)$$

$$J = \frac{2\pi V\cos\alpha}{\omega_p d_p}$$

Advance ratio

- Parameter values taken from model of NASA’s GL-10 aircraft

Pre-Mission Trajectory Planner

- Full trajectory optimization with polynomial parameterization
  - Simplified vehicle dynamics, acoustic source model, and propagation model
  - Implemented as a 2nd order Hermite interpolation problem
  - Bézier polynomial representation of spatial path and parametric speed
    - Computationally efficient algorithms
    - No discretization of trajectory or constraint functions
    - Constraints can be satisfied to arbitrary precision
  - Assumes differential flatness of dynamics and constraints
  - Numeric (discrete) evaluation of mid- to high-fidelity acoustic source and propagation models

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Pre-Mission Trajectory Planner

- Differentially flat dynamics

$$\dot{\boldsymbol{x}}(t) = V(t)\begin{bmatrix}\cos(\gamma(t))\cos(\chi(t))\\ \cos(\gamma(t))\sin(\chi(t))\\ -\sin(\gamma(t))\end{bmatrix}$$

$$m\dot{V}(t) = T(t) - D(t)$$

- Spatial path and timing law
  - Derive all other variables from path and timing law

$$\boldsymbol{x}(\zeta) = \sum_{k=0}^{5} \bar{\boldsymbol{x}}_k b_k^n(\zeta), \qquad \zeta \in [0,1]$$

$$\theta = \frac{\mathrm{d}\zeta\left(\hat{t}\right)}{\mathrm{d}\hat{t}} = \sum_{k=0}^{n_\theta} \bar{\theta}_k b_n^k\left(\hat{t}\right), \qquad \hat{t} = \frac{t}{t_f}$$

$$\zeta\left(\hat{t}\right) = \int_0^{\hat{t}} \theta(\tau)\mathrm{d}\tau$$

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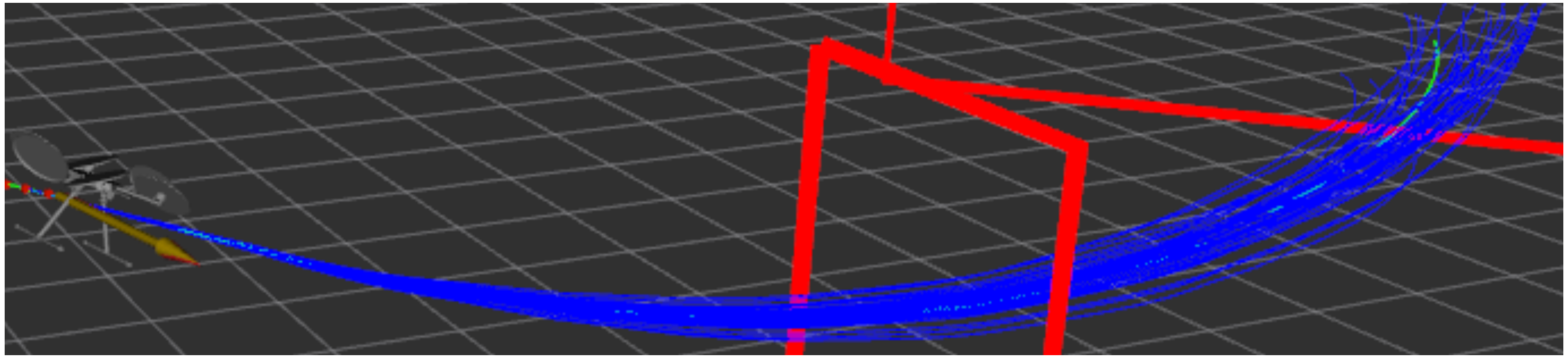
MPC Motion Planner*

- Model Predictive Path Integral Control (MPPI)**
  - Sample thousands of control sequences, $\boldsymbol{\nu}_t \sim \mathcal{N}(\boldsymbol{u}_t, \boldsymbol{\Sigma})$, propagate trajectories in parallel
  - Exponential cost-weighted averaging to update mean of optimal control distribution, $\boldsymbol{u}_t$
  - Propagate mean optimal control sequence to obtain nominal trajectory



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MPC Motion Planner

- Implementation*
  - Discrete-time dynamics $\boldsymbol{z}_{t+1} = \boldsymbol{f}(\boldsymbol{z}_t, \boldsymbol{\nu}_t),\ \boldsymbol{\nu}_t \sim \mathcal{N}(\boldsymbol{u}_t, \boldsymbol{\Sigma})$
  - Cost functional

$$\boldsymbol{J}(\boldsymbol{U}) = \mathbb{E}\left[\phi(\boldsymbol{z}_{t+T}) + \sum_{k=t}^{t+T-1} q(\boldsymbol{z}_k) + \lambda \boldsymbol{u}_k^{\mathsf{T}} \boldsymbol{\Sigma}^{-1}(\boldsymbol{\nu}_k - \boldsymbol{u}_k)\right]$$

  - State cost and control weight for each control sequence

$$S(\boldsymbol{V}_t^i) = \phi(\boldsymbol{z}_{t+T}^i) + \sum_{k=t}^{t+T-1} q(\boldsymbol{z}_k)$$

$$w(\boldsymbol{V}_t^i) = \exp\left[-\frac{1}{\lambda}\left(S(\boldsymbol{V}_t^i) - \sum_{k=t}^{t+T-1} \boldsymbol{u}_t' T \boldsymbol{\Sigma}^{-1} \boldsymbol{\nu}_k^i - \beta\right)\right]$$

  - Approximate optimal control

$$\boldsymbol{u}_t^* \approx \boldsymbol{u}_t = \boldsymbol{u}_t' + \frac{1}{\sum_{i=1}^{N_s} w(\boldsymbol{V}_t^i)} \sum_{i=1}^{N_s} w(\boldsymbol{V}_t^i)(\boldsymbol{\nu}_t^i - \boldsymbol{u}_t^i),$$

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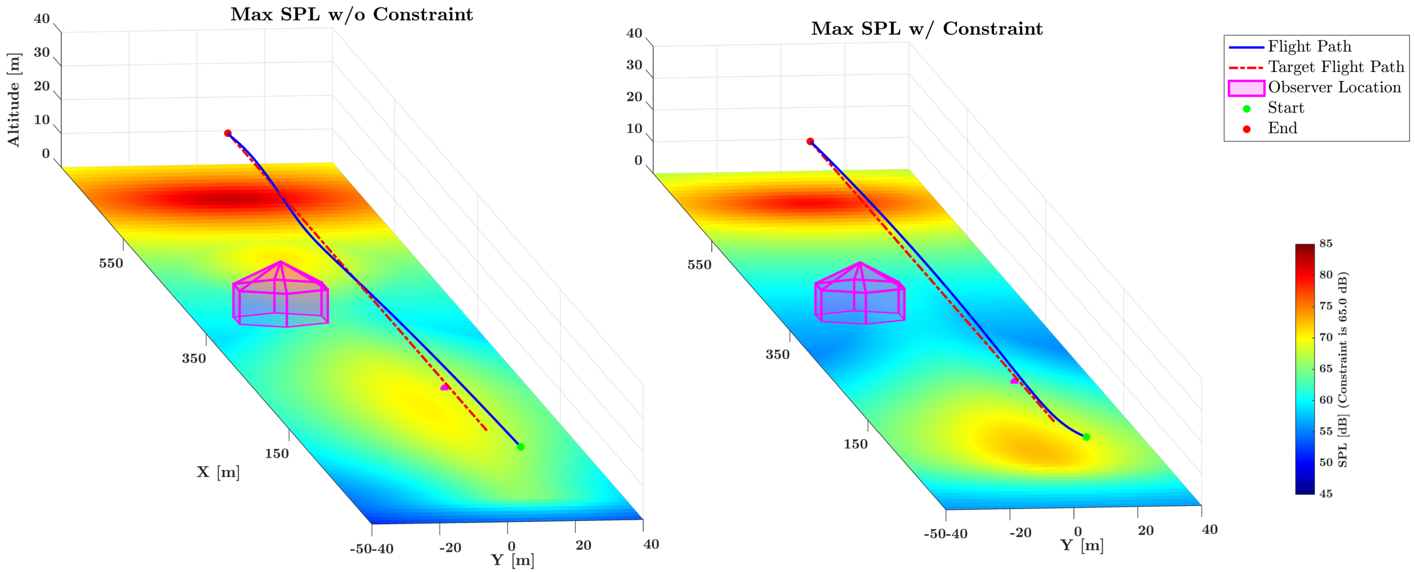
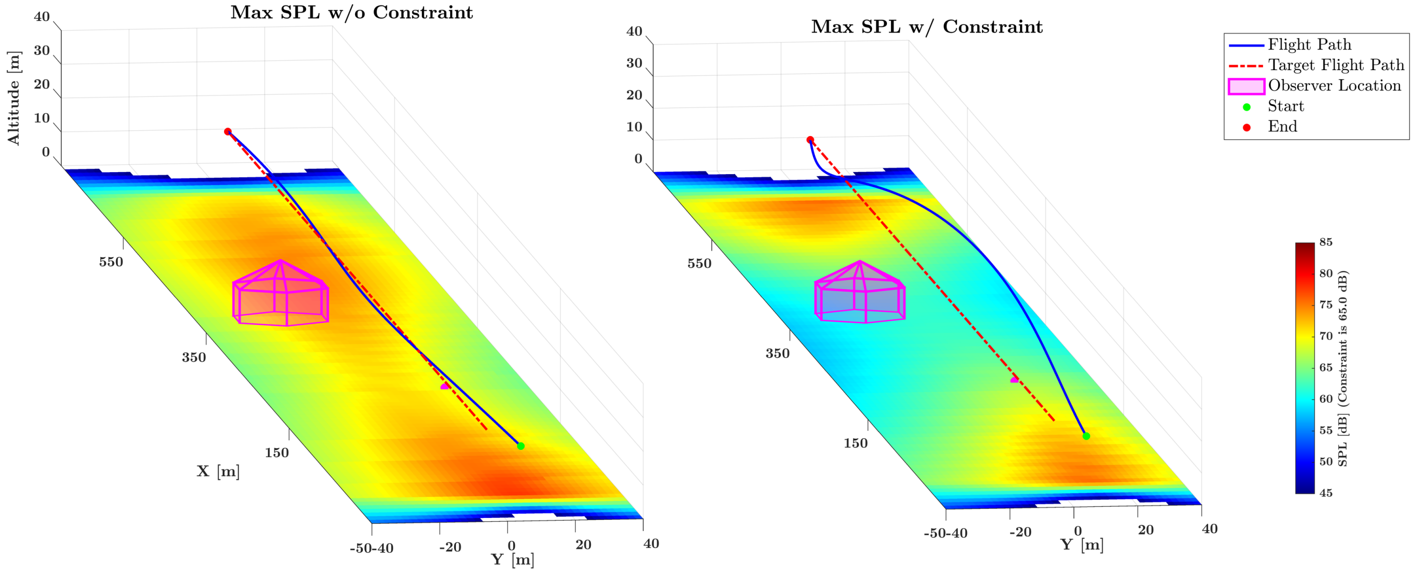
Noise Model Comparison – Pre-mission Planner

Omni-Directional Model



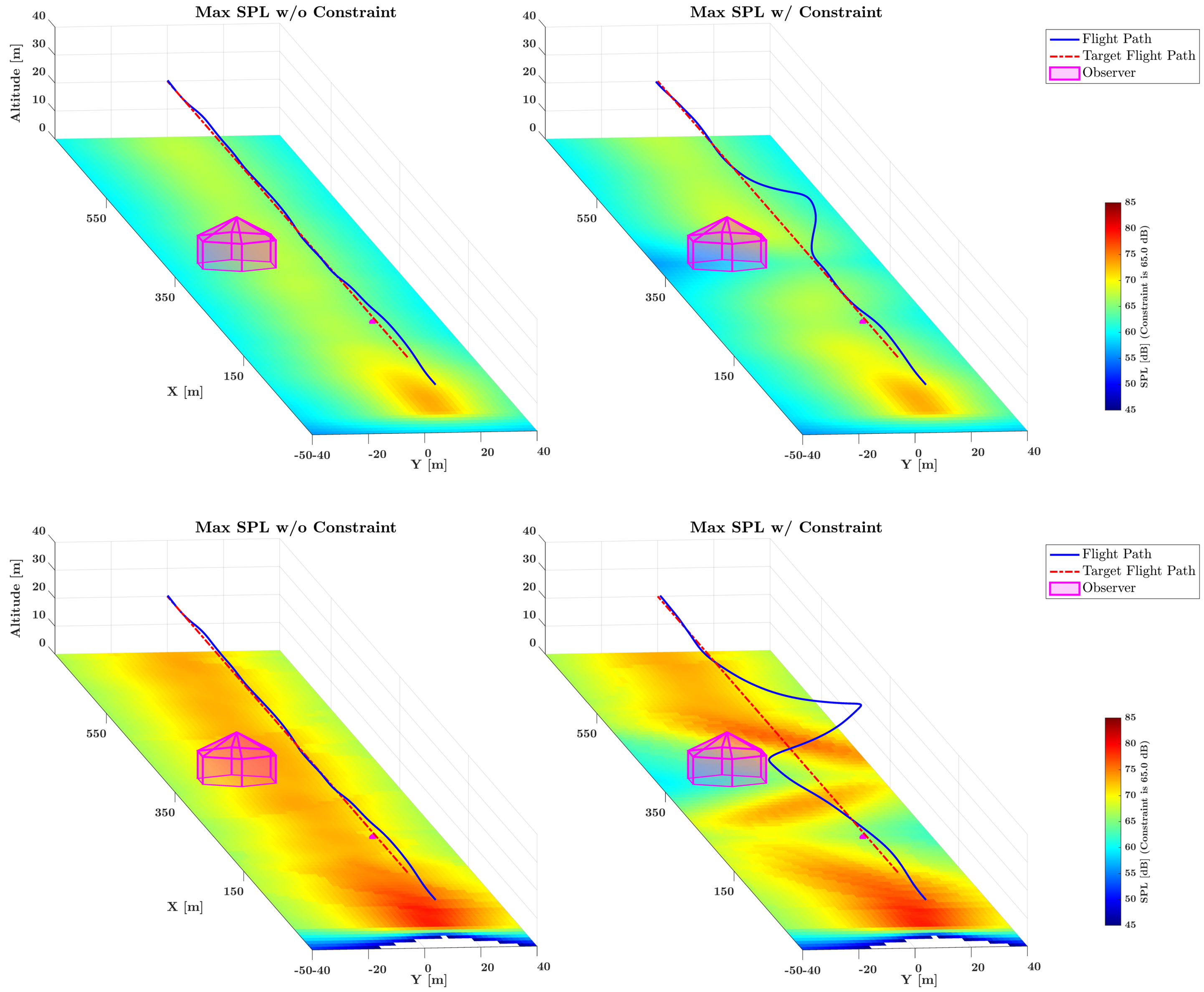
Hemisphere Model



Noise Model Comparison – MPC Planner

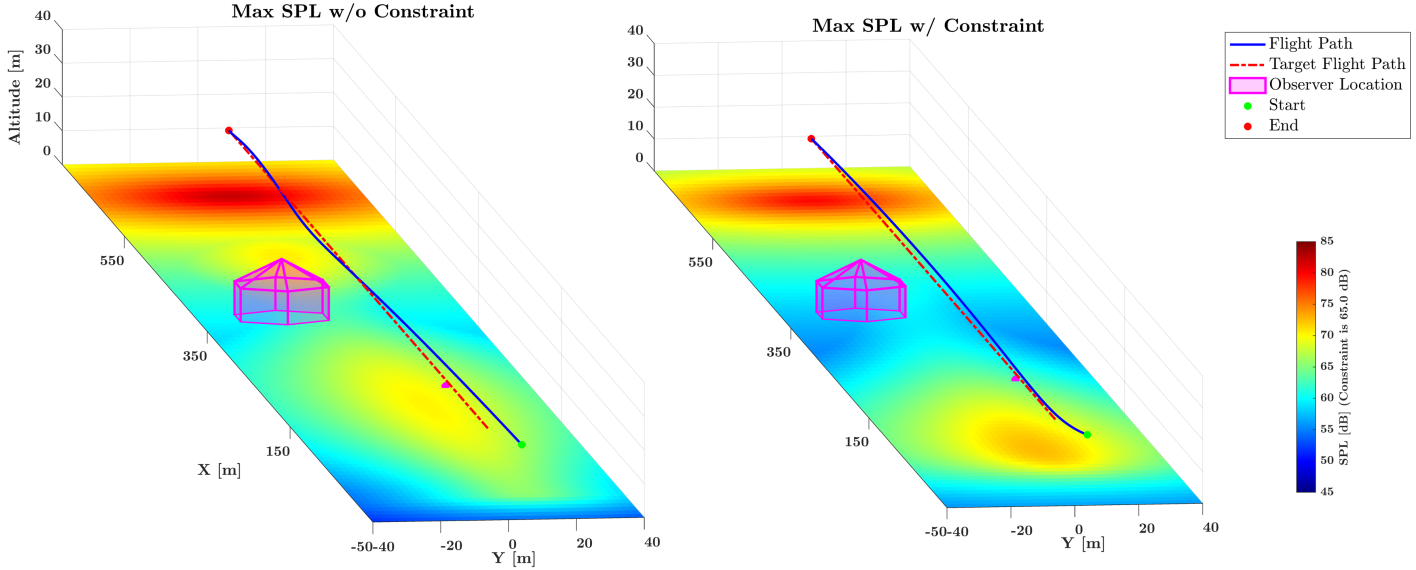
Omni-Directional Model

Hemisphere Model

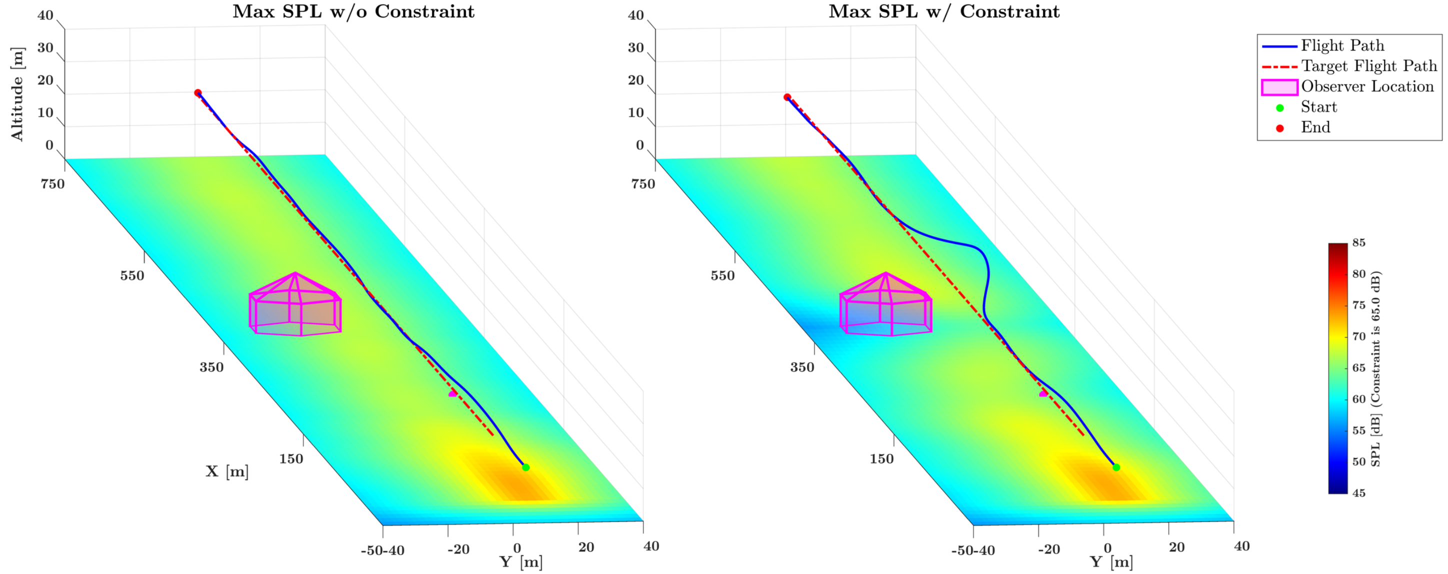


Planner Comparison – Omni-directional model

Pre-mission Planner



MPC Planner



Planner Comparison – Hemisphere Model

Pre-Mission Planner

MPC Planner