Autonomy Capabilities for Self-Propelled and Wind-Driven Aerobots

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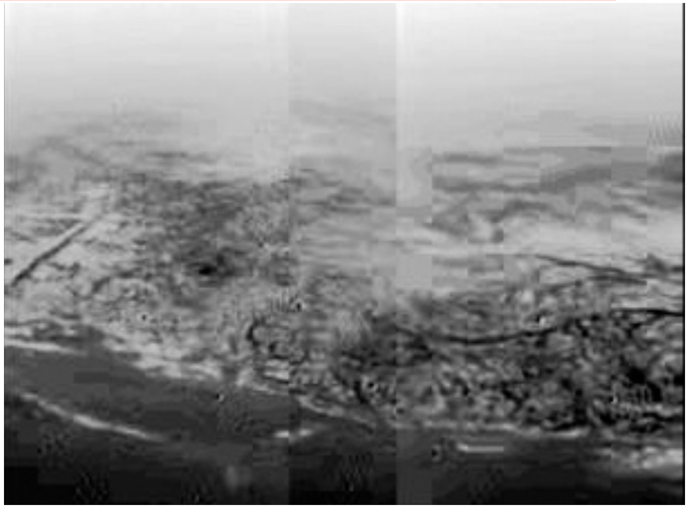
Exploring Titan

- The Titan environment is very well suited for exploration by aerobot (robotic lighter-than-air) vehicles:
  - The dense atmosphere (4.5x higher than on Earth) allows for large payloads carried by compact vehicles
  - The atmosphere is clear below 10 km allowing for high resolution imaging
  - Huygens measured very low wind speeds near the surface, allowing for slow overflights and/or station-keeping by self-propelled aerobots
  - The 90 K cryogenic temperature allows for hot air ("Montgolfiere") balloons with MMRTG-like ~2 kW heat inputs (on Earth it takes 50 – 100 kW of heat because of the much greater radiative heat losses)
- A Titan aerobot will face challenges that include:
  - A largely unknown environment of operation (due to hydrocarbonate haze in the upper atmosphere and limited Huygens/Cassini data)
  - Complex topography: max elevation ~2 km
  - Nominal round-trip comm time: 2.6 h
  - Comm blackouts of up to 9 days, depending on Titan rotation (16 days) and occlusion by Saturn
  - Wind: <1 m/s at surface to 20 m/s at 20 km



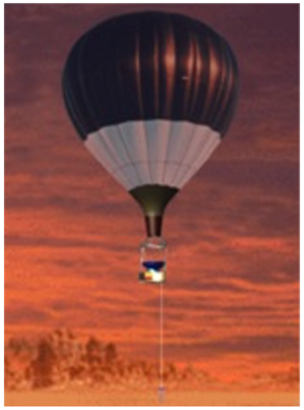
Huygens aerial view of Titan

Titan Montgolfiere balloon concept

Titan Aerobot Options

Montgolfiere (hot air) Balloon

Wind-driven

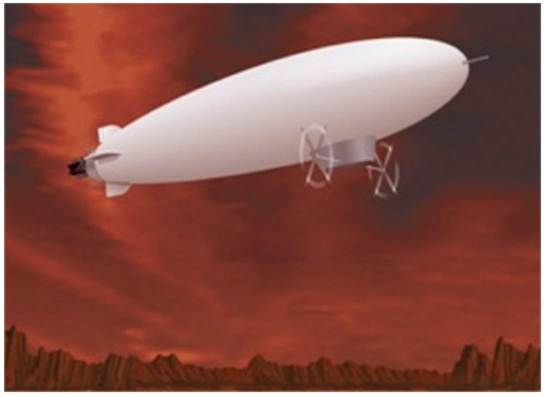


- Buoyancy produced by RTG-heated ambient atmosphere
- Altitude control via gas venting
- Moves with the winds
- Limited trajectory control via different wind directions at different altitudes
- Can acquire surface samples
- No loitering or station-keeping
- Essentially unlimited lifetime

Self-propelled

- Same as wind-driven Montgolfiere except for addition of 1 or more propellers for augmented trajectory control and station-keeping under some conditions.

Self-propelled Airship (blimp)



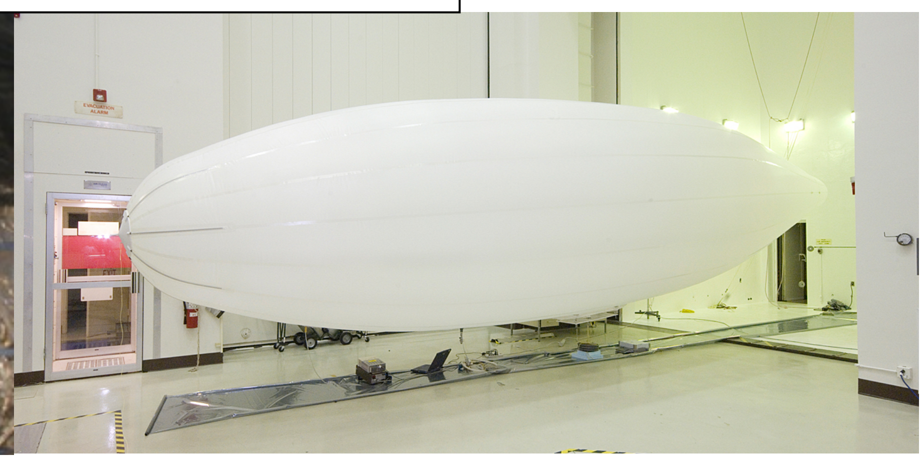
- Buoyancy produced by hydrogen gas
- Altitude control primarily via propulsion
- Propellers generate 1-2 m/s flight speeds for precise trajectory control
- Loitering and station-keeping possible under expected Titan wind speeds
- Can acquire surface samples
- Lifetime limited by loss of hydrogen, but some replenishment possible from atmospheric methane

Aerobot Technology Status (1)

- JPL has been working on Montgolfiere balloon technology since the mid-1990s
- Since 2002, JPL has invested substantial resources to mature a broad spectrum of Titan-specific aerobot technologies centering on the key problems of:
  - **The 90 K cryogenic Titan environment** requires alternate balloon construction materials, payload thermal protection and balloon thermodynamic design modifications
  - The remoteness of Titan from Earth (2+ hours round trip light time) precludes human piloting and requires **significantly autonomous operations**
  - An aerobot must be folded up for the trip to Titan and then **automatically deployed and inflated upon arrival**.
- Progress has been made in many areas to build confidence in the viability of both Montgolfiere and powered blimp vehicles for Titan

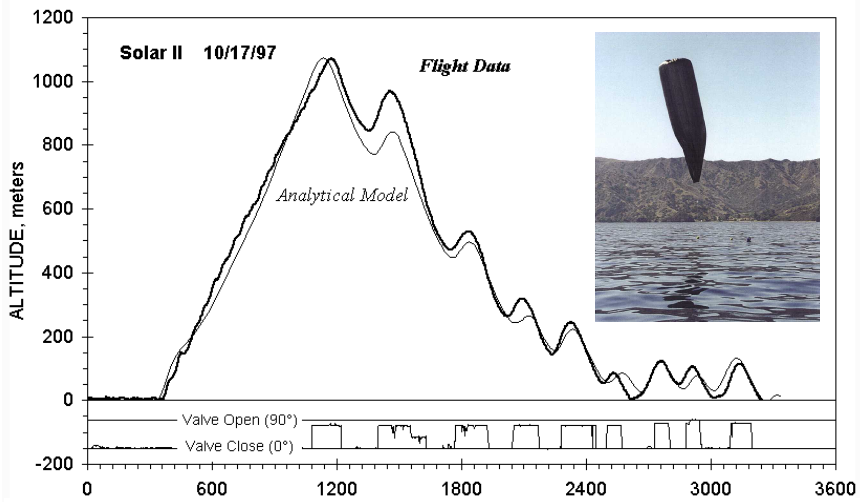
Successful development of 93 K balloon material

4.3 m blimp tested at 93 K



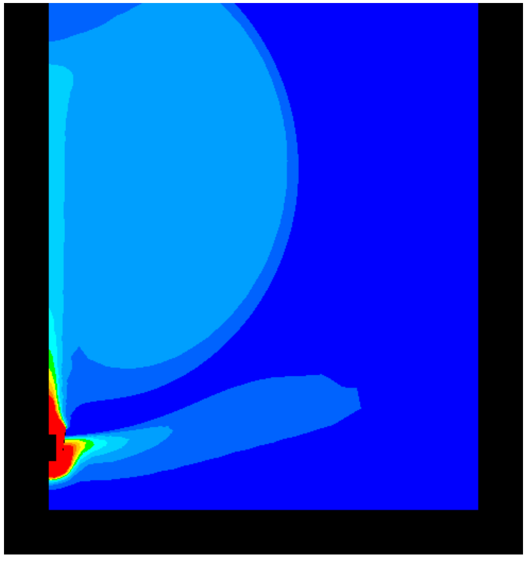
13 m blimp leak test

Aerobot Technology Status (2)

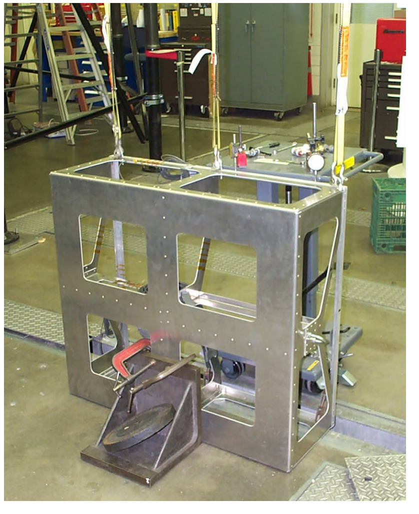


Earth solar Montgolfiere altitude control flight tests (1997)

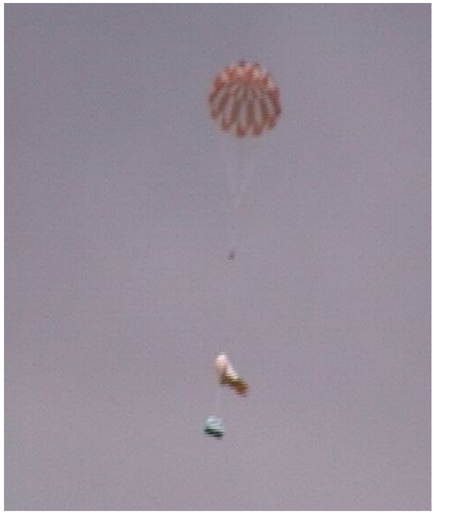
JPL autonomy flight tests (since 2002)



Montgolfiere CFD analysis



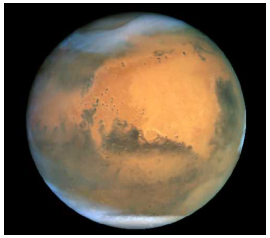
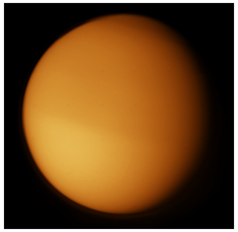
Gondola structural mockup static load test



Aerial deployment & inflation test

Robotic Exploration: Autonomy

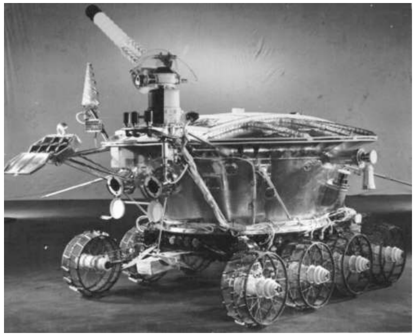


~1 - 10 s

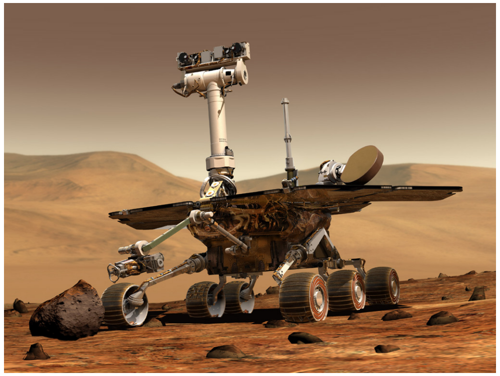
~10 - 30 min

> 1 h



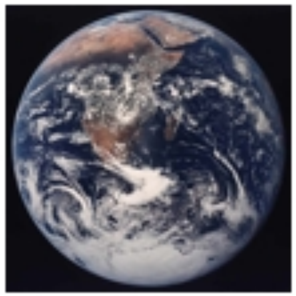
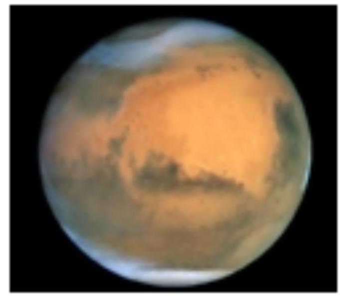
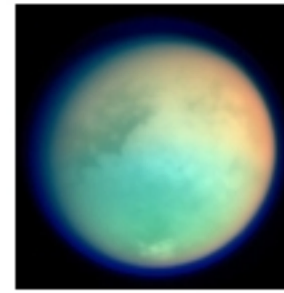
Teleoperation

Batch Autonomy

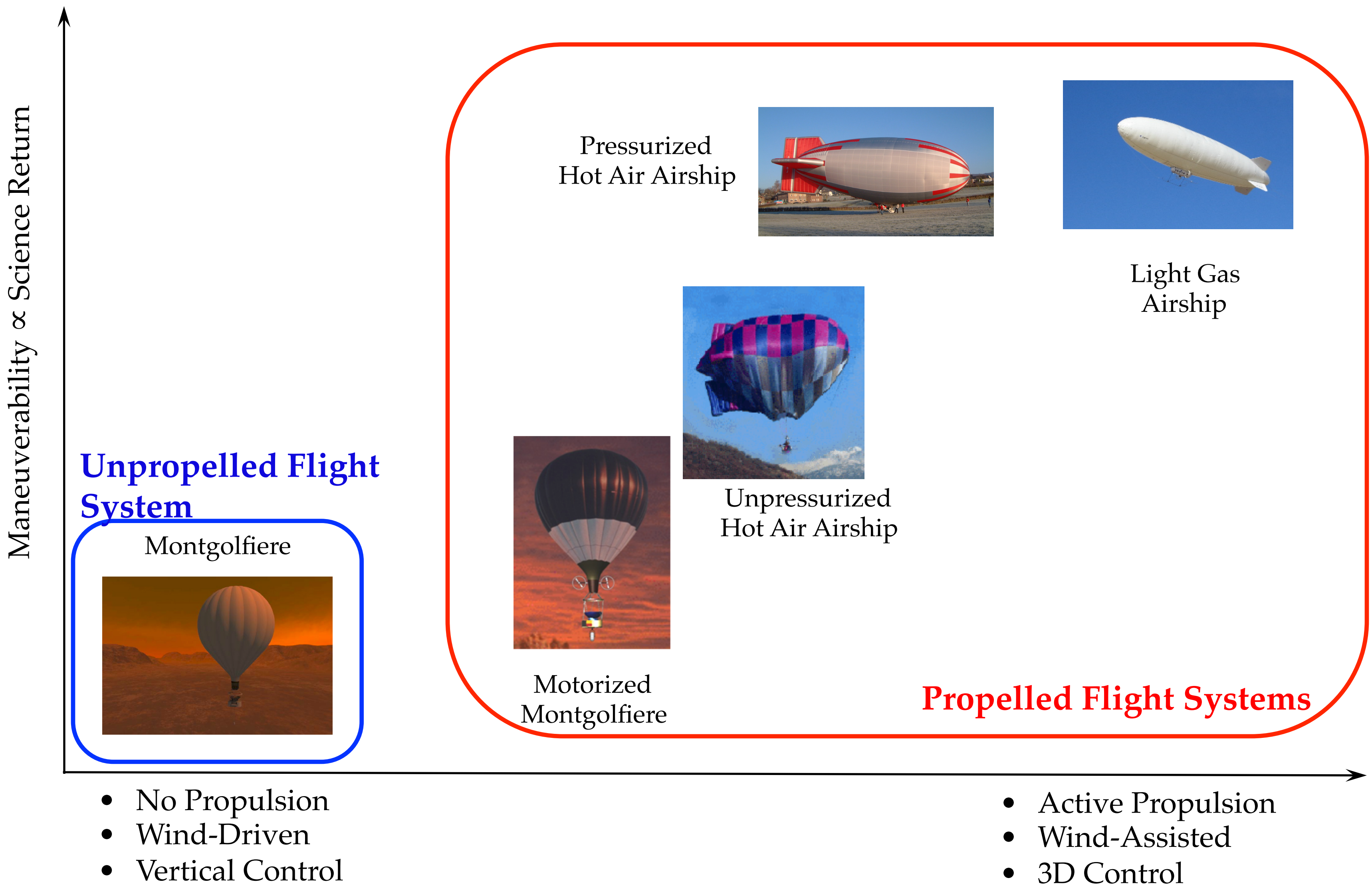


Unsupervised Autonomy

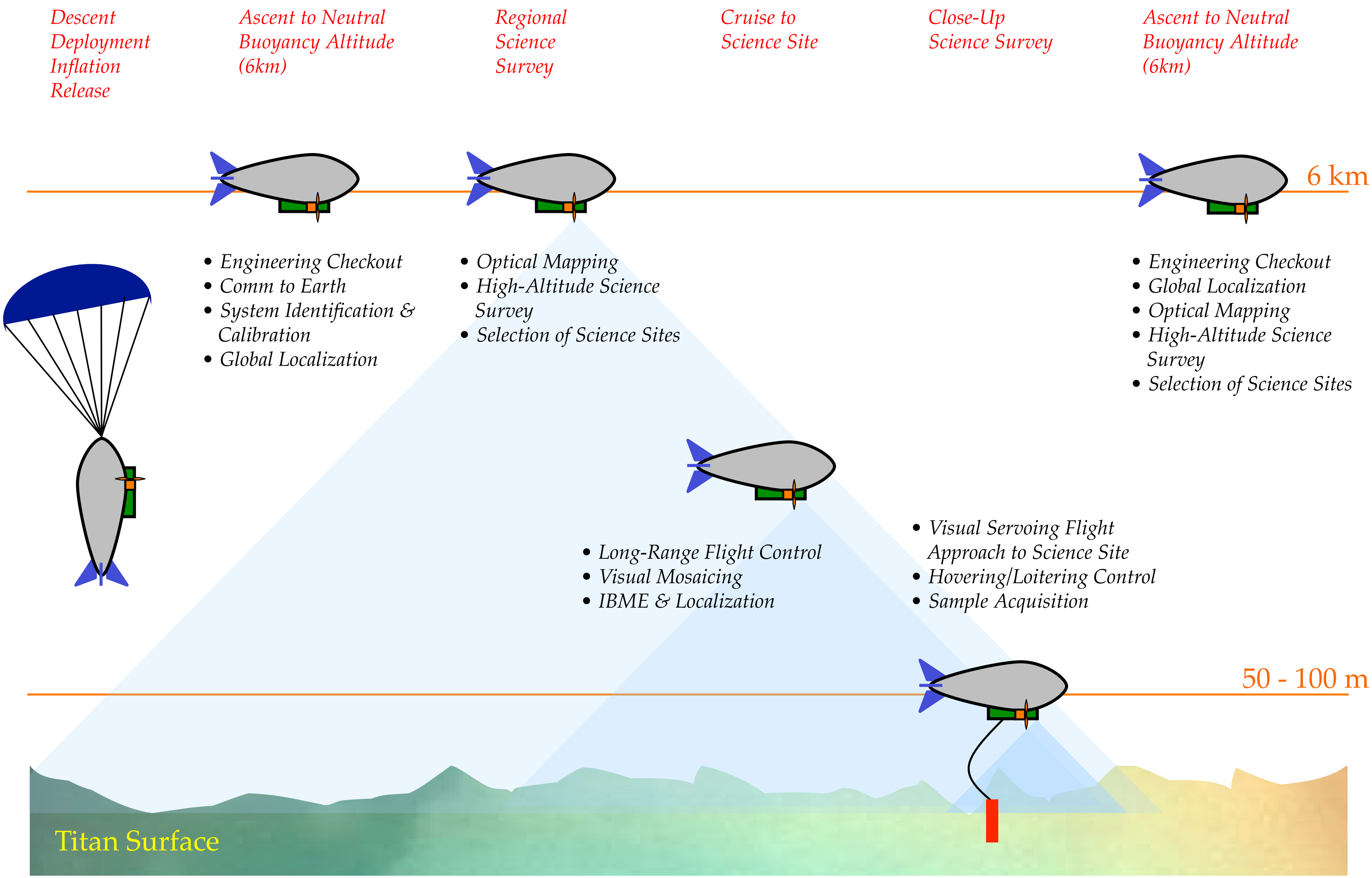
Robotic Exploration: Autonomy

In-Situ Exploration Systems			
Target			
Vehicle			
Environment	Known	Partially known	Largely unknown
Autonomy	Telerobotics	Batch autonomy	Unsupervised autonomy
Safety	Return to base	Stop and call home	Active vehicle safing

Aerobot Design Space



Aerobot Flight Phases

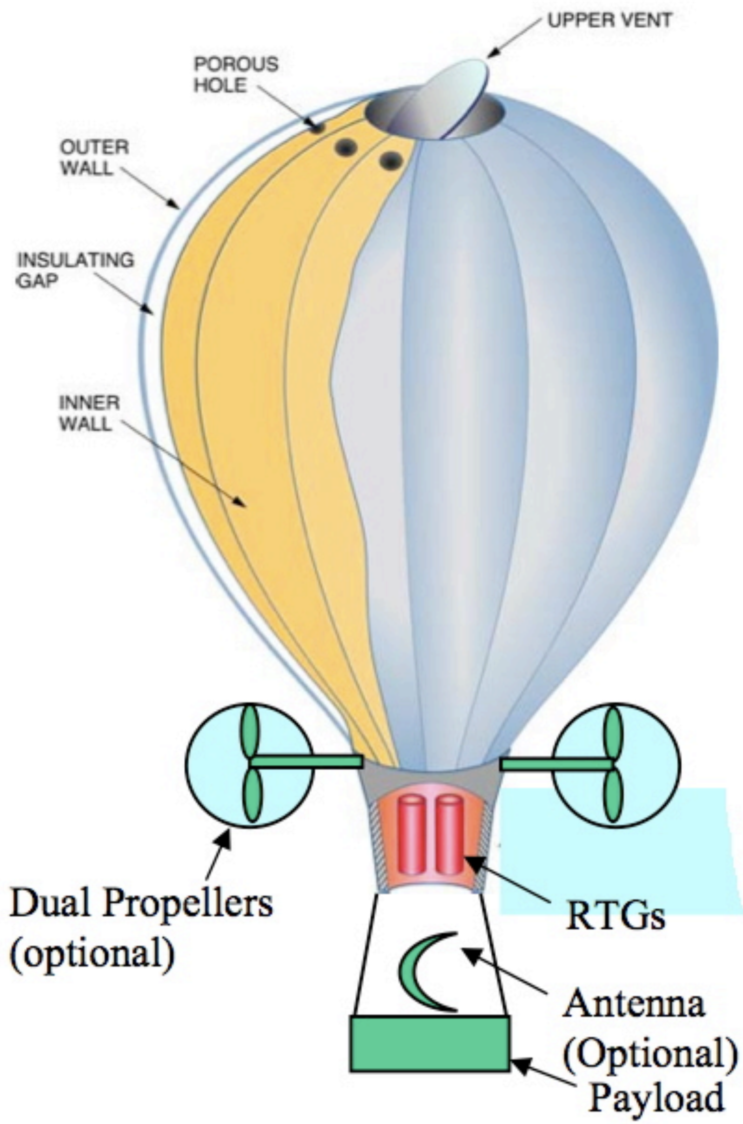


Core Aerobot Autonomy Technologies

TITAN AEROBOT AUTONOMY DEVELOPMENT AREAS		
Core Technologies	**Passive Flight System**	**Active Flight System**
Aerobot Modelling		
State Estimation		
Flight Control		
Sensing and Mapping		
Navigation		
Science Autonomy		
Surface Sampling		
Aerobot Autonomy Architecture		
Mission Operations		
Aerobot Testbed		
Flight Testing		

JPL Aerobot Testbed

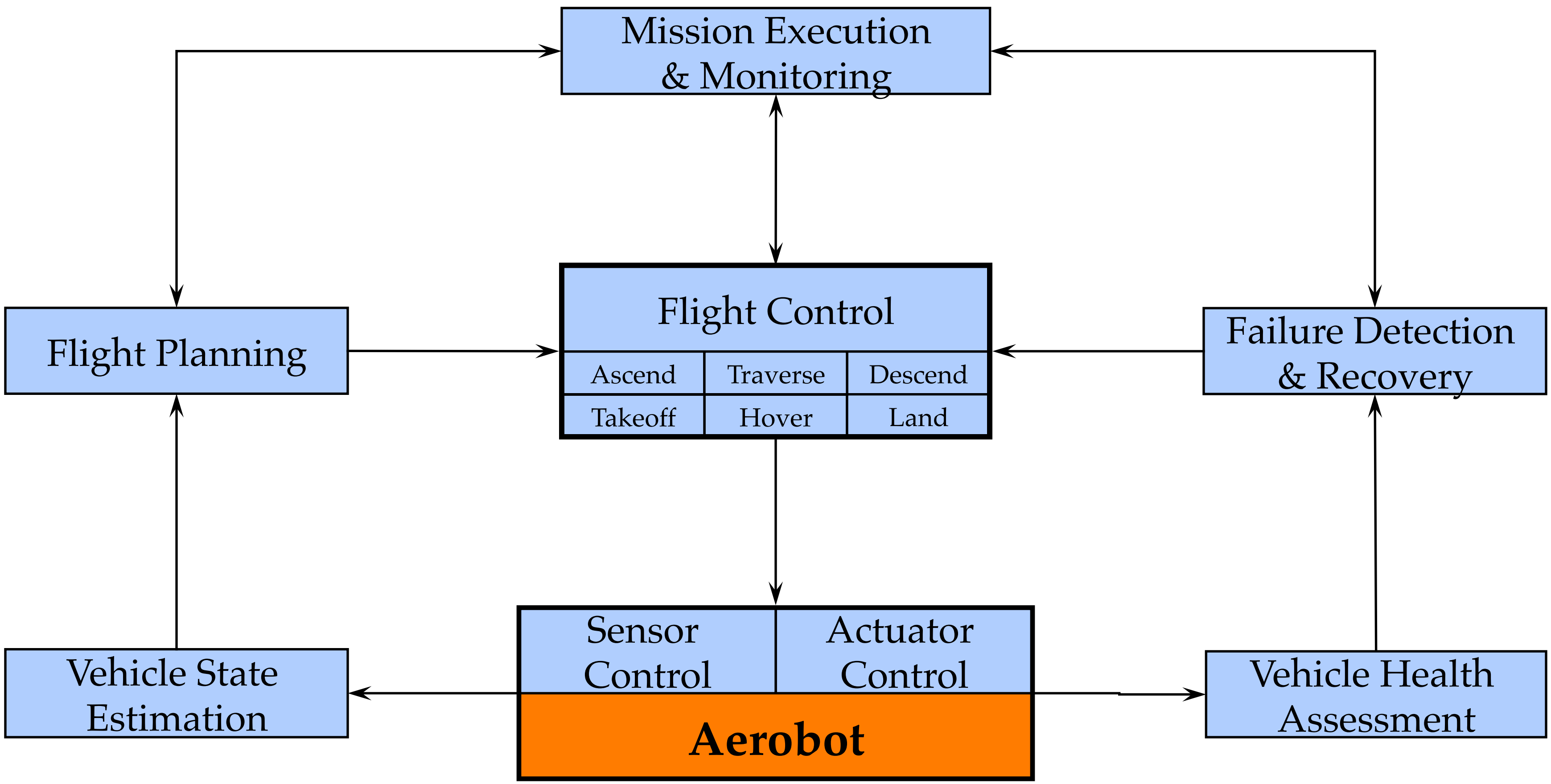
Aerobot Montgolfiere Testbed



Aerobot Flight Testing: SCLA / Mojave

Video 1

Aerobot Autonomy Architecture



Aerobot Modeling: Kinematics

$$\begin{pmatrix} \dot{R}_x \\ \dot{R}_y \\ \dot{R}_z \end{pmatrix} = R_z(-\psi) R_y(-\theta) R_x(-\phi) \begin{pmatrix} u \\ v \\ w \end{pmatrix}$$

$$\begin{pmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{pmatrix} = \begin{bmatrix} 1 & \tan\theta \sin\phi & \tan\theta \cos\phi \\ 0 & \cos\phi & -\sin\phi \\ 0 & \dfrac{\sin\phi}{\cos\theta} & \dfrac{\cos\phi}{\cos\theta} \end{bmatrix} \begin{pmatrix} p \\ q \\ r \end{pmatrix}$$

$$u = V \cos\beta \cos\alpha$$

$$v = V \sin\beta$$

$$w = V \cos\beta \sin\alpha$$

$$\tan\alpha = w / u$$

$$\sin\beta = v / V$$

$$V^2 = (u - W_x)^2 + (v - W_y)^2 + (w - W_z)^2$$

R_x, R_y, R_z = components of distance of point mass from Titan's center

ψ = attitude yaw angle of flight vehicle wrt. local tangent plane

θ = attitude pitch angle of flight vehicle wrt. local tangent plane

ϕ = attitude roll angle of flight vehicle wrt. local tangent plane

u = velocity component along body-fixed x-axis

v = velocity component along body-fixed y-axis

w = velocity component along body-fixed z-axis

α = angle of attack

β = angle of sideslip

W_x, W_y, W_z = components of wind speed in body frame

Aerobot Modeling: Dynamics

$$(m - X_{\dot u})\dot u = (m - Y_{\dot v})rv - (m - Z_{\dot w})qw + m\left[d_x\left(r^2 + q^2\right) - d_z pr\right] - \left(md_z - X_{\dot q}\right)\dot q + [-mg + B]\sin\theta + X + T_x$$

$$(m - Y_{\dot v})\dot v = (m - Z_{\dot w})\,pw - (m - X_{\dot u})ru + m[-d_x pq - d_z pr] - (md_x - Y_{\dot r})\dot r - \left(-md_z - Y_{\dot p}\right)\dot p + [mg - B]\cos\theta\sin\phi + Y + T_y$$

$$(m - Z_{\dot w})\dot w = (m - X_{\dot u})qu - (m - Y_{\dot v})\,pv + m\left[-d_x pr + d_z\left(p^2 + q^2\right)\right] + \left(-md_x - Z_{\dot q}\right)\dot q + [mg - B]\cos\theta\cos\phi + Z + T_z$$

$$\left(J_{xx} - L_{\dot p}\right)\dot p = -\left(J_{zz} - J_{yy}\right)qr + J_{xz}\left(\dot r + pq\right) + md_z\left(ur - wp\right) + \left(-md_z - L_{\dot v}\right)\dot v + L + L_T + B_p + W_p$$

$$\left(J_{yy} - M_{\dot q}\right)\dot q = -\left(J_{xx} - J_{zz}\right)pr + J_{xz}\left(r^2 - p^2\right) + md_x\left(vp - uq\right) - md_z\left(wq - vr\right) - \left(md_z - M_{\dot u}\right)\dot u - \left(-md_x - M_{\dot w}\right)\dot w + M + M_T + B_q + W_q$$

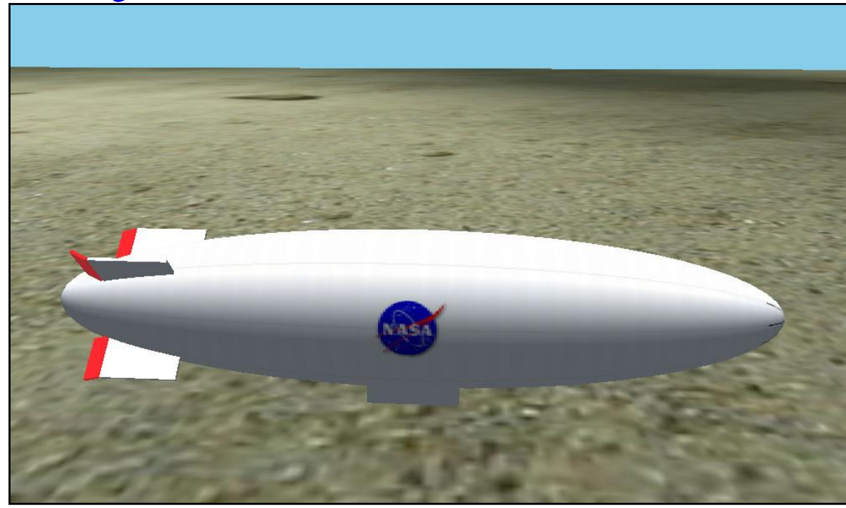
$$\left(J_{zz} - L_{\dot r}\right)\dot r = -\left(J_{yy} - J_{xx}\right)pq + J_{xz}\left(\dot p - qr\right) - md_x\left(ur - wp\right) + \left(md_x - N_{\dot v}\right)\dot v + N + N_T + B_r + W_r$$

$$L = qSbC_l$$
$$M = qScC_m$$
$$N = qSbC_n$$
$$X = -D\cos\alpha + L\sin\alpha$$
$$Y = -C\cos\beta + D^{*}\sin\beta$$
$$Z = -D\sin\alpha - L\cos\alpha$$
$$D = D^{*}\cos\beta - C\sin\beta = qSC_D$$
$$L = qSC_L$$
$$C = qSC_Y$$

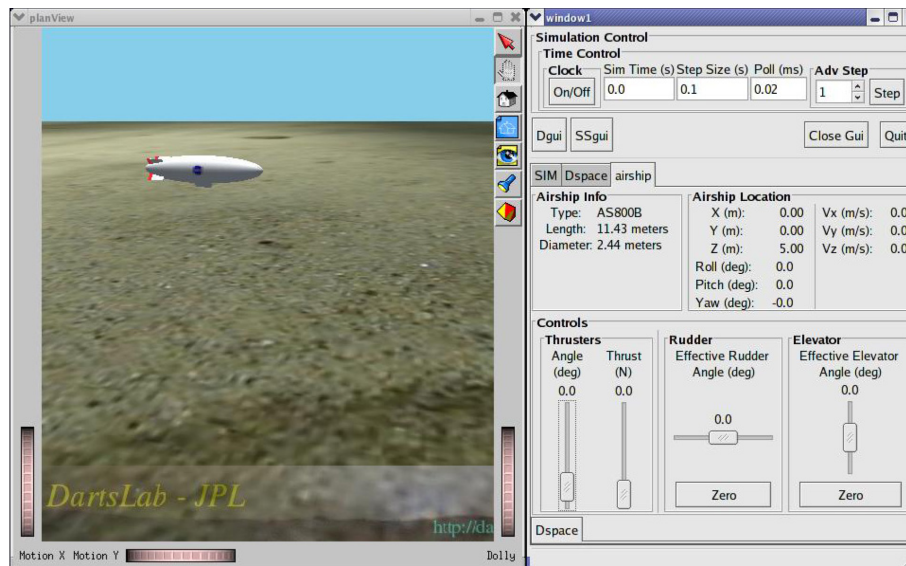
m = total vehicle mass
B_x, B_y, B_z = components of buoyancy in body frame
T_x, T_y, T_{z7} = components of thrust in body frame
D^{*} = drag force, L = lift force, C = side force
q = dynamic pressure, S = exposed area
X_u, Y_v, Z_w = components of added mass in body frame
J_{xx}, J_{yy}, J_{xx}, J_{xz} = total vehicle moments of inertia
d_x, d_z = distances from center of mass to CB=CV in body frame
B_p, B_q, B_r = components of buoyancy torques in body frame
W_p, W_q, W_r = components of weight torques in body frame
L, M, N = aerodynamic force moments in body frame
L_T, M_T, N_T = components of thrust moment in body frame
X_u, Y_v, Z_w = components of added mass in body frame

DARTS Aerobot Aerodynamic Simulator

- Created in Darts/Dshell environment.
- High-fidelity physics model for aerodynamics, mass properties, buoyancy, kinematics, dynamics, control surfaces, etc.
- Generic, parameterized model suitable to represent many types of aerobots.
- Initial implementation based on parameters for JPL's airship.
- Will serve as simulation platform to develop control software.
- GUI available to test controls and monitor airship response. Simulations run with or without GUI.

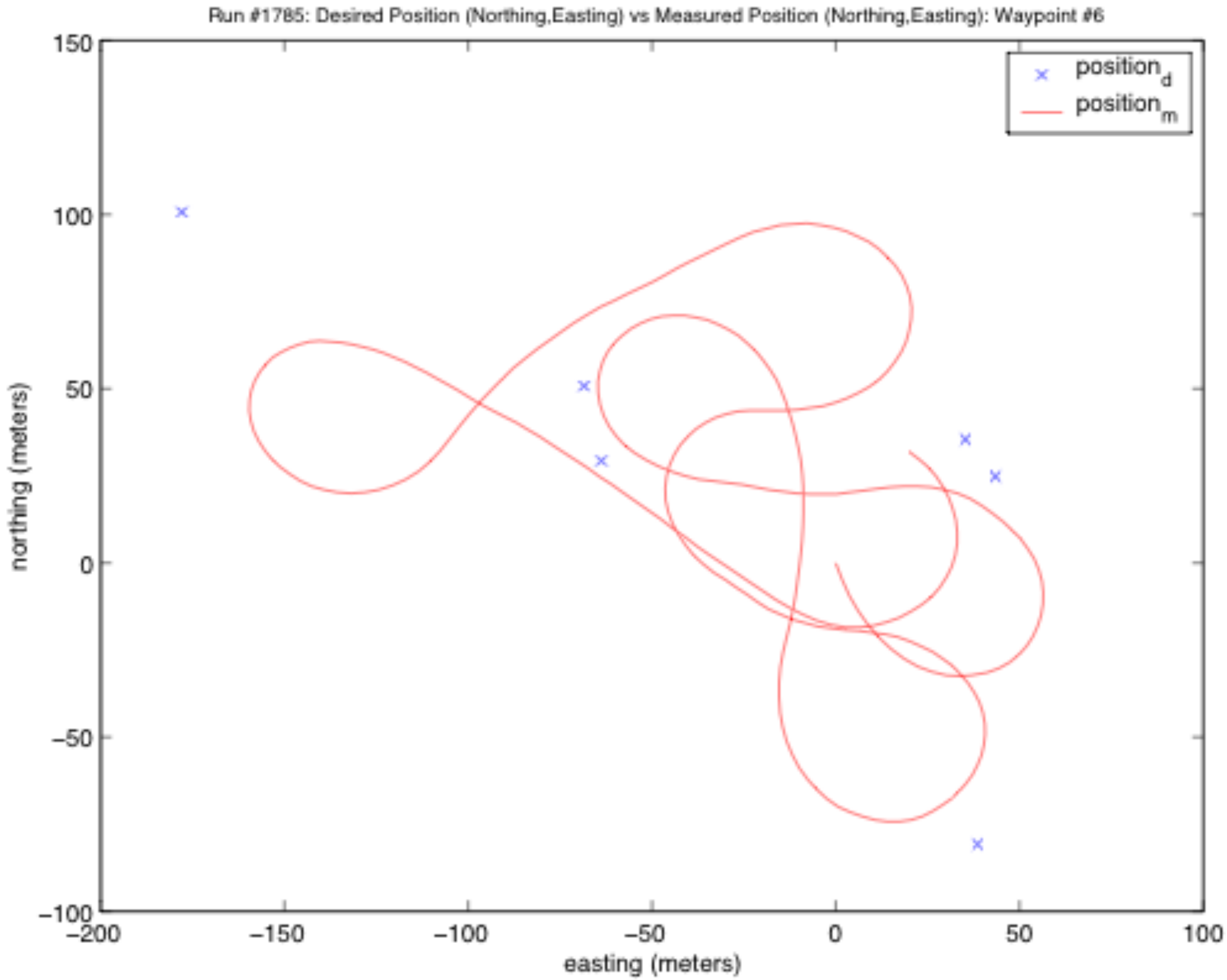


AS800B Airship Simulation

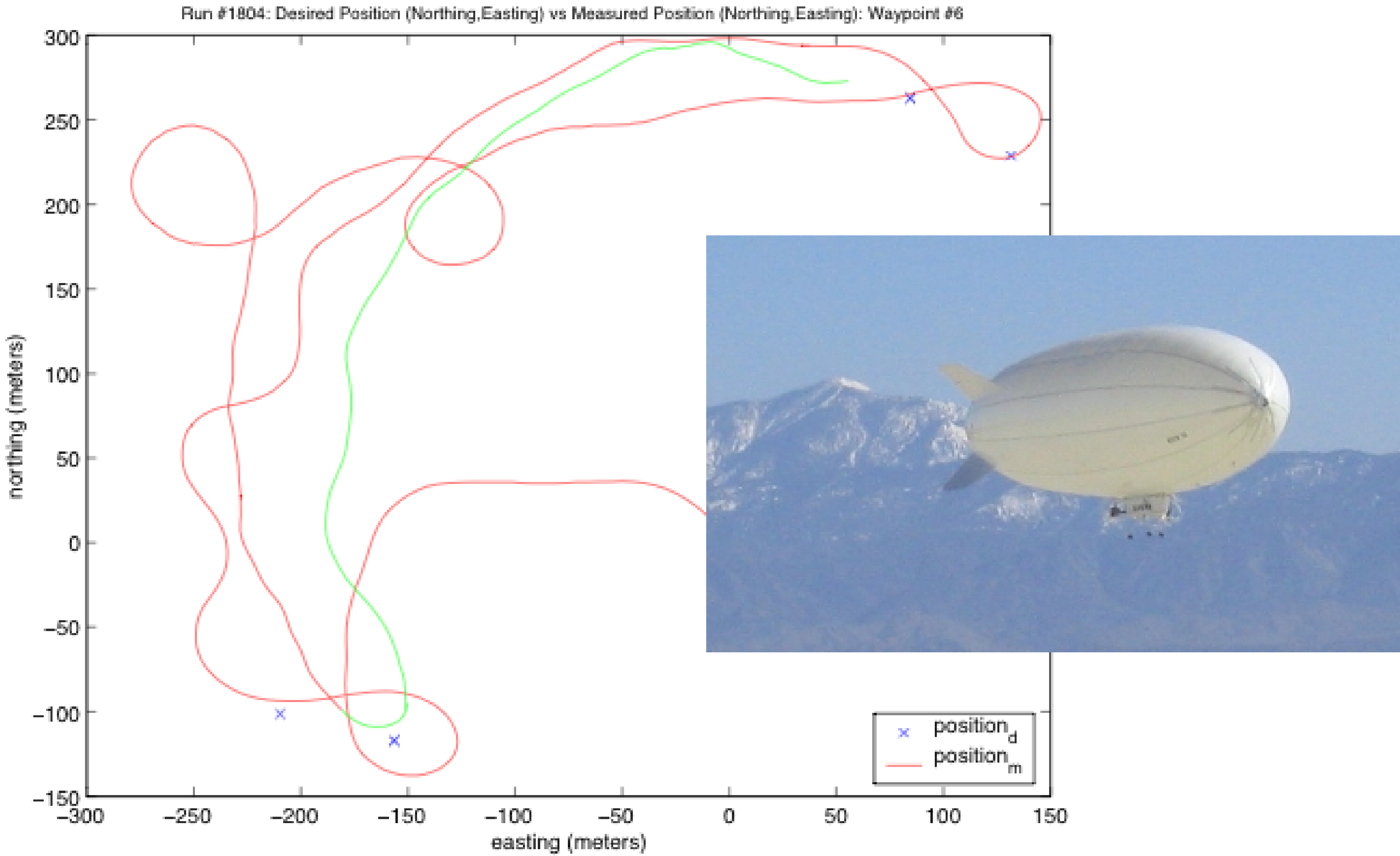


Simulation with Control Interface GUI

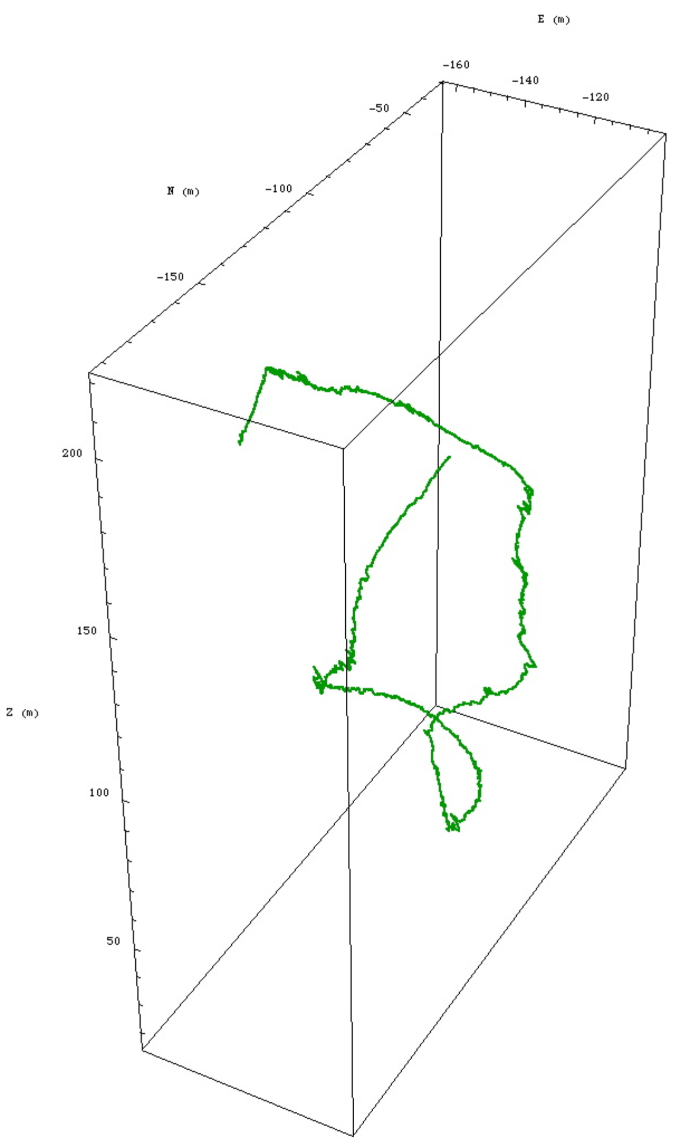
Waypoint Navigation: Orientieering

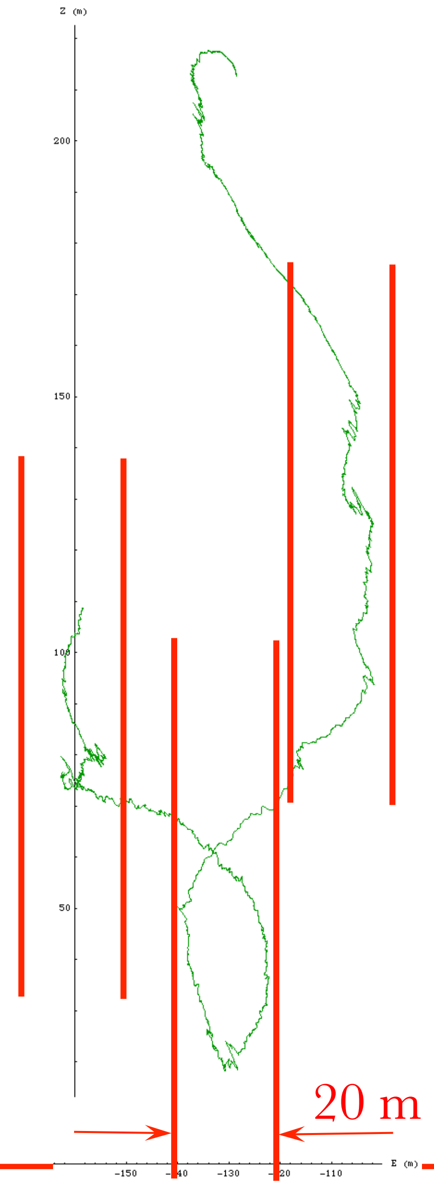


Autonomous Flight Control: Severe Wind Disturbances



Hover / VAD Experiments





Vision-Assisted Flight Control

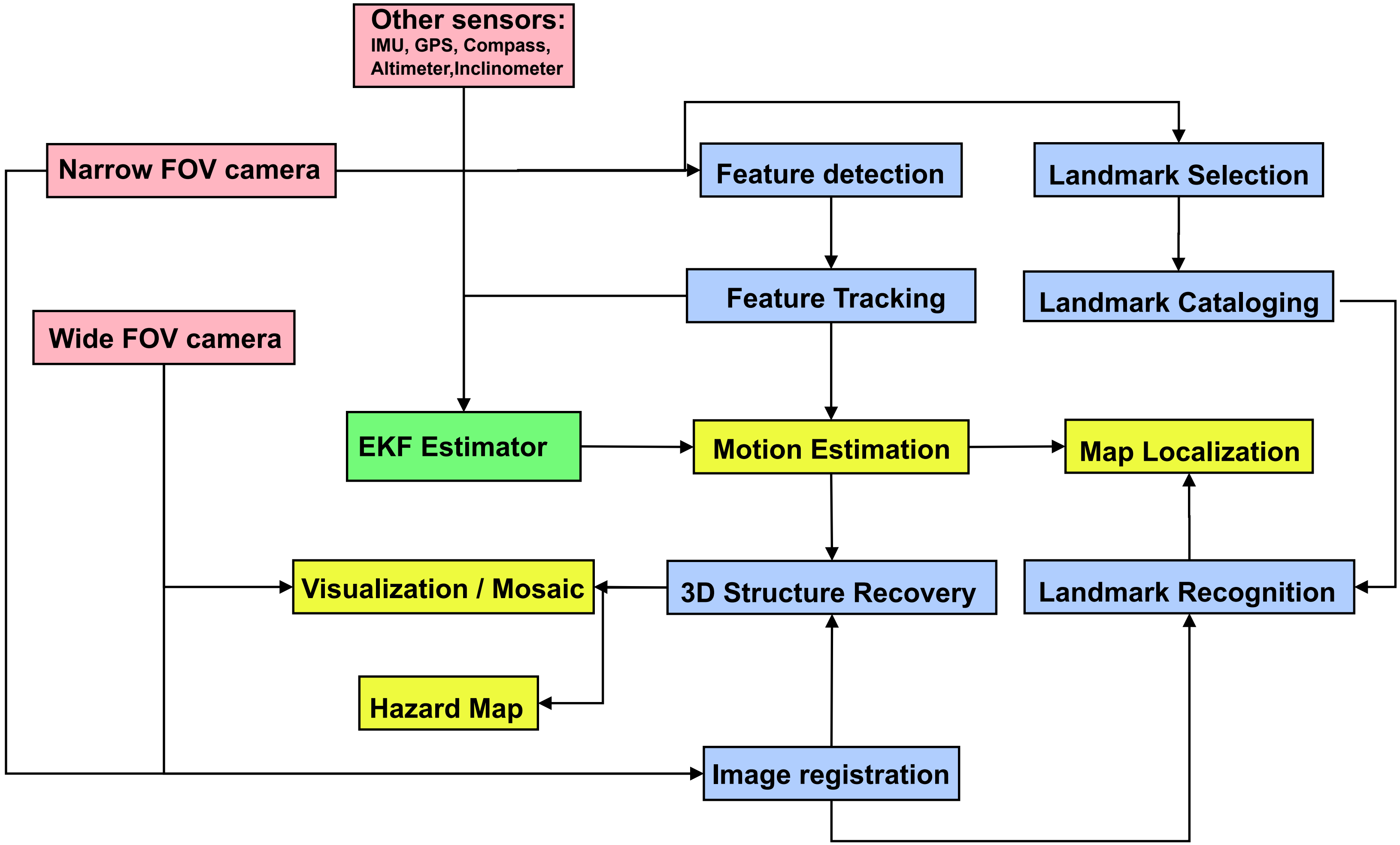
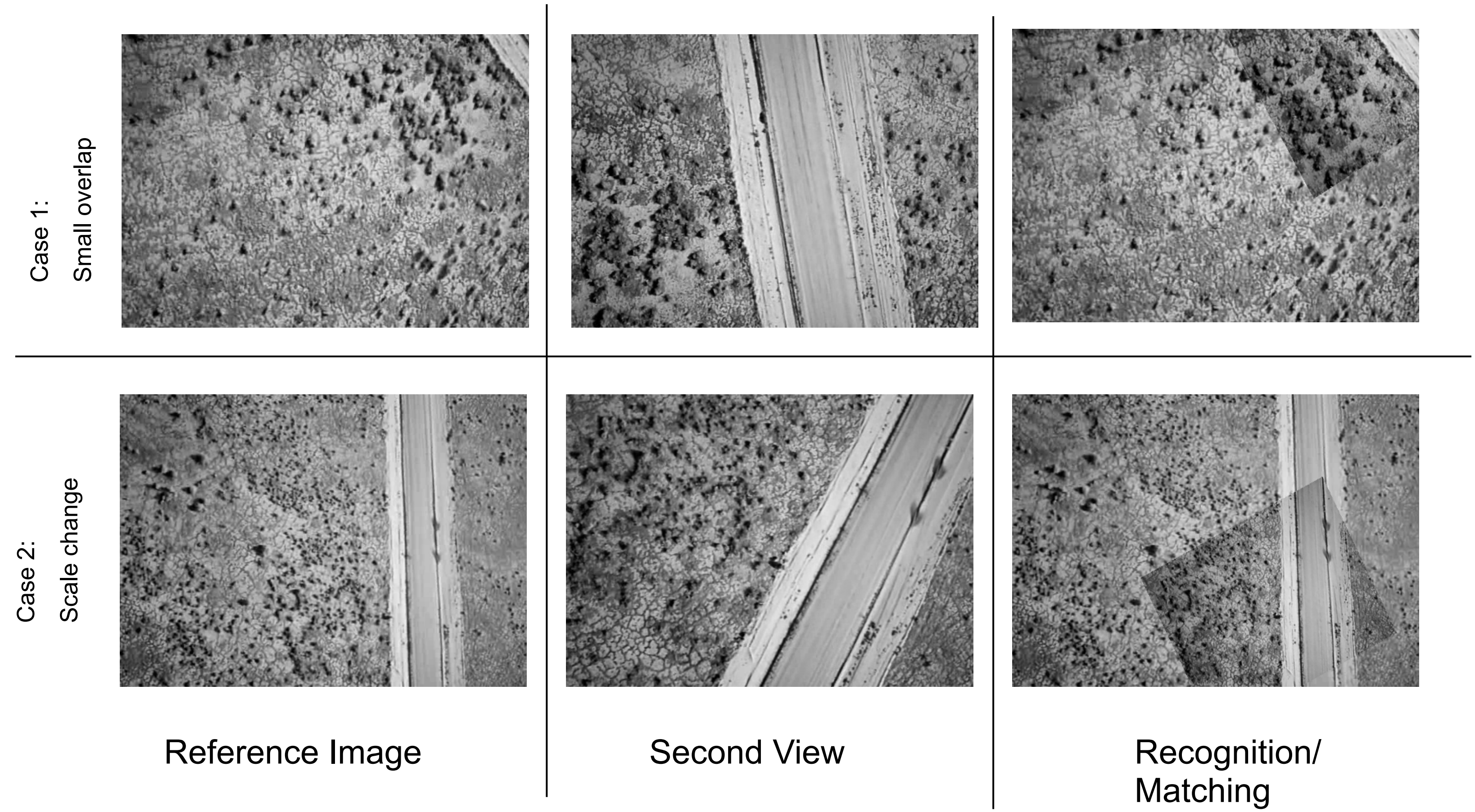
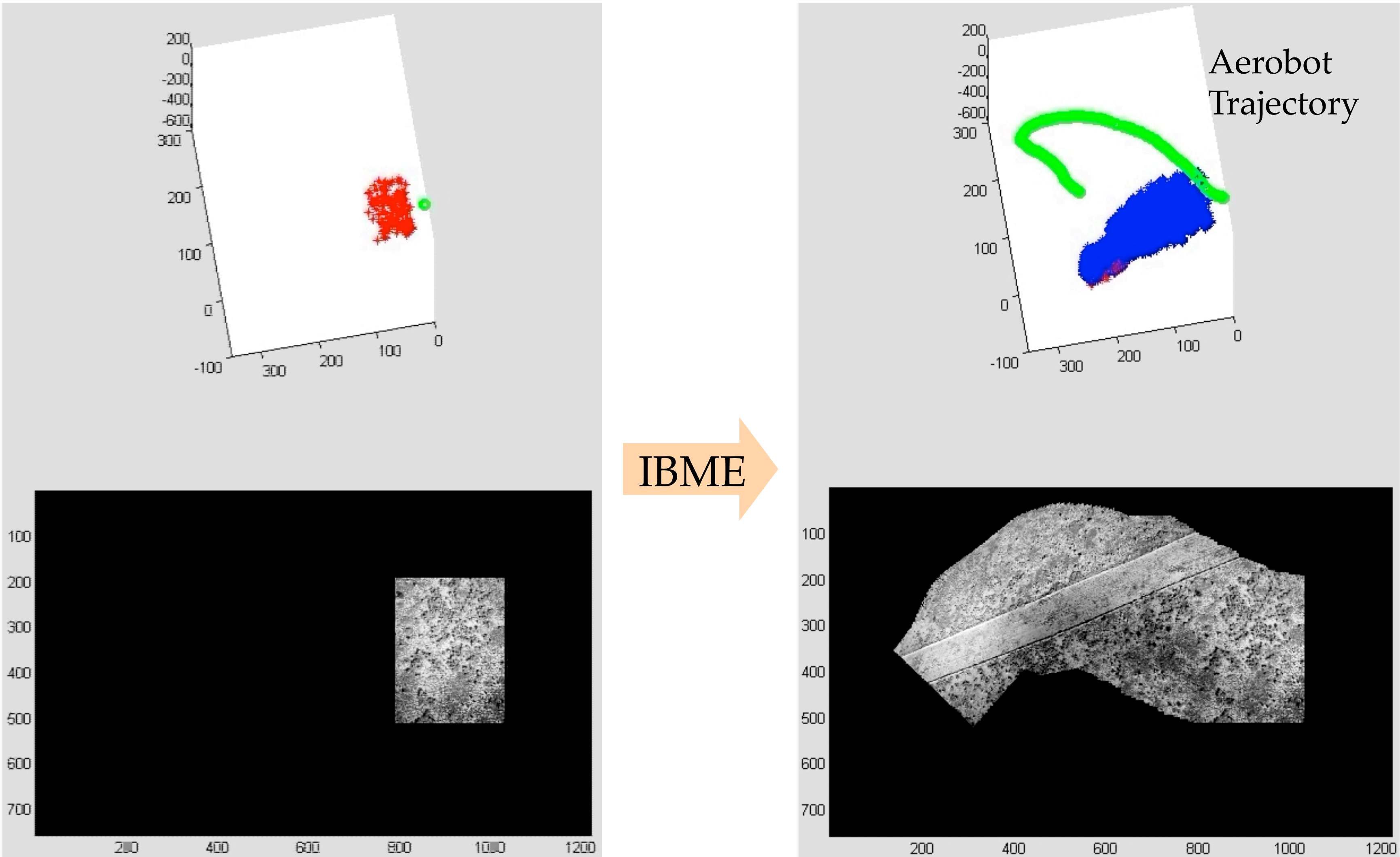


Image-Based Localization



GPS-Denied Operation Using IBME



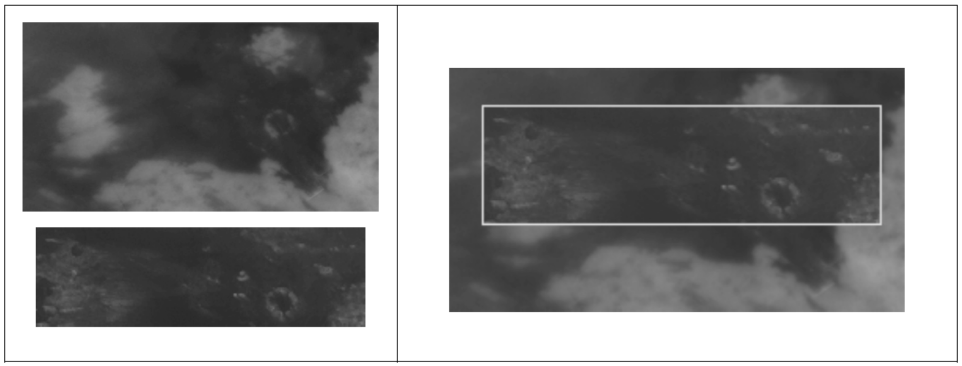
Mosaicked Visual Map

Aerobot Flight Testing: SCLA / Mojave

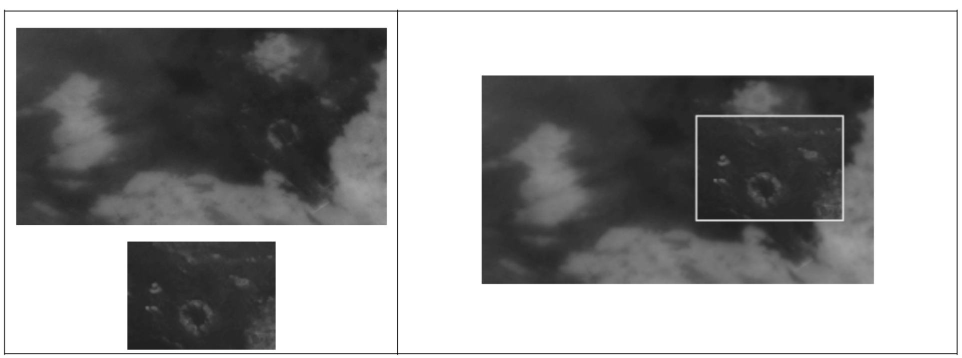
Video 2

Orbital Multi-Modal Image Registration

- Mutual Information approach: uses statistical measure of image similarity based on joint and marginal probabilities
- Capable of matching across widely varying sensor response



Large SAR template matched to ISS Image – Large overlap region provides easier overall match but subject to geometric distortion

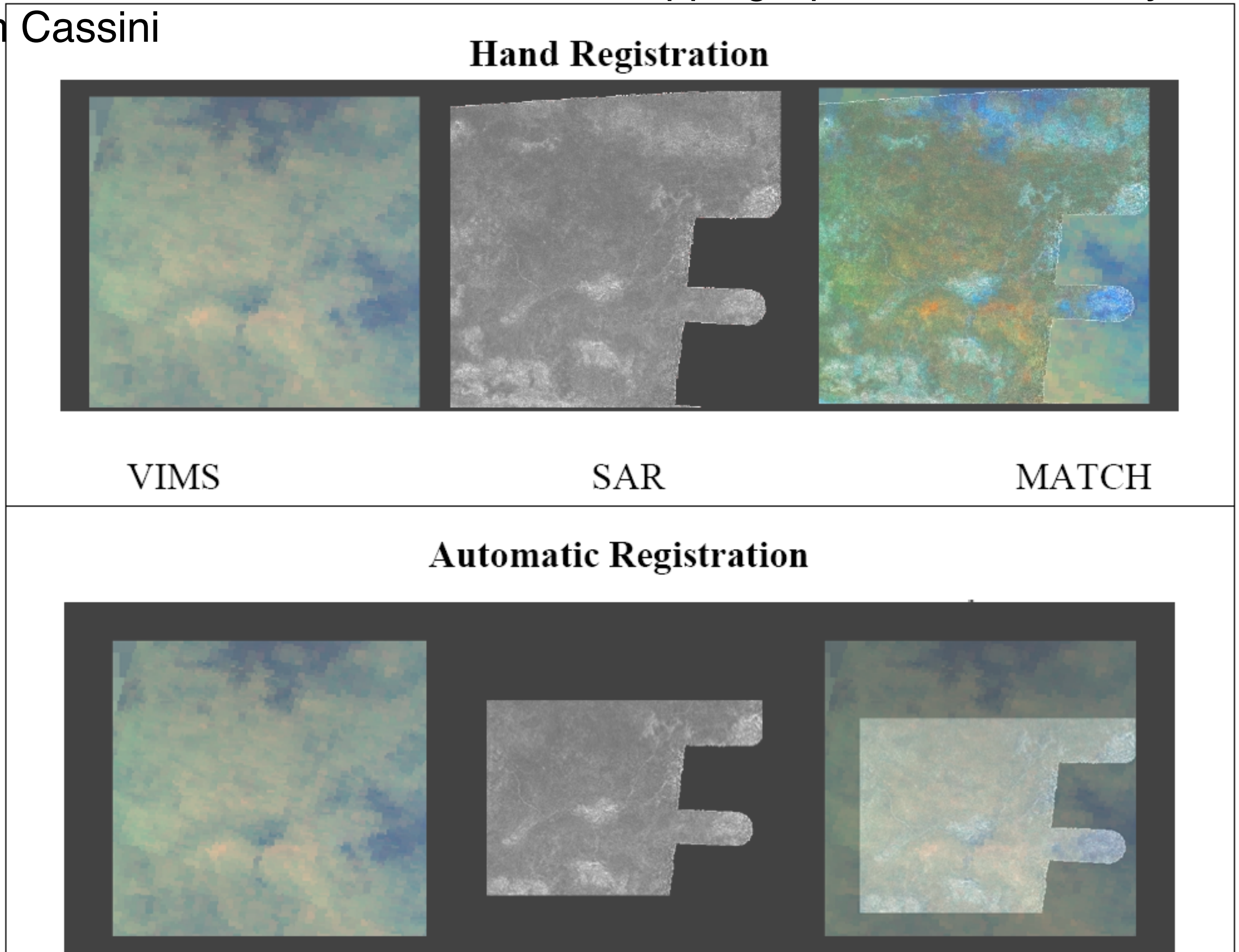


Small SAR template matched to ISS Image – Small overlap region harder to match without initialization but suffers from little distortion. Note that in this case, the match is blind, i.e. no initialization was required.

Match between Imaging Science Subsystem (ISS) and Synthetic Aperture Radar (SAR) data from Cassini

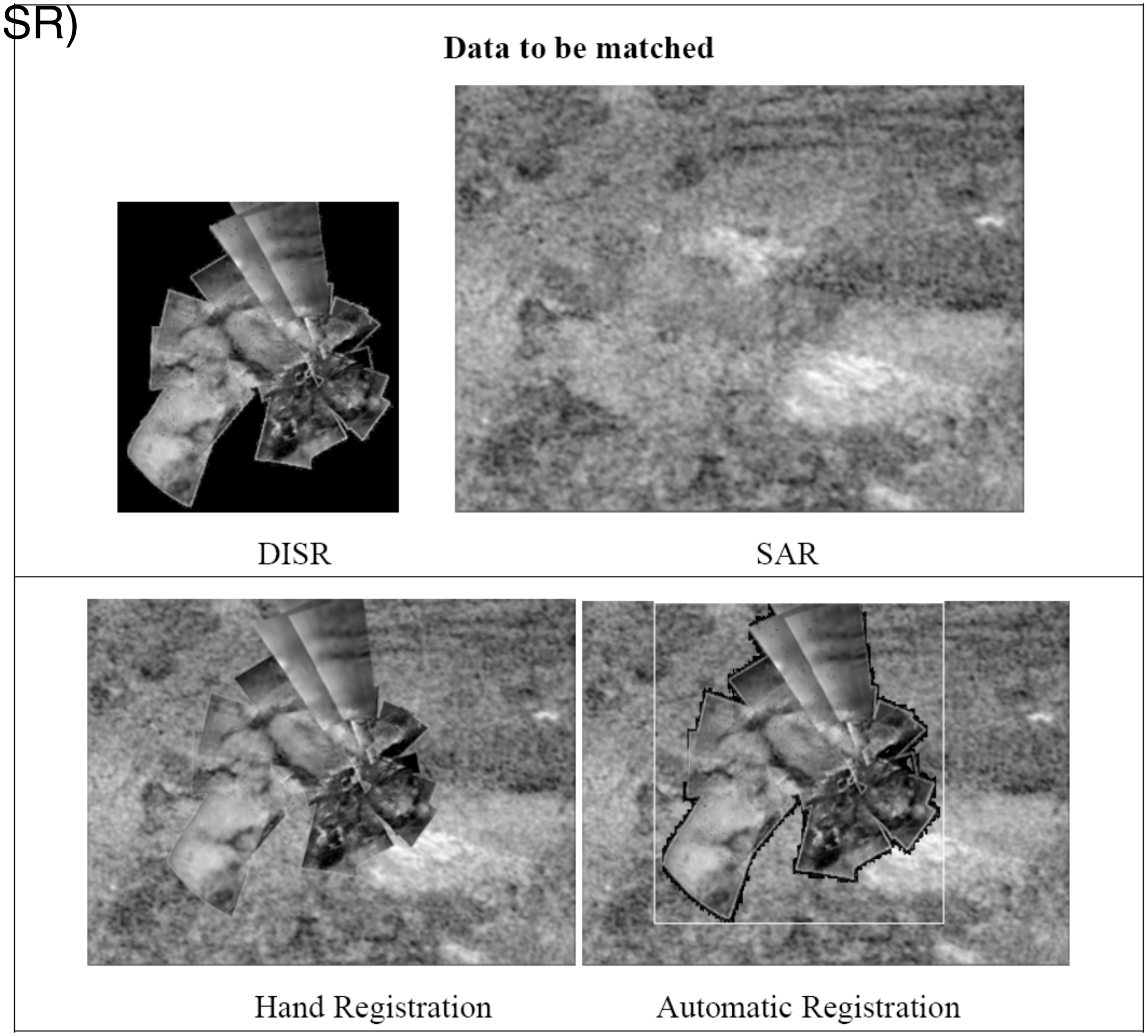
Orbital Multi-Modal Image Registration

Match between SAR and Visible Infrared Mapping Spectrometer Subsystem (VIMS) data from Cassini

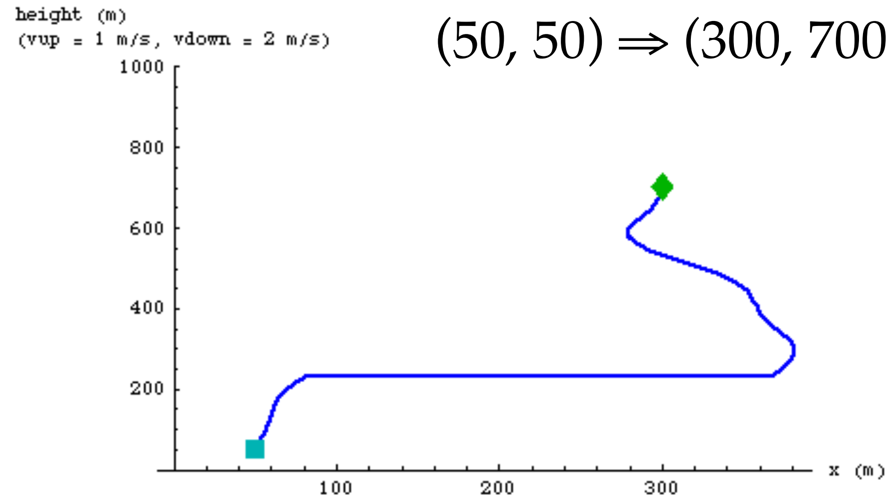


Aerobot Localization: Orbital+Aerial Image Registration

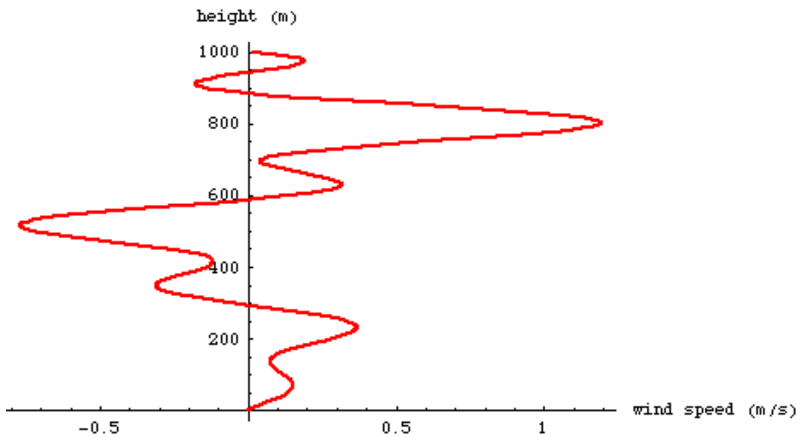
Match between Cassini SAR and mosaicked Huygens Descent Imager Spectral Radiometer (DISR)

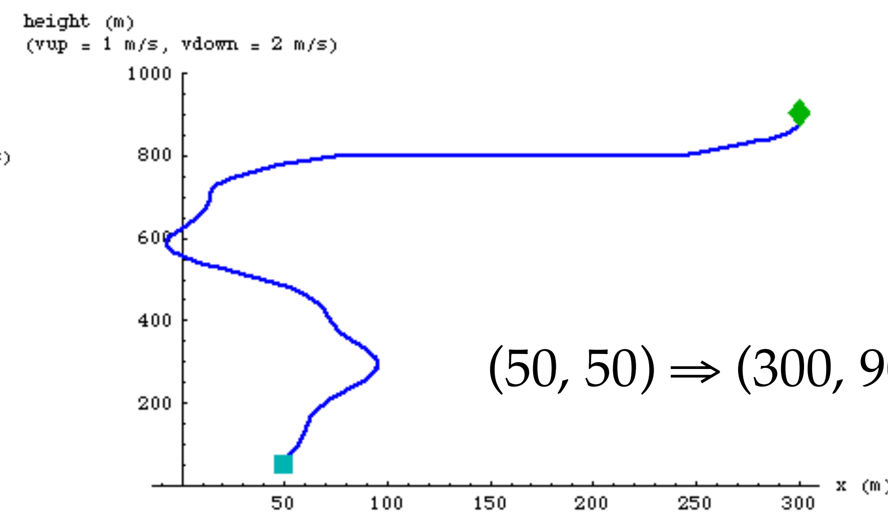


2D Case: Examples



(50, 50) ⇒ (300, 700)

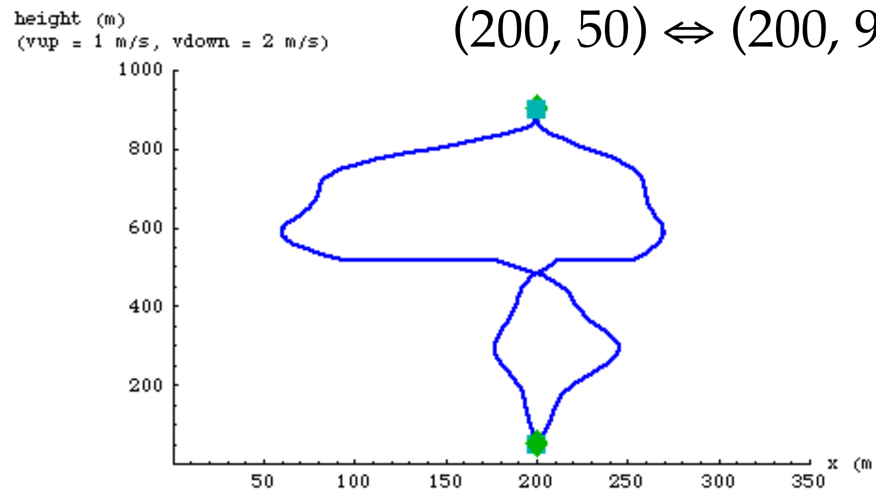


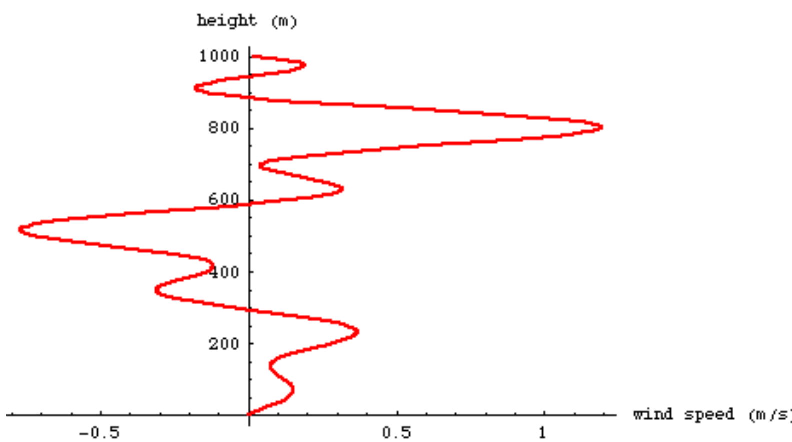


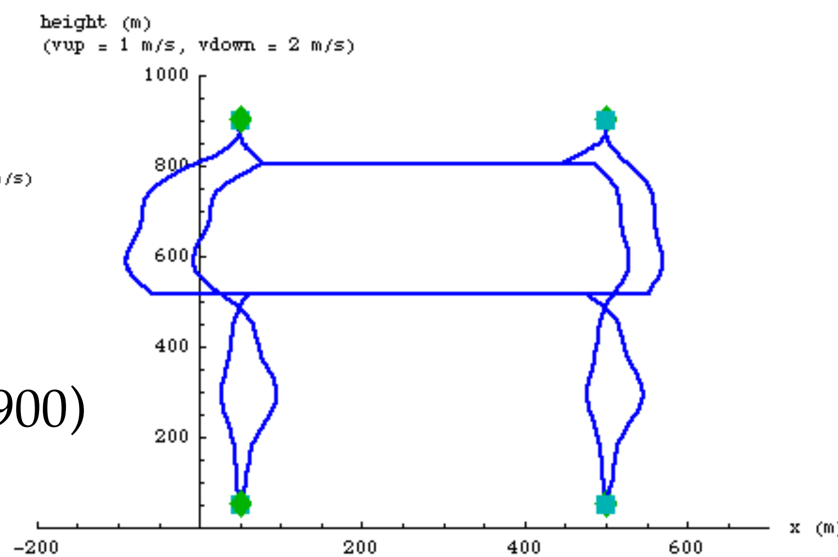
(50, 50) ⇒ (300, 900)

2D Case: Examples

(200, 50) ⇔ (200, 900)

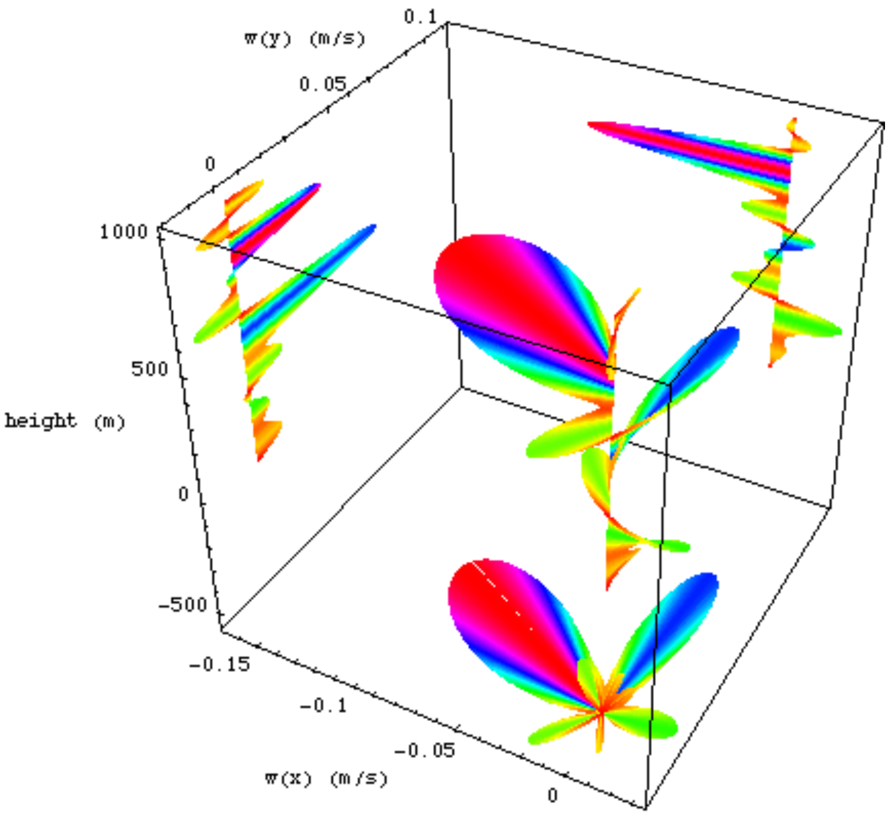


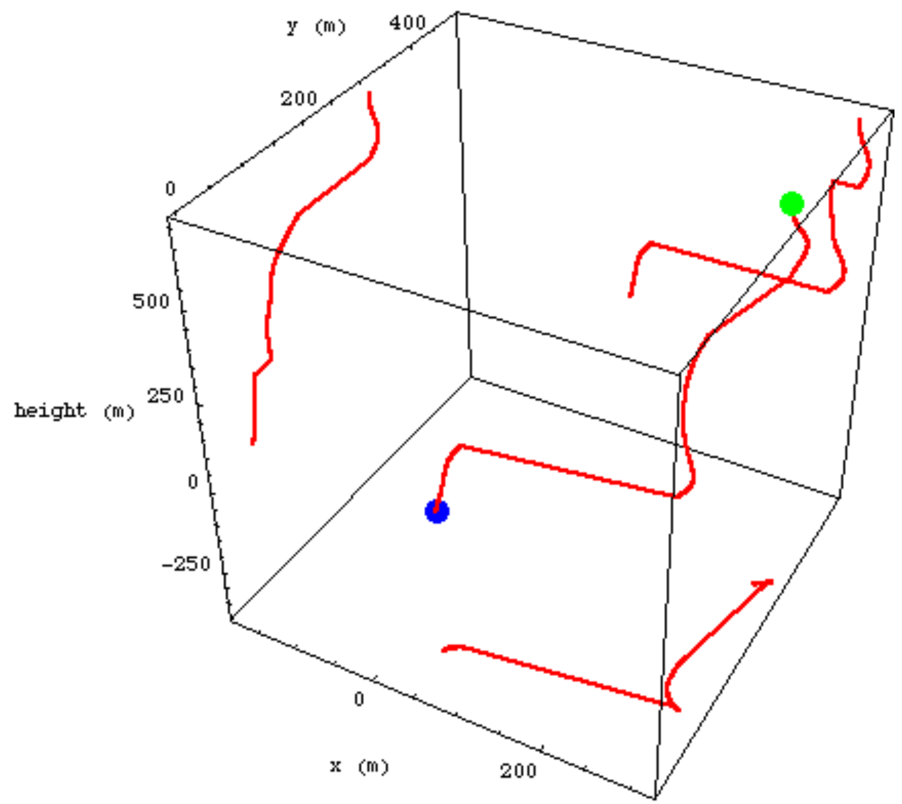




(50, 50) ⇔ (500, 900)

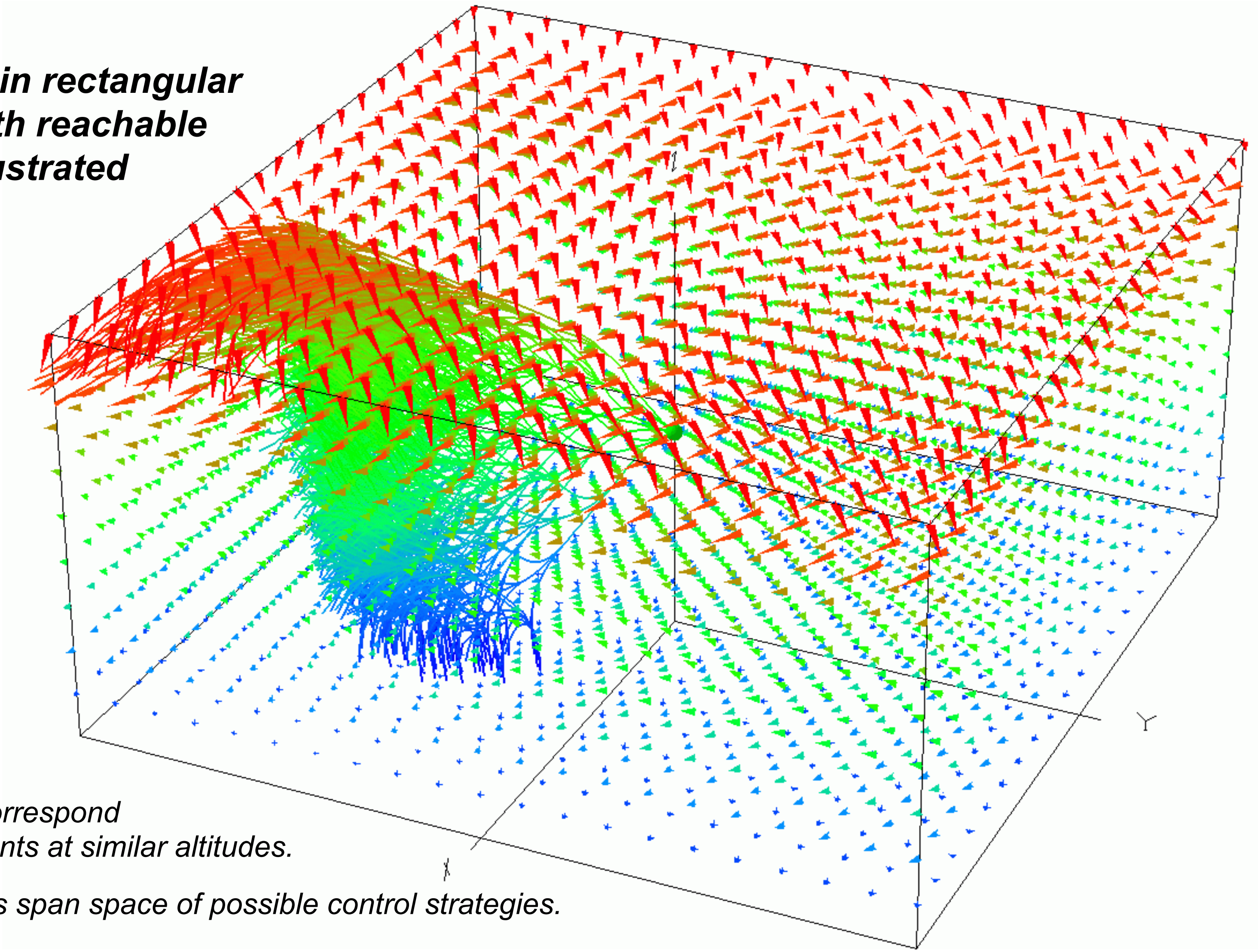
3D Case: Example





Visualization of Reachability

Wind field in rectangular volume with reachable volume illustrated

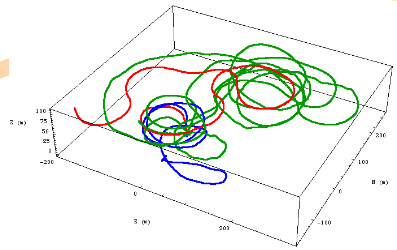


Paths start at center. Path colors correspond to wind pennants at similar altitudes.

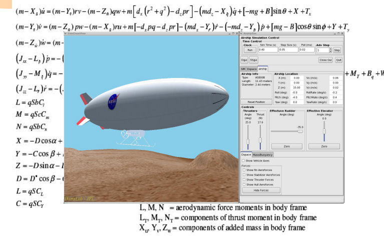
Different paths span space of possible control strategies.

Core Aerobot Autonomy Technologies

Aerobot Testbed

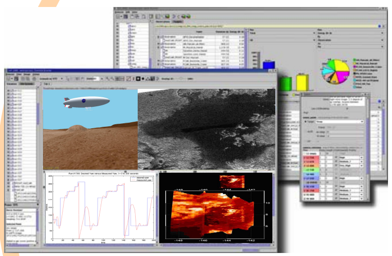


Flight Testing



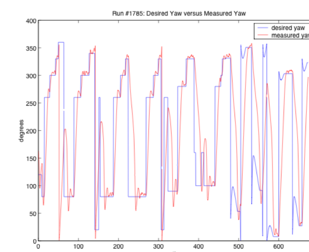
Aerobot Modelling

State Estimation

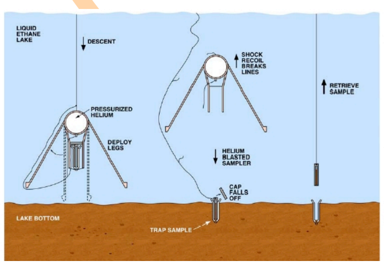


Mission Operations

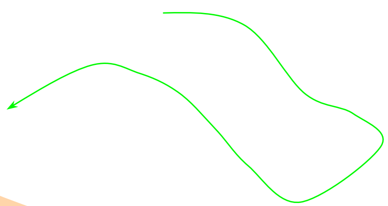
Aerobot Autonomy
Architecture



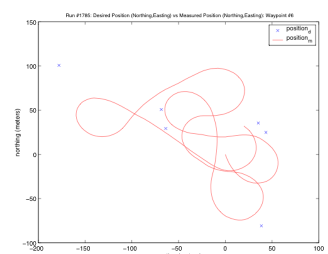
Flight Control



Surface Sampling



Science Autonomy



Navigation

Sensing and Mapping