



*Center for Autonomous Vehicle Research*

*Mechanical & Aerospace Engineering*

# Wireless Communication Networks Between Distributed Autonomous Systems Using Self-Tuning Extremum Control

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# Milestones

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❖ Motivation and Issues

❖ Comms Propagation Modeling

❖ Self-Tuning Extremum Control

❖ Flight Test Results





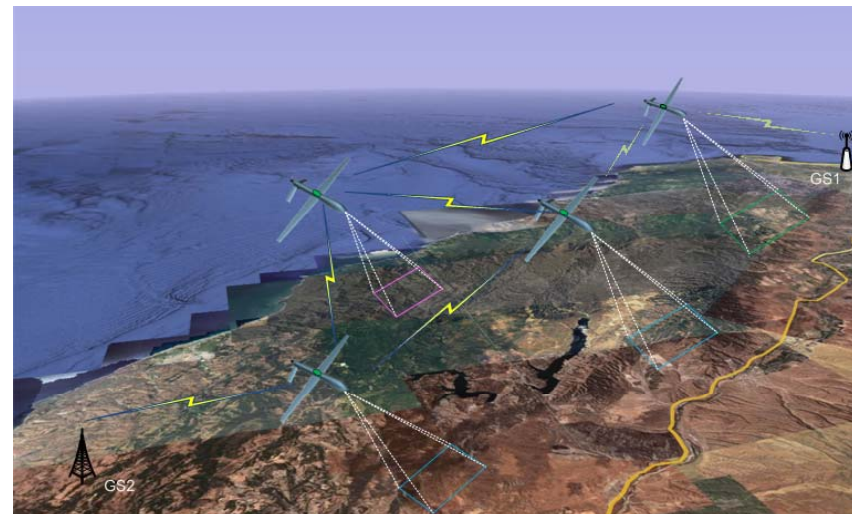
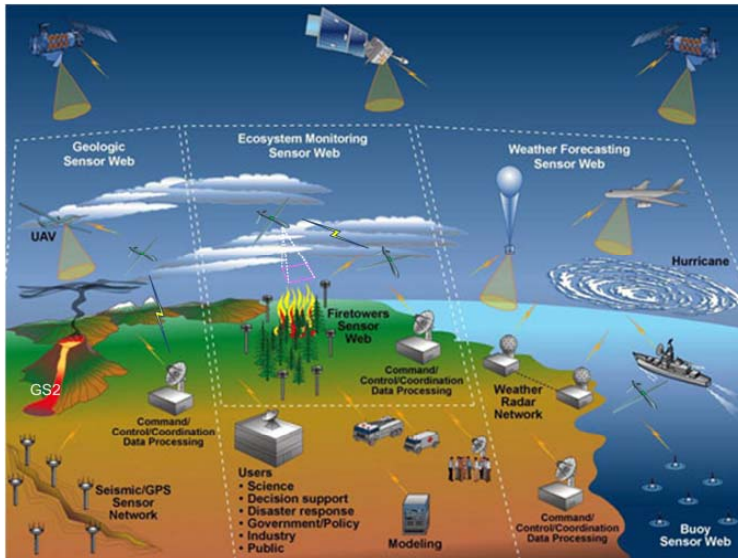
# Sensor Networks with Multiple UAS

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## ❖ Applications

- Nature Monitoring - Civil (Disaster, Forest Fire, Weather)
- Surveillance & Coverage - Military (SA, Decision Support, ISR)
- Remote Sensing - Science (GIS, Ocean Map Building, etc)





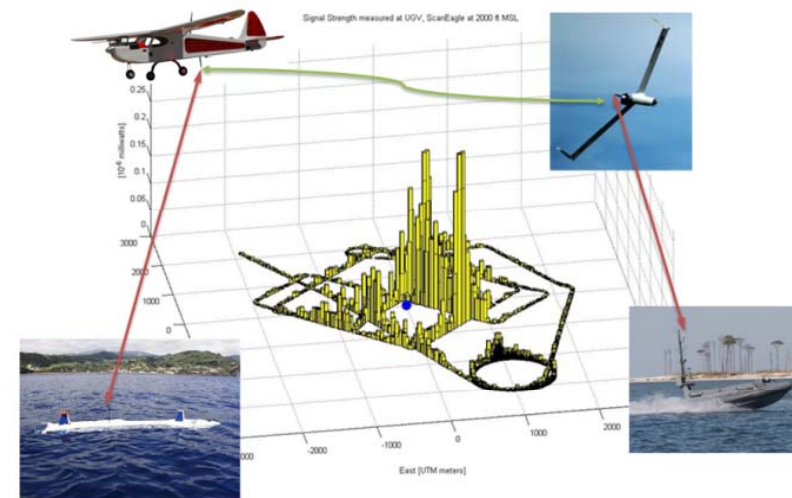
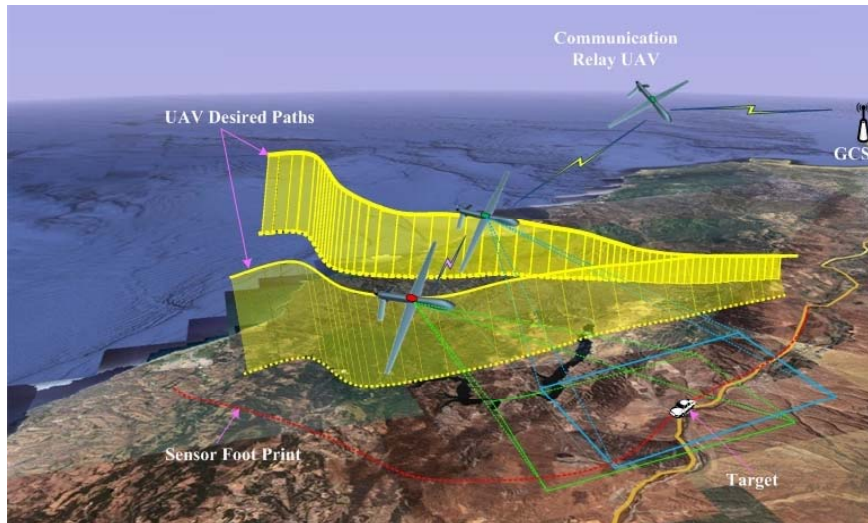
# Research Goals & Issues

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## ❖ Research Goals

- ❑ Dispatch a swarm of networked UAVs as communication relay nodes for real-time decision-making support and situational awareness





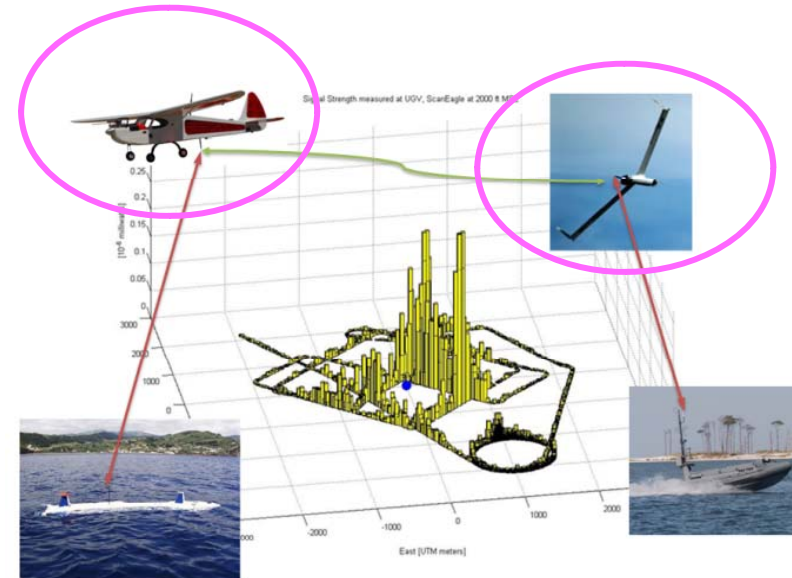
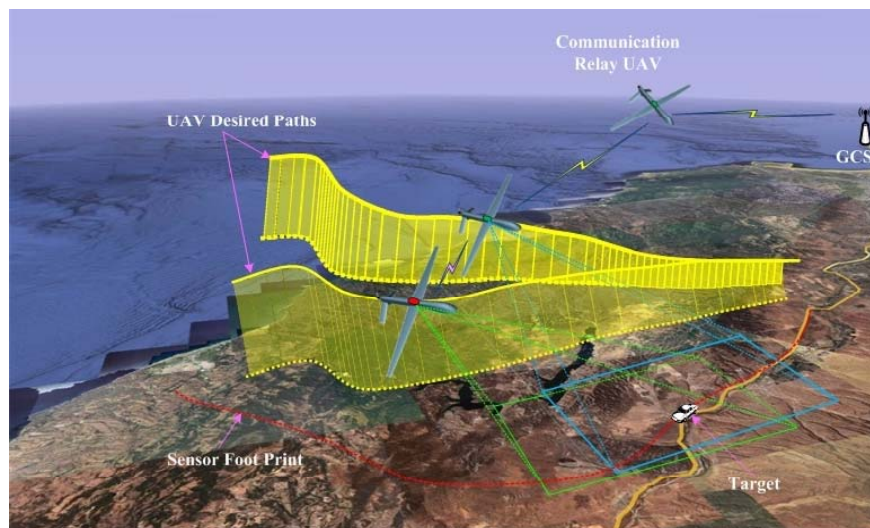
# Research Goals & Issues

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## ❖ Research Issues

- ❑ High Bandwidth Communication Links (Max. Throughputs)
- ❑ Wide Area/Range Coverage (Network Coverage Control)
- ❑ Long-Term Communication Relay (Aerial Platforms)





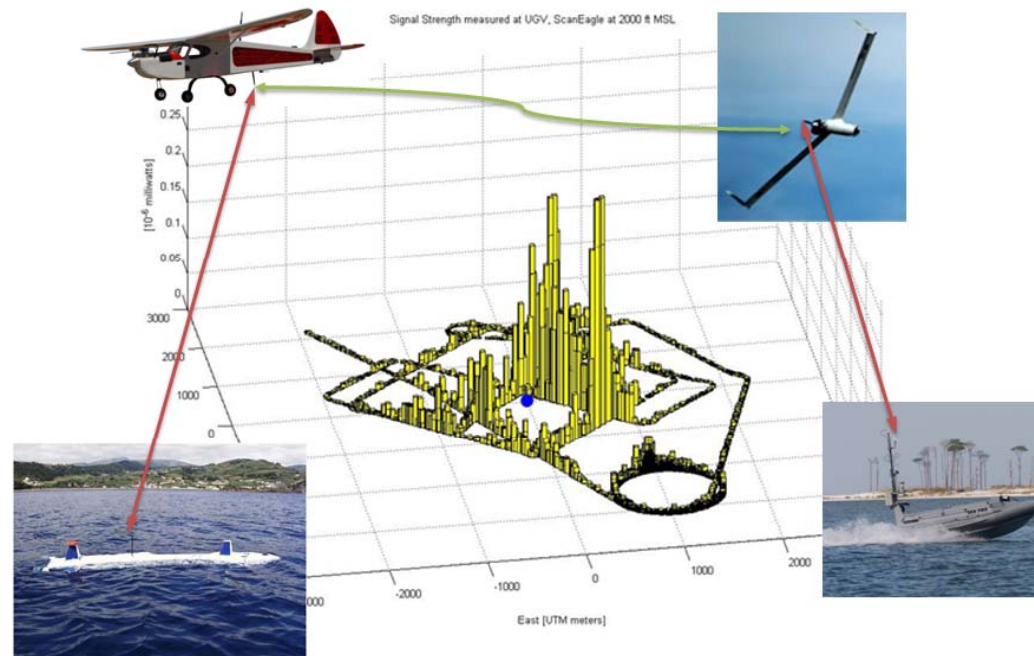
# Maximum Comms Networking

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## ❖ Objective and Approach

- ❑ Develop control algorithms that allow UAVs to **reposition themselves autonomously at optimal flight location** to maximize the communications link quality



Concept for Sensor Networking Between Heterogeneous Vehicles



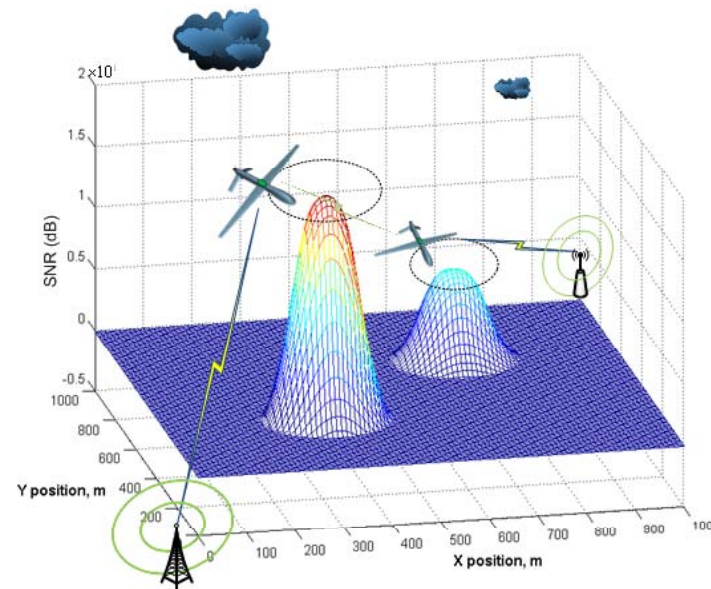
# Strategy

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## ❖ Control Method

- Methods for controlling flying platforms to operate continually at the maximum point of a performance function can be termed real-time optimization or **extremum control**







# Approaches I

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## ❖ Real-Time Optimization

- Cost Function : Communication performance
- Constraint : UAV positioning equation

$$\max_{\mathbf{x}_k \in D} J_k(\mathbf{x}_k) \quad \text{subject to } \mathbf{x}_{k+1} = f(\mathbf{x}_k, u_k)$$

### □ Cost Function (J)

$$J(\mathbf{x}_k) = J(x_k, y_k, z_k, \phi_k, \mathbf{x}_{node,i})$$

$\mathbf{x}_{node,i}$  = communications nodes  $(x_k, y_k, z_k, \phi_k)$  = UAV position and attitude (bank)

### □ Equations of 3D/2D UAV Motion

$$f(\mathbf{x}_k) : \begin{cases} x_{k+1} = x_k + v \cos(\psi_h) \Delta t \\ y_{k+1} = y_k + v \sin(\psi_h) \Delta t \end{cases}$$

where  $v$  is body-axis speed and  $\psi_h$  is the yaw angle of the vehicle



# Approaches I

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## ❖ Real-Time Optimization

- If partial derivatives of the cost function are known
- Solution: Extremum Control (Gauss-Newton Optimization)

$$\mathbf{x}_{k+1} = \mathbf{x}_k + \mathbf{u}_k = \mathbf{x}_k - \alpha_k \mathbf{H}_k^{-1}(\mathbf{x}_k) \nabla J(\mathbf{x}_k)$$

$$\text{where } \mathbf{H}_k = h_{ij}(\mathbf{x}_k) = \frac{\partial^2 J}{\partial x_{i,k} \partial x_{j,k}}(\mathbf{x}_k), \quad \nabla J(\mathbf{x}_k) = \left( \frac{\partial J}{\partial x_{1,k}}(\mathbf{x}_k), \dots, \frac{\partial J}{\partial x_{n,k}}(\mathbf{x}_k) \right)^T$$

- Issue: 3-D Complex Optimization Problem

$$J(x_k, y_k, z_k, \phi_k, \mathbf{x}_{node,i}) = J(\phi_k, \|\mathbf{d}\|)$$

$$\text{where } \|\mathbf{d}\| = \sqrt{(x_{uav} - x_{node})^2 + (y_{uav} - y_{node})^2 + (z_{uav} - z_{node})^2}$$



# Methodology

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## ❖ Gradient-Type Extremum Control

- Measured SNR is discontinuous and slow (1 Hz)
- Subjective to noise and cluttered environment
- Affected by the orientation of a UAV (fast maneuver)

✓ Computation of gradient/hessian values is nontrivial

## ❖ Approaches and Solutions

### ➤ Mathematical Communications Modeling

- Provide continuous reference values at fast mode
- Predict a maximum operation point

### ➤ Model-Free Adaptive Extremum Control

- Gradient is obtained by numerical method without model
- Robust to noise and cluttered environment



# Milestones

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❖ Motivations

❖ Communication Modeling

❖ Self-Tuning Extremum Control

❖ Flight Test Results





# SNR Model for Cost Function

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## □ Why Signal-to-Noise Ratio Model

$$C = W \log_2(1 + SNR) : \text{Shannon-Hartley Theorem}$$

where  $C$  is channel capacity (bits per second)       $W$  - bandwidth (Hz) of the channel

✓ Channel capacity ( $C$ ) is proportional to the SNR and the bandwidth ( $W$ )

## □ Signal-to-Noise Ratio (SNR) Model

$$SNR(dBm) = \frac{P_r(dBm)}{P_n(dBm)} = \left( \frac{\lambda}{4\pi \|\mathbf{d}\|} \right)^2 \frac{G_t G_r}{L_{ap}}$$

where  $P_r(dBm)$  is the receiver power       $P_n(dB)$  is noise power (-95 dBm)

$G_r(dB)$  is receiver antenna gain       $G_t(dB)$  is transmitter antenna gain

$\lambda = c/f$  where  $f$  is the transmission frequency       $c = 3 \times 10^8$  m/s       $\|\mathbf{d}\|$  = distance

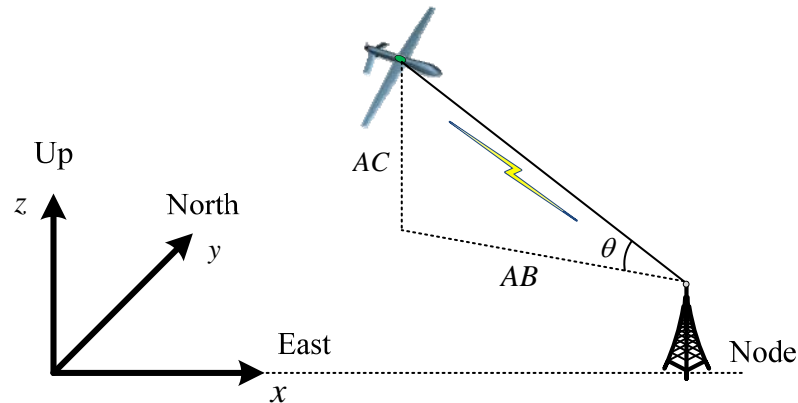
$$L_p(dB) \equiv (4\pi \|\mathbf{d}\| / \lambda)^2 \text{ is path loss}$$

$$L_{ap}(dB) \text{ is antenna pattern loss}$$

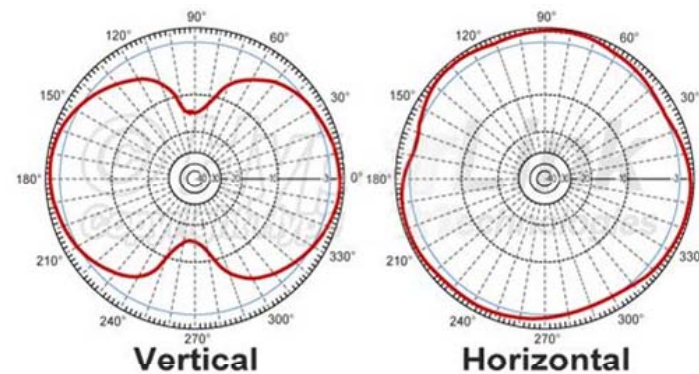


# Antenna Pattern Loss on SNR

## □ Model for UAV Orientation Effects



**Effect of the Arrival Angle  
on Antenna Pattern Loss**



**Antenna Pattern Loss in the Horizontal and Vertical Planes**

## ➤ Antenna Pattern Loss : Function of Arrival Angle $\gamma_i(t)$

$$\gamma_i(t) = -\theta_i(t) - \phi(t) \sin(\varphi_i(t) - \psi(t))$$

which is the angle between the incident ray and horizontal wing of a UAV

$$\theta_i(t) = \tan^{-1} \left( \frac{(z(t) - z_{node,i})}{\sqrt{(x(t) - x_{node,i})^2 + (y(t) - y_{node,i})^2}} \right)$$

$$\varphi_i(t) = \tan^{-1} \left( \frac{y(t) - y_{node,i}}{x(t) - x_{node,i}} \right)$$

$\phi(t)$  is the UAV bank angle

$\psi(t)$  is the heading angle of the UAV

$\varphi_i(t)$  is the bearing angle

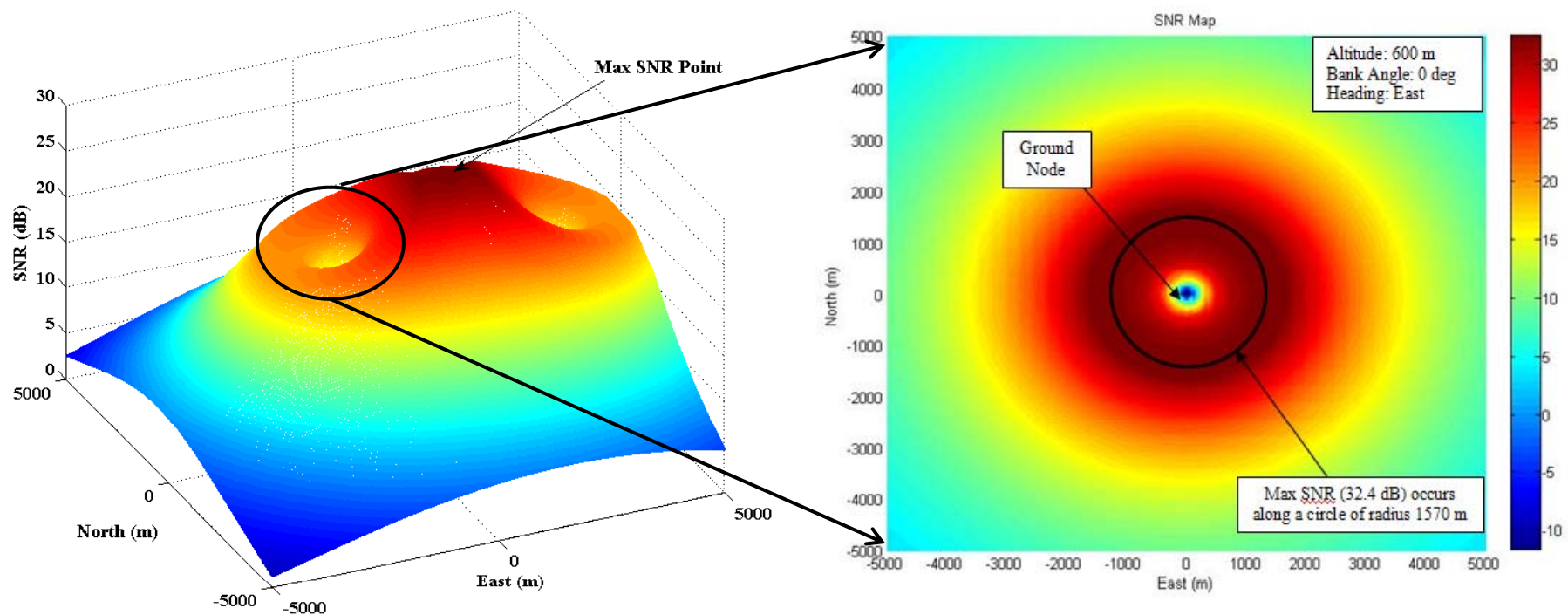


# SNR Map Example

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- ❑ Static SNR Map in East-North-Up coordinates
  - Fixed altitude, heading & bank angle
  - Path loss, Antenna pattern loss



SNR Map (3-D View)

SNR Map (2-D Top View)



# Milestones

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❖ Motivations

❖ Communication Modeling

❖ Self-Tuning Extremum Control

❖ Flight Test Results





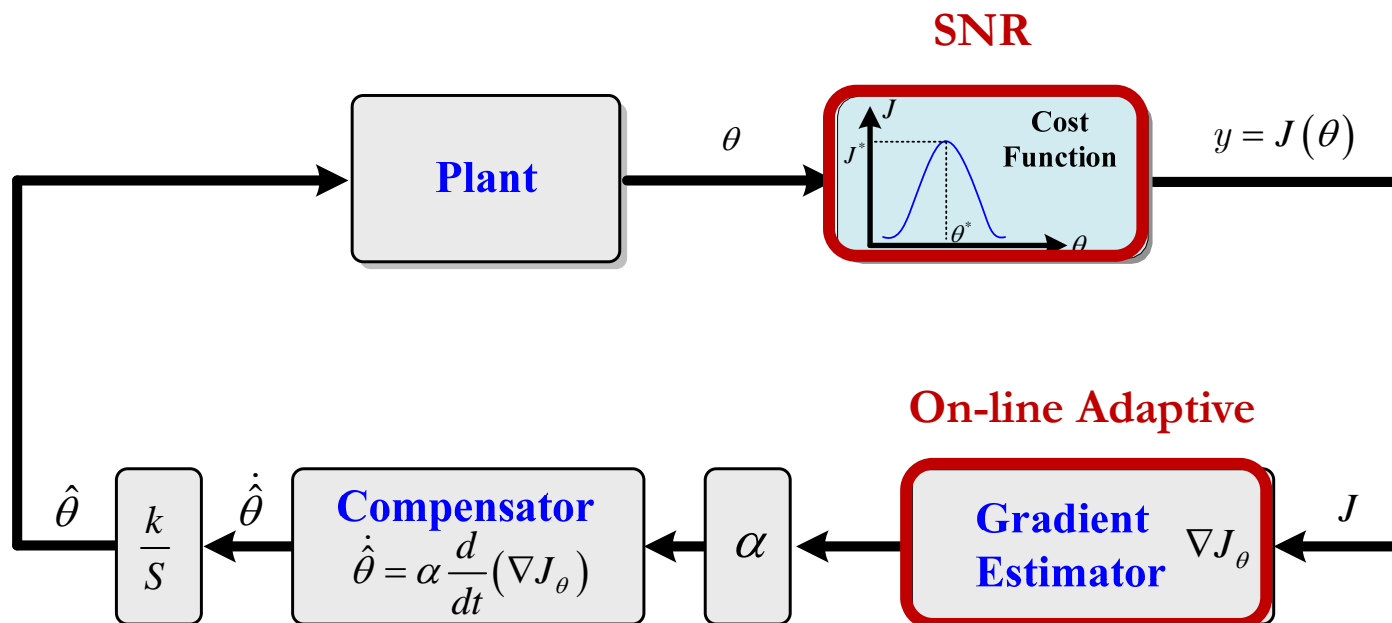


# Self-Tuning Extremum Control

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- Use **on-line gradient estimation** of SNR function to drive the set point to its max location
- On-line estimator does not require a precise model



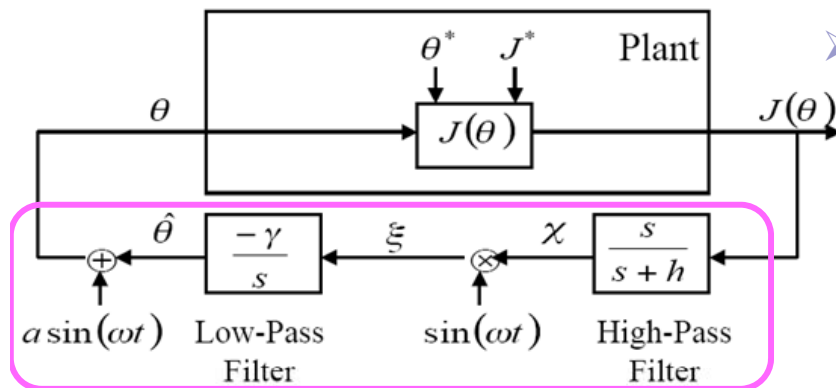
**Self-Estimating Extremum Control Architecture**



# On-Line Gradient Estimator

## □ Perturbation Based Gradient Estimator

- The purpose is to make  $\theta - \theta^*$  as small as possible, so that the output is driven to its minimum  $J^*$



$$J(\theta) = J^* + \frac{J''}{2} (\theta - \theta^*)^2, \quad J'' > 0$$

**Peak-Seeking Architecture**  
(Stability Proof by Krstic, 2001)

- Applying **high-pass filter (differentiator)** gets rid of constant term and leads to

$$y_H \approx a \frac{\partial J}{\partial \theta} \Big|_{\theta=\hat{\theta}} \sin \omega t$$

### ➤ How It Works ?

- Let  $y = J(\theta)$  be a general mapping function
- Assume  $\hat{\theta}$  be a current parameter
- **Perturbation**  $a \sin \omega t$  around  $\hat{\theta}$  leads to
 
$$y = J(\hat{\theta} + a \sin \omega t) \approx J(\hat{\theta}) + a \frac{\partial J}{\partial \theta} \Big|_{\theta=\hat{\theta}} \sin \omega t$$



# On-Line Gradient Estimator

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- Demodulating  $y_H$  with  $\sin wt$  divides the signal into a low-frequency signal and high-frequency signal

$$\zeta = \frac{1}{2} a \frac{\partial J}{\partial \theta} \Big|_{\theta=\hat{\theta}} - \frac{1}{2} a \frac{\partial J}{\partial \theta} \Big|_{\theta=\hat{\theta}} \cos 2wt$$

- Applying low-pass filter (integrator) gets rid of the sinusoidal term and provides an estimate of the gradient of  $J(\theta)$

$$y_L \approx \frac{1}{2} a \frac{\partial J}{\partial \theta} \Big|_{\theta=\hat{\theta}}$$

- The estimated gradient can be expressed by the parameter change

$$\dot{\hat{\theta}} = k \frac{1}{2} a \frac{\partial J}{\partial \theta} \Big|_{\theta=\hat{\theta}}$$

**Self-Tuning Estimator**

- Denote  $\tilde{\theta} = \hat{\theta} - \theta^*$  the convergence error, and taking a derivative of the errors leads to

$$\dot{\tilde{\theta}} = \dot{\hat{\theta}} \approx k \frac{1}{2} a J''(\theta^*) \tilde{\theta}$$

- ❖ which become stable with a proper choice of the parameter,  $a$  and  $k$  i.e.,  $kaJ''(\theta^*) < 0$



# Autonomous Controller Design

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## □ How Self-Tuning Extremum Control Works ?

- Key idea is to integrate **an on-line gradient estimator** into an extremum control to get optimal location for UAVs

### □ Consider 2-D Motion in $\{I\}$ Frame

$$f(\mathbf{x}_k) : \begin{cases} \dot{x}(t) = v(t) \cos(\psi_h(t)) \\ \dot{y}(t) = v(t) \sin(\psi_h(t)) \end{cases}$$

where  $v$  is body-axis speed and  $\psi_h$  is the yaw angle of the vehicle

### □ Motion with Constant Speed

$$\begin{aligned} x(t) &= v \cos(\psi_h(t)) = f_1(\psi_h(t), x_0) \\ y(t) &= v \sin(\psi_h(t)) = f_2(\psi_h(t), y_0) \end{aligned}$$

where  $v = \text{const}$



# Autonomous Controller Design

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- Then SNR function becomes an implicit function of heading angle

$$J = SNR(x(t), y(t)) = SNR(x(\psi_h(t)), y(\psi_h(t))) \\ = J(\psi_h(t))$$

- Gradient Descent Extremum Control is expressed by

$$\psi_{k+1} = \psi_k + \alpha_k \nabla J_\psi$$

where  $\nabla J_\psi = \partial J / \partial \psi \in \mathfrak{R}$

- Assume that SNR is a quadratic function

$$J(\hat{\psi}(t)) = J^* + \frac{\mu}{2} (\hat{\psi}(t) - \psi^*)^2 + w(t)$$

$\hat{\psi}(t)$  is the current heading angle estimate

$J^*$  is the maximum attainable value of the cost function,  $w(t)$  is a zero-mean white noise

$\mu$  is the sensitivity of the quadratic curve **Unknown**

$\psi^*$  is the heading angle maximizing  $J$



# Adaptive Convergence Control

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## ➤ Adaptive Convergence Rate $\alpha_k$

### □ Armijo-Wolfe Conditions

$$J(\mathbf{x}_k + \alpha_k \mathbf{d}_k) \leq J(\mathbf{x}_k) + c_1 \alpha_k \mathbf{d}_k^T \nabla J(\mathbf{x}_k)$$

$$\mathbf{d}_k^T \nabla J(\mathbf{x}_k + \alpha_k \mathbf{d}_k) \geq c_2 \mathbf{d}_k^T \nabla J(\mathbf{x}_k)$$

where  $0 < c_1 < c_2 < 1$

the *Armijo* condition that prevents steps that are too long

the *Wolfe* condition which restricts steps that are too short

### □ Adaptive Convergence Control Law

$$\alpha_{k+1} = \gamma \alpha_k, \text{ where } \begin{cases} 0 < \gamma < 1, & \text{if } \Delta J_{k+1} > \tau_{tv} \\ \gamma \geq 1, & \text{else } \Delta J_{k+1} < \tau_{tv} \end{cases}$$

where

$$\Delta J_{k+1} = J_{k+1} - J_k \text{ or } d(\nabla J_{\hat{\psi}(t)}) / dt$$

$\tau_{tv}$  : a specified threshold value

$$u_{com}(t) = \begin{cases} \dot{\psi}_{com}(t) = \dot{\psi}_{ss} & \text{if } |\dot{\psi}_{com}(t) - \dot{\psi}_{ss} = v / R_{ss}| \leq \varepsilon_{ss} \\ \dot{\psi}_{com}(t) = \dot{\psi}_{ss} + \mu \gamma \alpha(t) \hat{\psi}(t) & \text{other} \end{cases}$$



# Autonomous Heading Controller Design

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- Applying On-Line Gradient Estimator

$$\nabla J_{\hat{\psi}(t)} \equiv \frac{\partial J(\hat{\psi}(t))}{\partial \hat{\psi}(t)} = \mu(\hat{\psi}(t) - \psi^*) , \quad \frac{d}{dt}(\nabla J_{\hat{\psi}(t)}) = \mu(\dot{\hat{\psi}}(t))$$

- Then the extremum controller is expressed by

$$\begin{aligned} \dot{\psi}_{com}(t) &= \frac{d\psi(t)}{dt} = \alpha(t) \frac{d}{dt}(\nabla J_{\psi}) \\ &= \mu \alpha(t) \dot{\hat{\psi}}(t) \end{aligned}$$

**On-line Gradient Estimator**

$\alpha(t)$ : step length along the direction  $\nabla J$     Optimal value can be obtained by *Armijo-Wolfe* conditions

- Orbit Circle Guidance at Final Steady-Stage

$$u(t) = \begin{cases} \dot{\psi}_{com}(t) = \dot{\psi}_{ss} & \text{if } |\dot{\psi}_{com}(t) - \dot{\psi}_{ss} = v / R_{ss}| \leq \epsilon_{ss} \\ \dot{\psi}_{com}(t) = \dot{\psi}_{ss} + \mu \alpha(t) \dot{\hat{\psi}}(t) & \text{other} \end{cases}$$

$\dot{\psi}_{ss}$  is introduced to guarantee that the UAV will orbit with a constant radius  $R_{ss}$  at the final stage.

$R_{ss} = v / \dot{\psi}_{ss}$  : a final approach circle radius.



# Milestones

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❖ Motivations

❖ Communication Modeling

❖ Self-Tuning Extremum Control

❖ Flight Test Results







# Flight Test Systems

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Rascal 110 UAV (ARF Airframe)



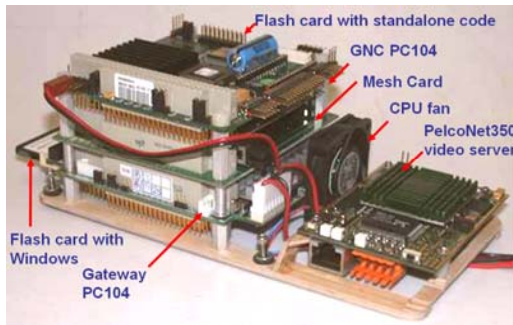
Piccolo Plus Autopilots



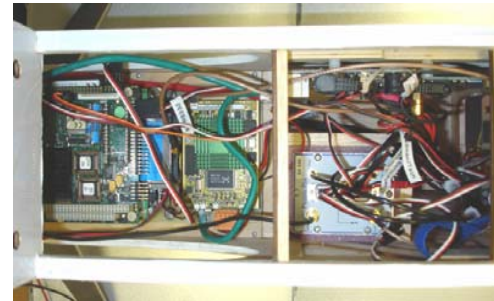
2-Stroke Gas Engine



Engine Mount



Onboard PC104 & Payload Stack



Avionics bay of Rascal UAV

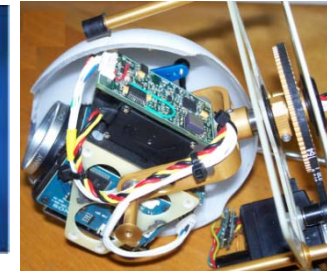


Mobile GCS

- ❖ **Rapid Flight Test Design Keys**
- ❑ Reduce development time
- ❑ Upgrade is flexible
- ❑ Convenience of high level programming



Tracking antenna and Wave Relay mesh link



Gimbal Camera



# Model Verification Flight Test

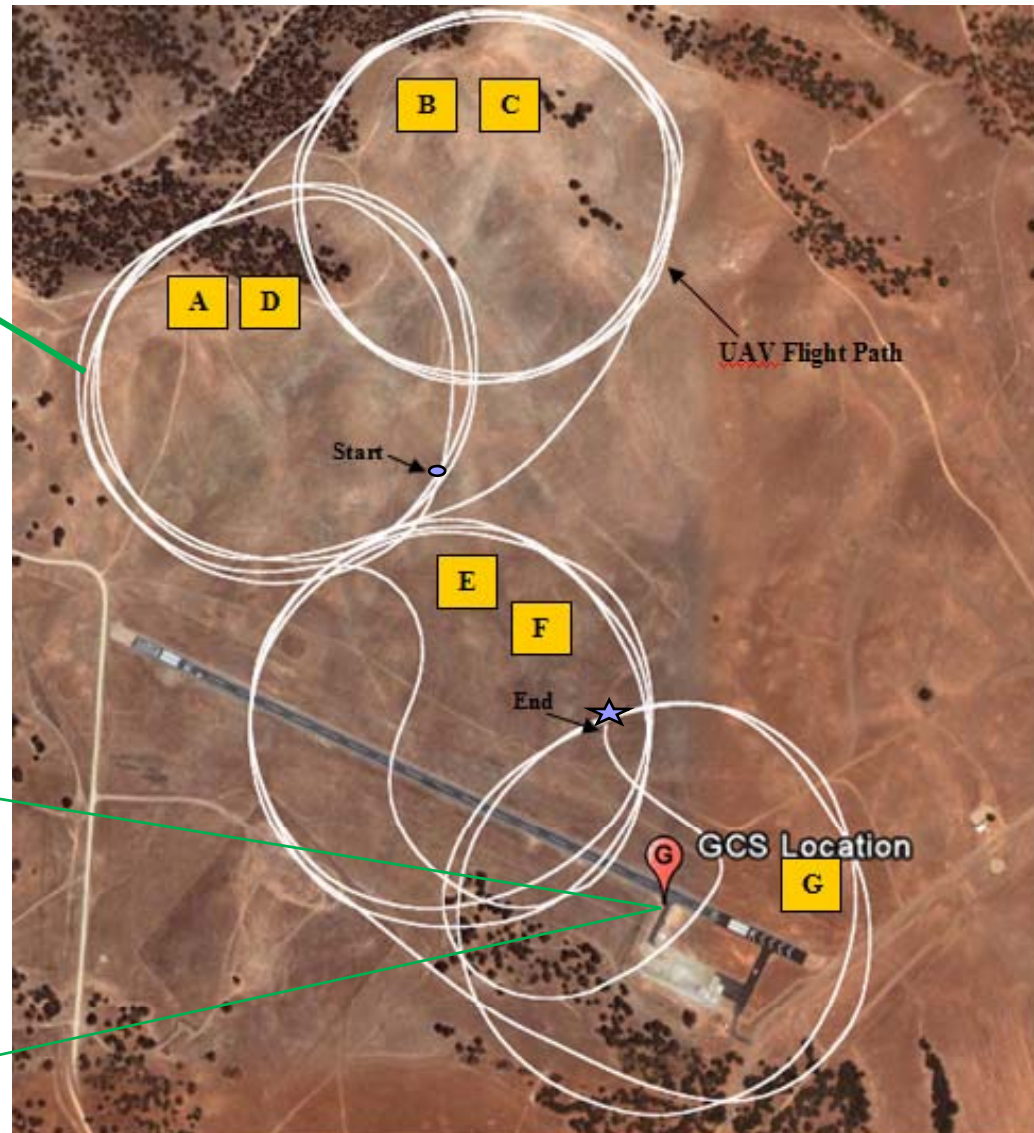
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3 dB Omni-  
Directional Antenna

9 dB Sector Antenna

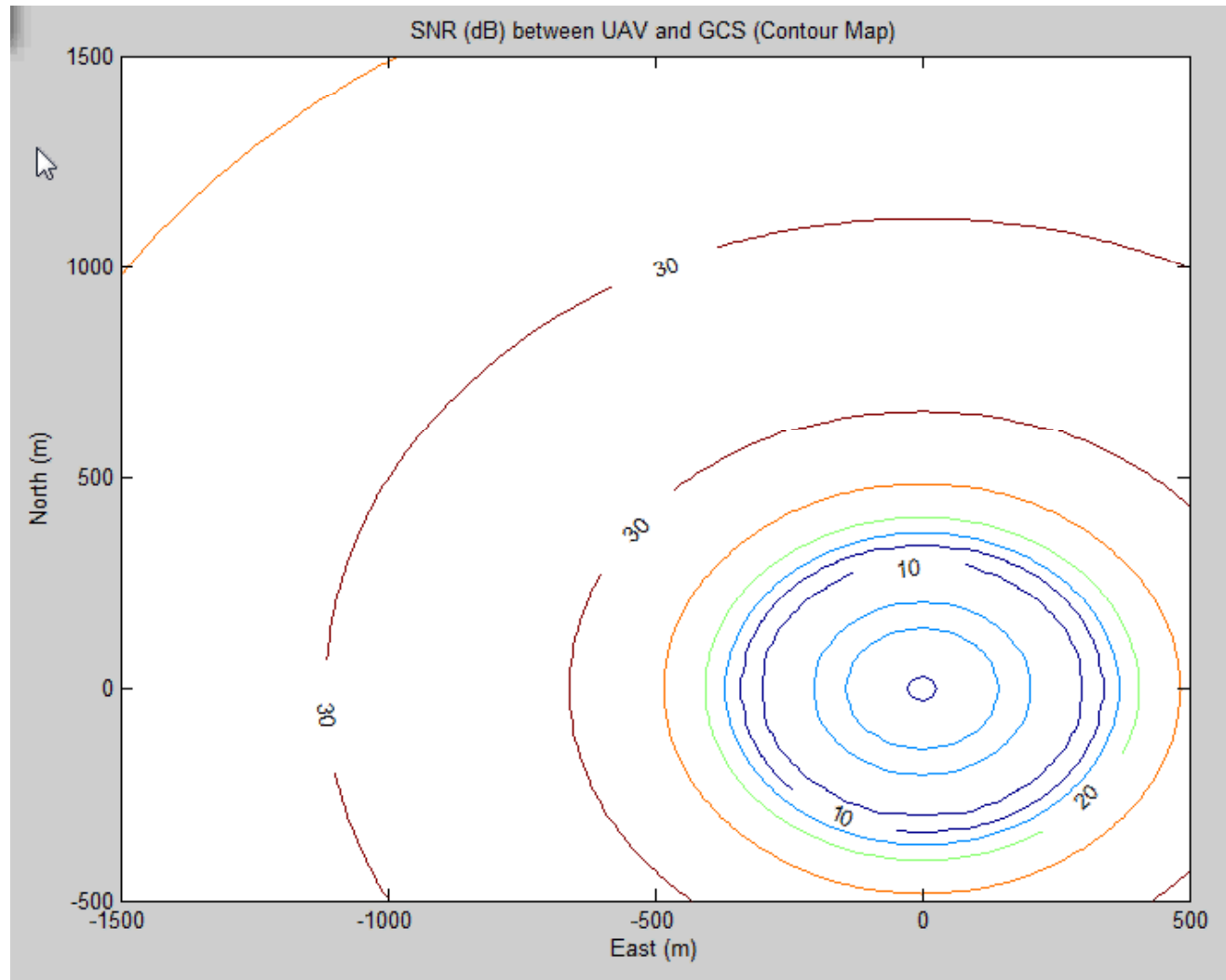




# SNR Model Verification

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Movie

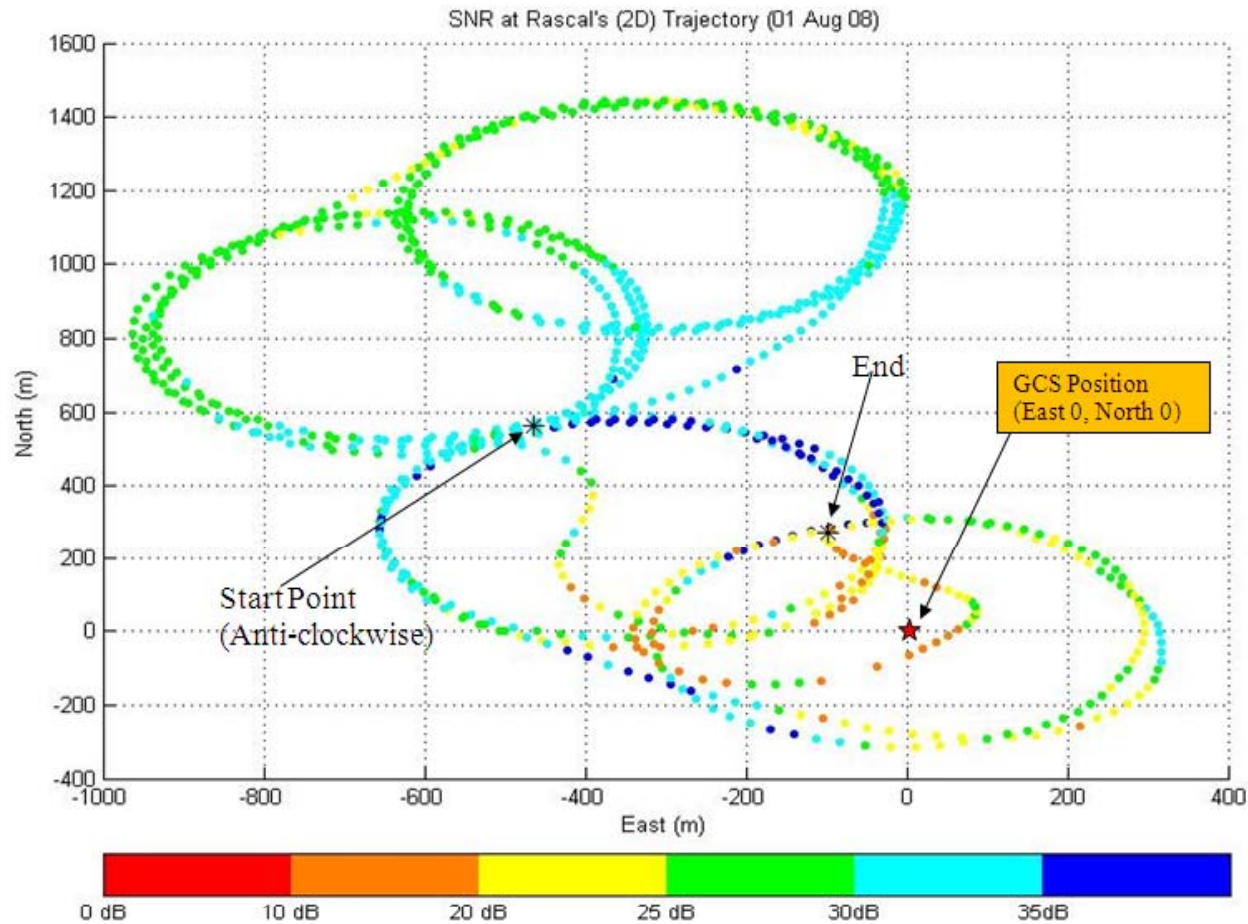
**SNR Model Verification with respect to UAV Trajectories**



# SNR Model Verification

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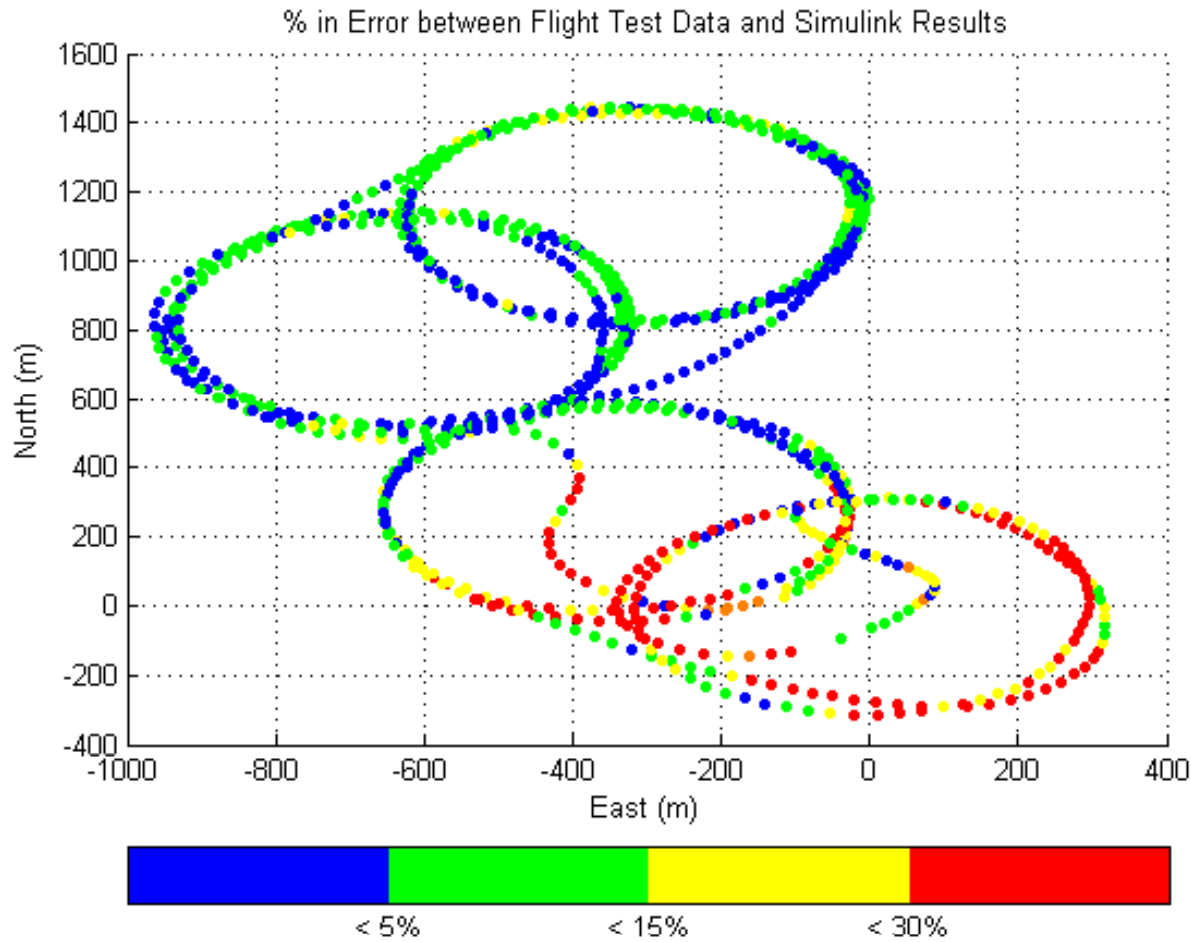
**SNR Variation with respect to UAV Trajectories**



# Comparison with SNR Model

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**SNR Error Plots Between Real and Model Values**

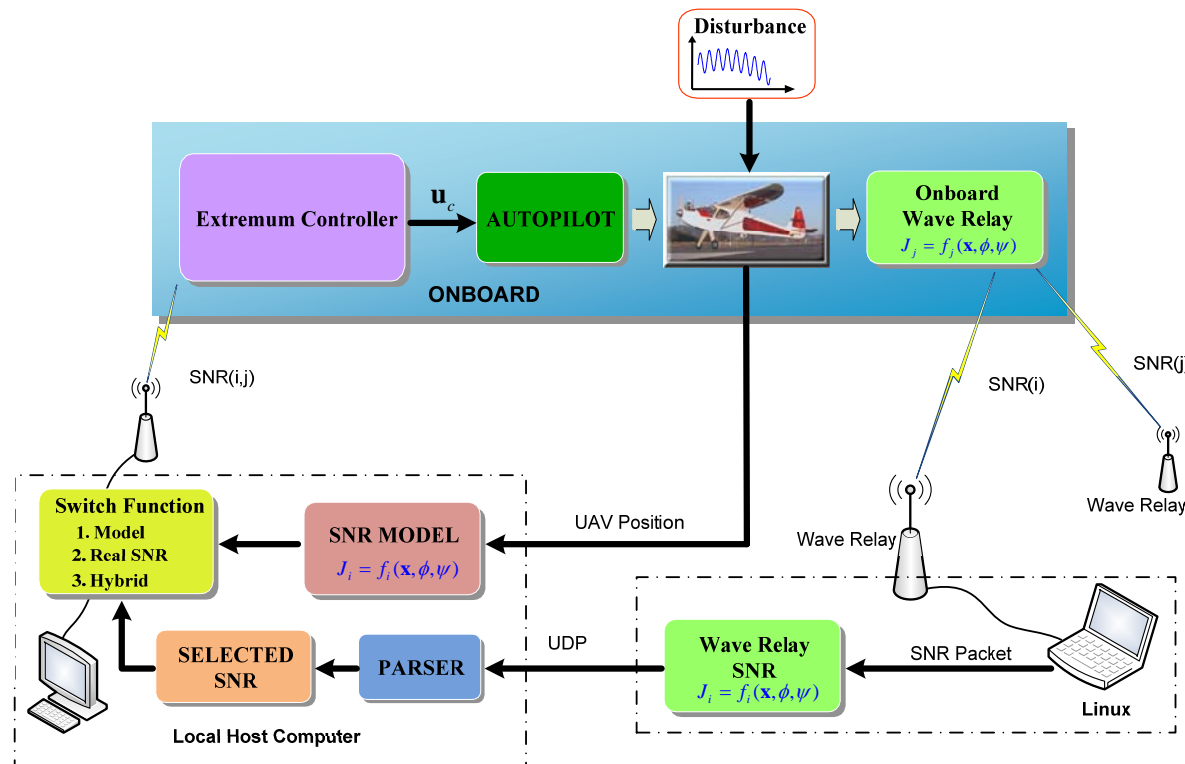


# High Band Comms Flight Test

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- ❖ Flight Test (Nov. 20, 2008)
  - Validate the designed onboard adaptive self-tuning controller & the communication models



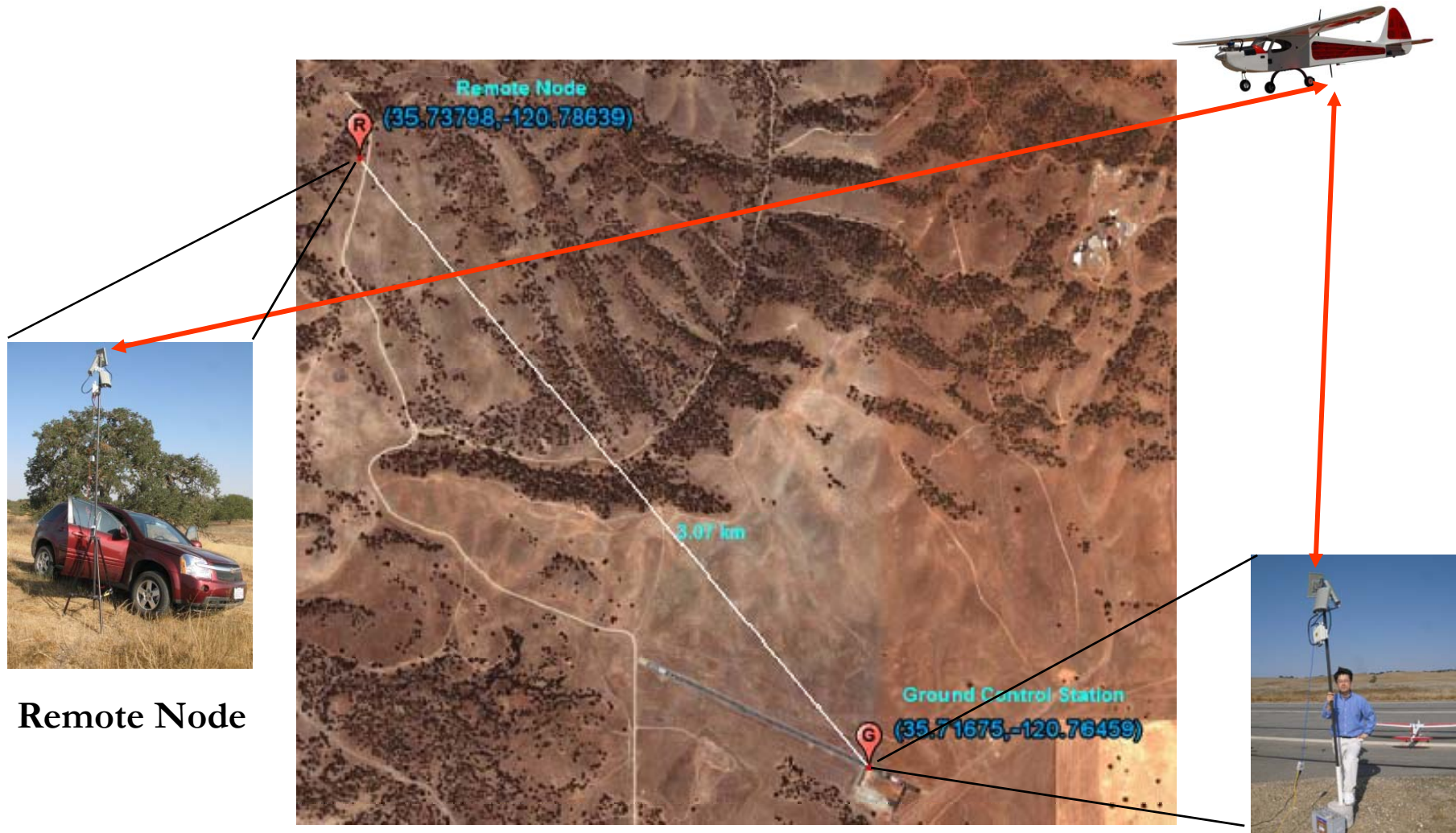
Network Coverage Control using Extremum-Seeking Control



# Flight Test Set-Up

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Remote Node

Sensor Node Locations & Flight Setup in Camp Roberts

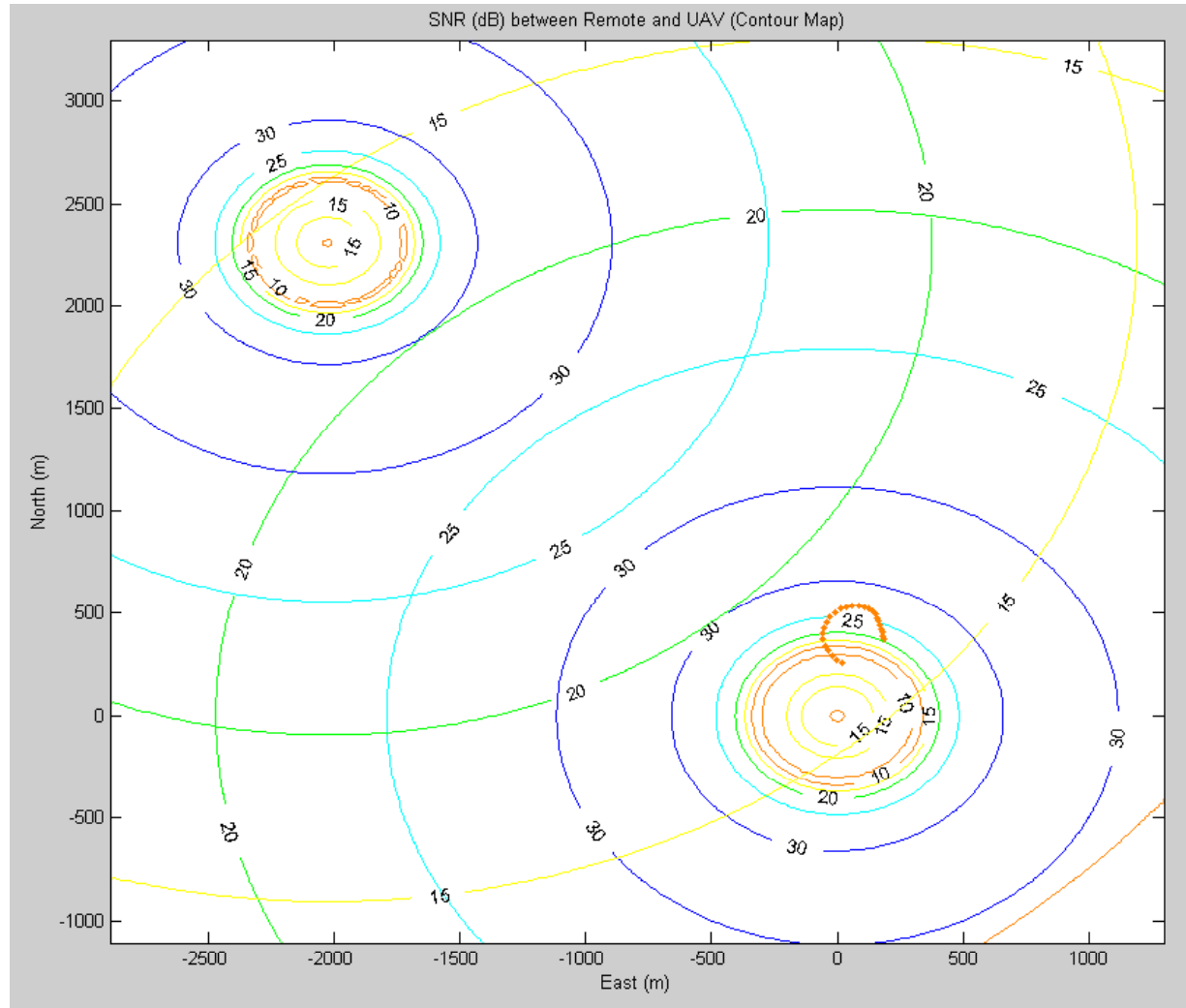
GCS



# UAV Trajectory over SNR MAP

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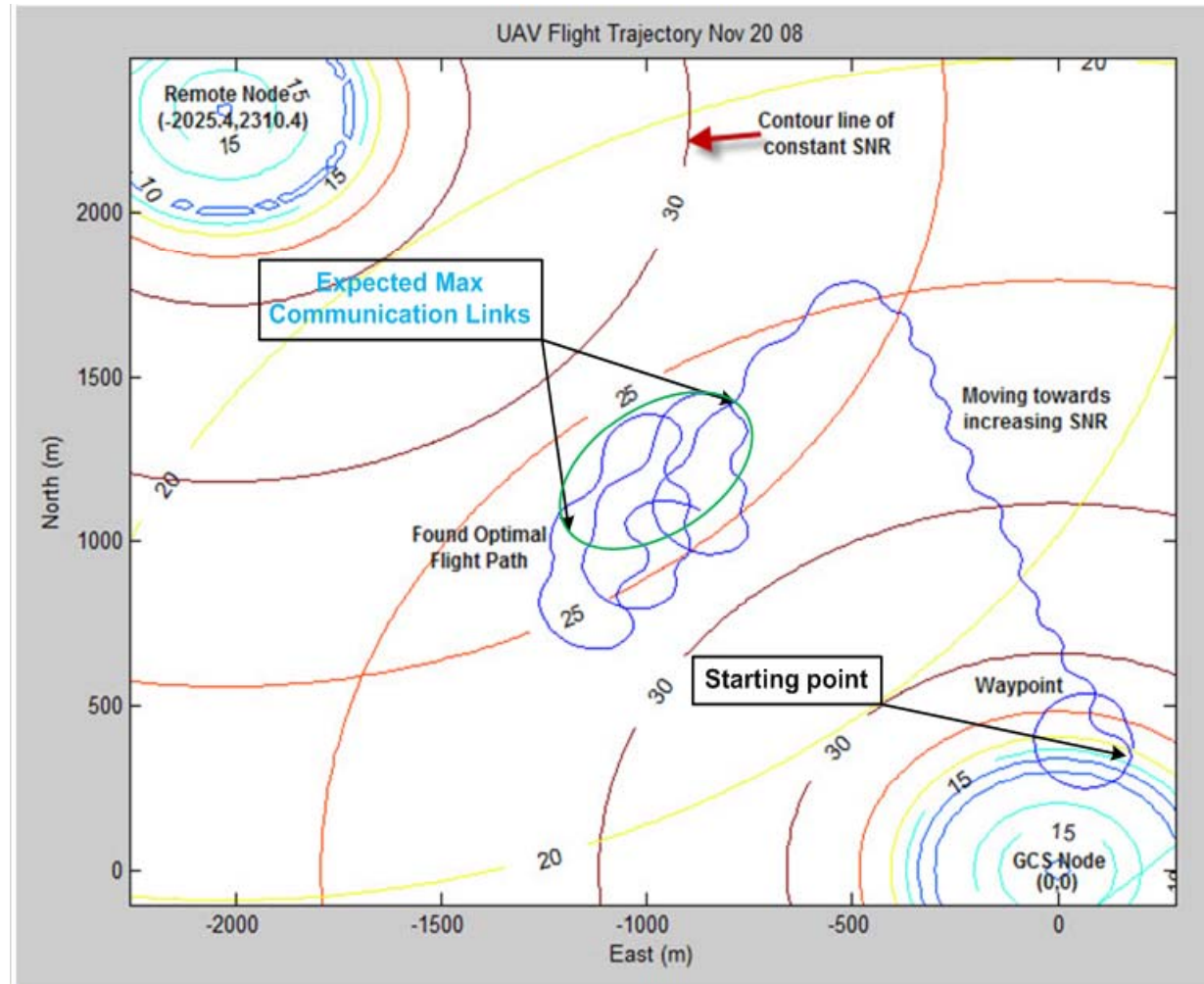
(Movie)

**UAV Trajectory Control for Max Communication Links (SNR)**





# UAV Path over SNR Map



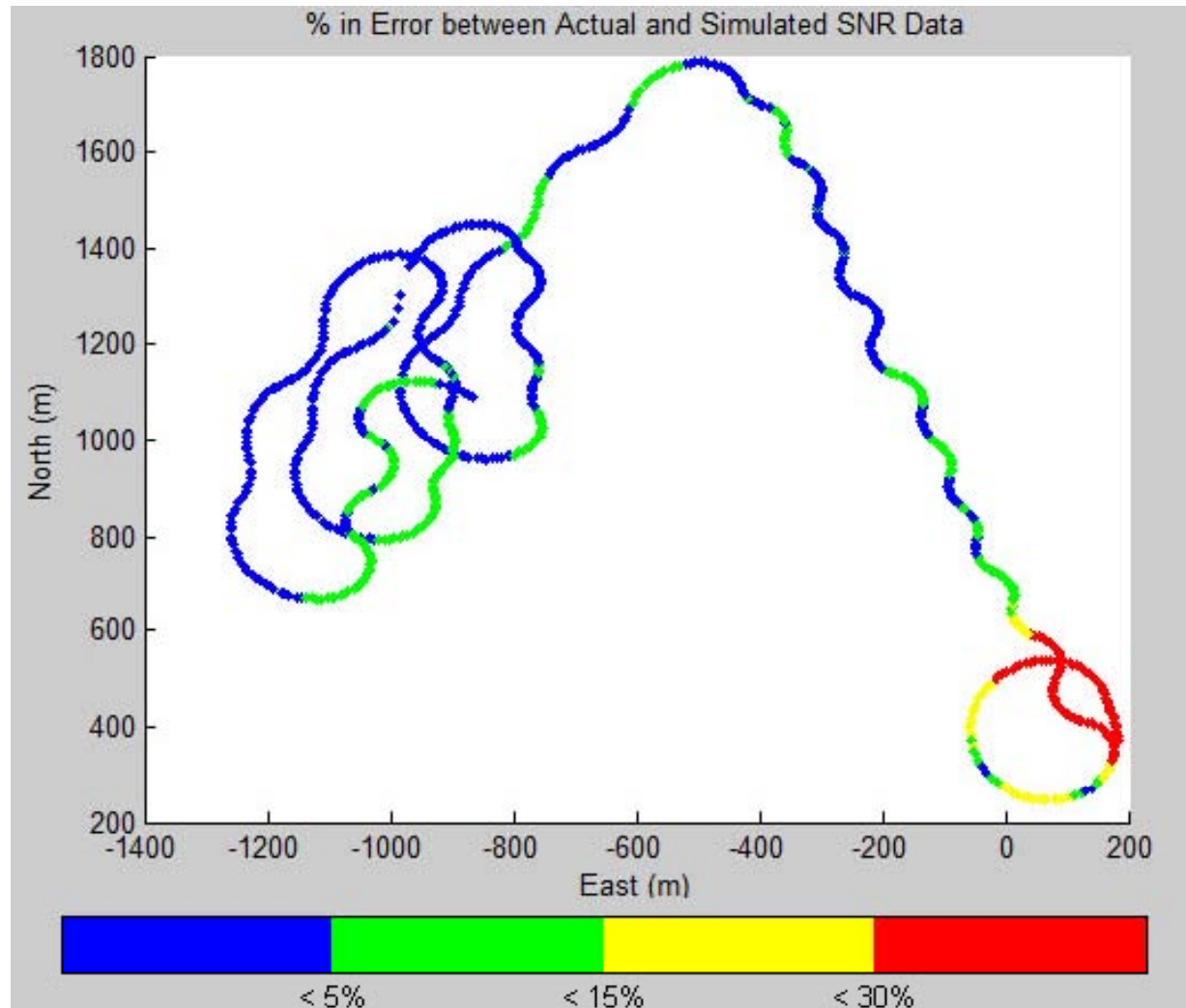
Plot of UAV Trajectory over SNR Maps



# SNR Model Errors

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Plot of SNR Errors Between Model and Observation Ones



# Conclusions

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## □ Communication Propagation Model

- Communication propagation model was developed, which include the effects of the path loss, antenna pattern loss, and the orientation of aerial platforms
- Proposed models were validated through real flight tests

## □ Self-Tuning Extremum Control for UAVs Location

- On-line adaptive gradient estimator was integrated into an extremum control architecture
- Proposed self-estimating extremum control is robust to even low signal-to-noise ratio signal
- Effectiveness of the self-tuning optimizer was validated through real time flight tests

## □ Applicable for Decentralized Network Coverage Control