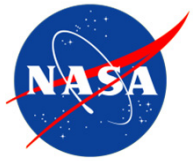


# Daytime Water Detection Based on Sky Reflections

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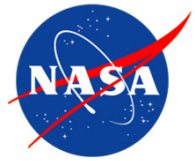
IEEE International Conference on Robotics and Automation (ICRA)
May 9-13, 2011

*This research was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under the Robotics Collaborative Technology Alliances program, through an agreement with NASA.*

# Topics Addressed




- RCTA program background
- Motivation for water detection
- Water detection methods explored under RCTA
- Observations about detecting water in open areas
- Modeling of reflection coefficient
- Water detection based on sky reflections
- Sample results under a variety of sky conditions
- Integration and field testing
- Summary

# RCTA Program Summary

- This work was funded by U.S. Army Research Laboratory (ARL) Robotics Collaborative Technology Alliances (RCTA) Program
  - Consortium of industrial, academic, and government lab partners
  - Focus on autonomous navigation technology development
  - Program duration: May 31, 2001 - Dec 31, 2009
  - JPL worked 3 Advanced Perception tasks:
    - Improvements to stereo vision
    - Pedestrian detection
    - Terrain classification (water, mud, near-to-far learning)

Stereo and water detection evaluation platform

GDRS Instrumented Train

Pedestrian detection evaluation platforms

GDRS Suburban GDRS Escape

Water detection evaluation platform

GDRS XUV

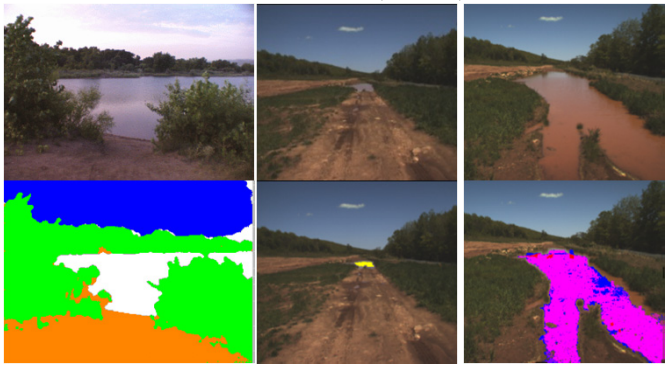
# Motivation for Water Detection

- **Problem:** Getting a UGV stuck in a water body can lead to:
  - Costly UGV damage
  - Need to allocate additional resources for recovery effort
  - Mission failure

- **Solution:** Detect water bodies and place them in a vehicle level map used to plan safe paths

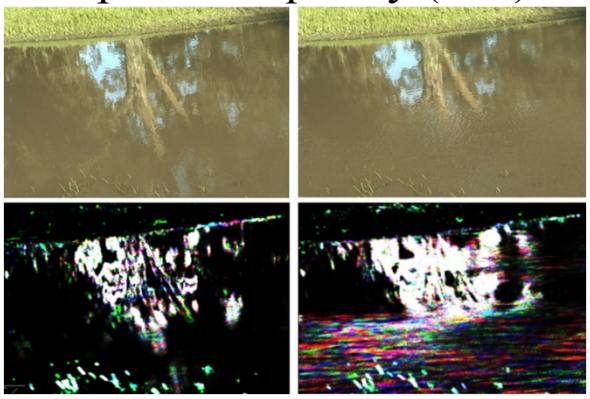
# RCTA Water Detection Methods

## Color (JPL)



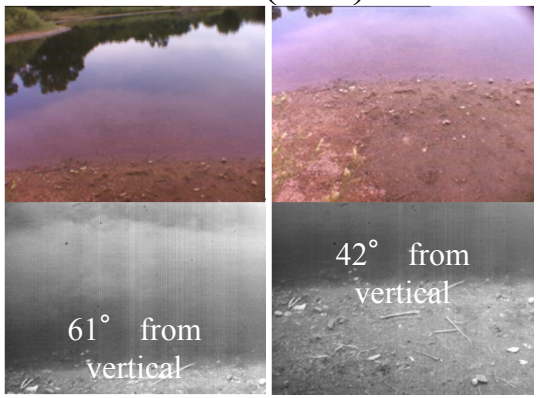
•RBG Bayesian classifier, supervised learning
•Detect far water body based on sky color
•Detect near-mid water body based on color variation

## Temporal Frequency (SRI)



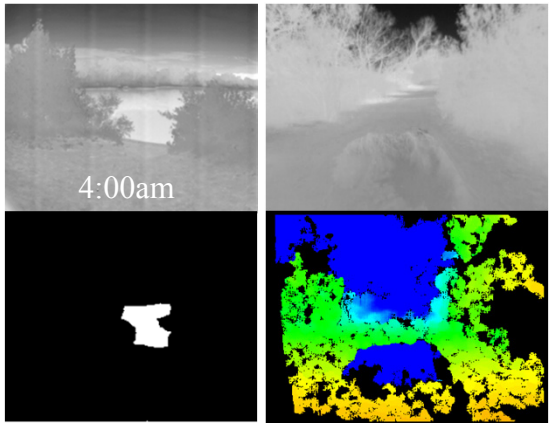
•Classification based on spatiotemporal properties to detect water disturbed by wind from a stationary platform

## SWIR (JPL)



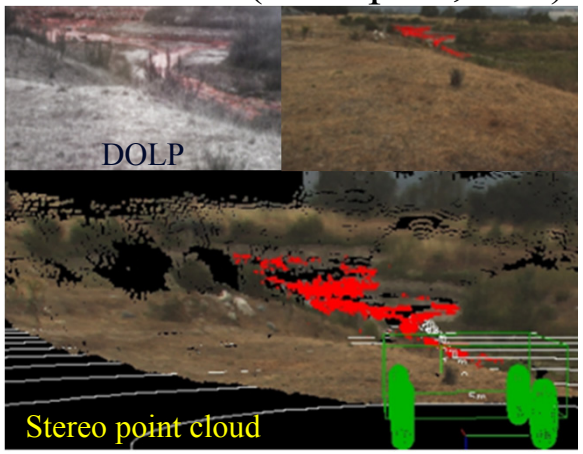

•Water is dark a low incidence angles
•Usefulness limited to daytime, incidence angles <60° (or airborne)

## Thermal Infrared (JPL)



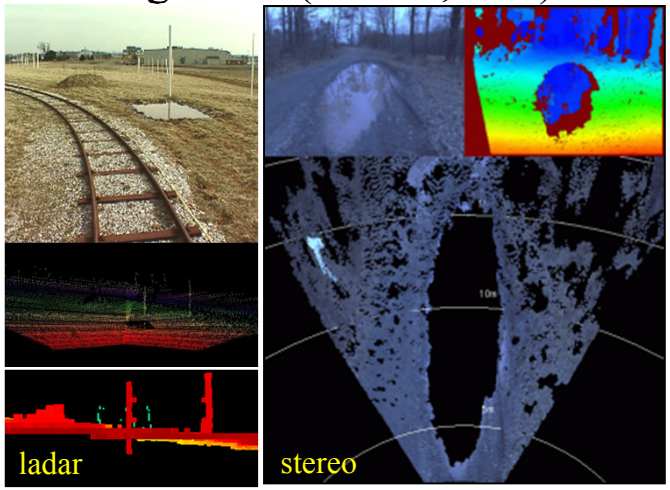

•Water may be warmer than surrounding terrain during much of the night (11pm-5am)
•Reflections of background objects are detectable in TIR stereo

## Polarization (Perceptek, JPL)




•Water tends to have a high degree of linear polarization (DOLP)

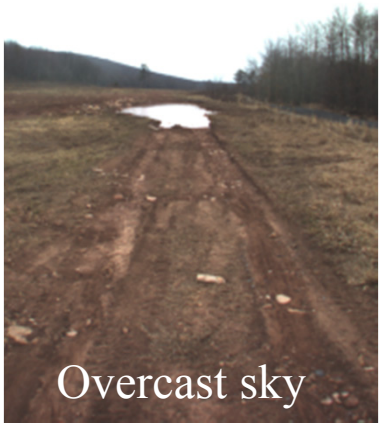
## Range data (GDRS, JPL)

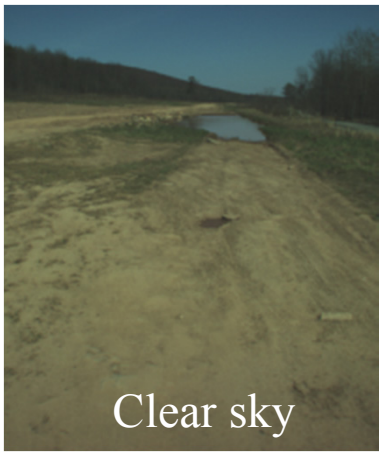



•**Ladar**: no return at high incidence angles, reflections of objects out to mid range
•**Stereo**: reflections of objects out to infinity

# Water Bodies in Wide Open Areas

- At far range, reflections of the sky dominates the color of water



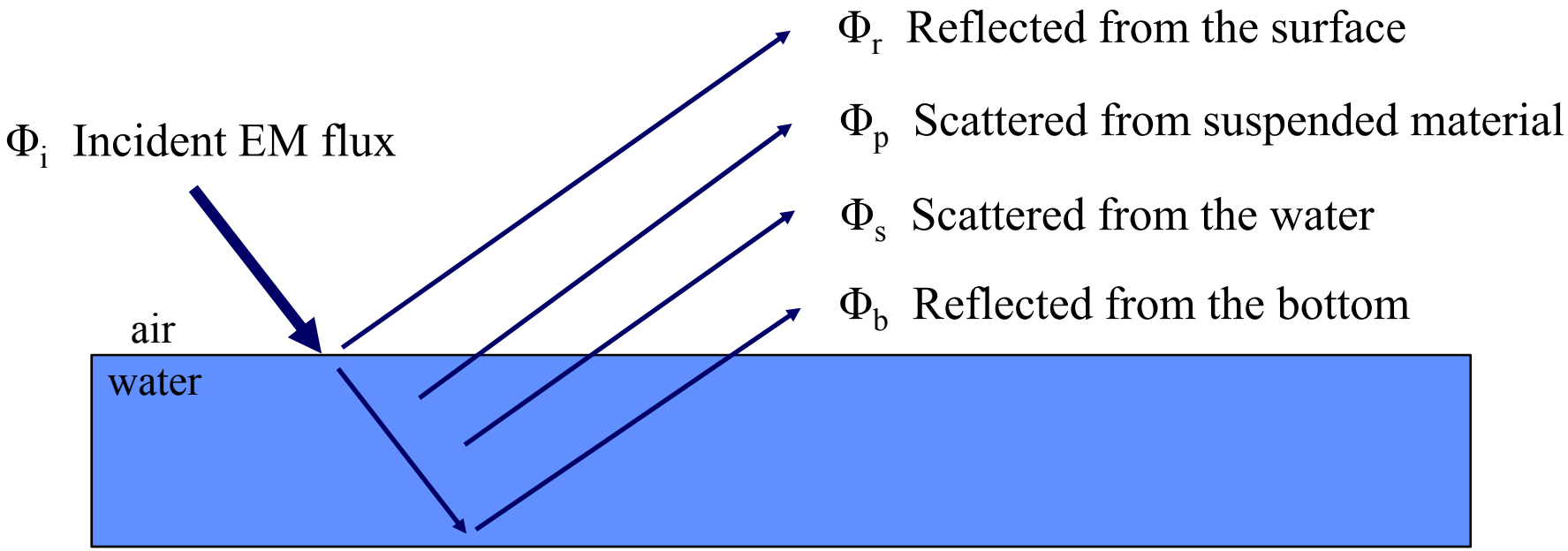






- At close range, the color coming out of a water body dominates

# Modeling Reflection Coefficient

- Simple model of EM flux leaving the surface of water




$$\Phi_{out} = \Phi_r + \Phi_p + \Phi_s + \Phi_b$$

$$R_{apparent} = \frac{\left(\Phi_r + \Phi_p + \Phi_s + \Phi_b\right)}{\Phi_i}$$

$$R_{apparent} = \frac{\Phi_r}{\Phi_i} + \frac{\Phi_p + \Phi_s + \Phi_b}{\Phi_i}$$

$$R_{apparent} = R_r + R_o$$

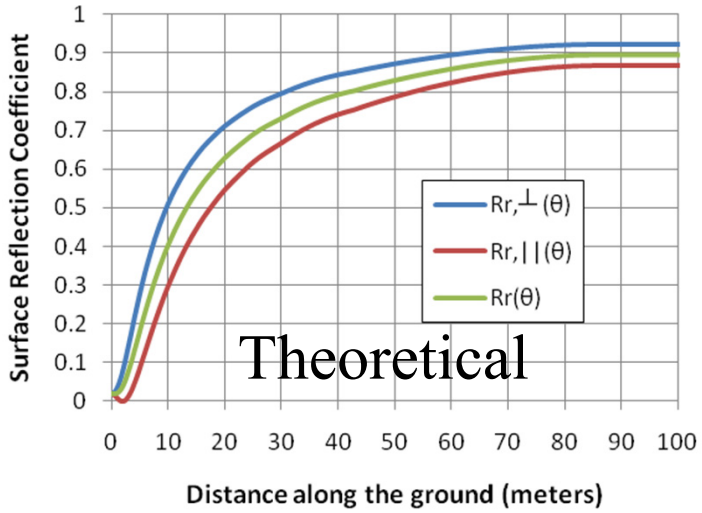
http://www.geog.umd.edu/

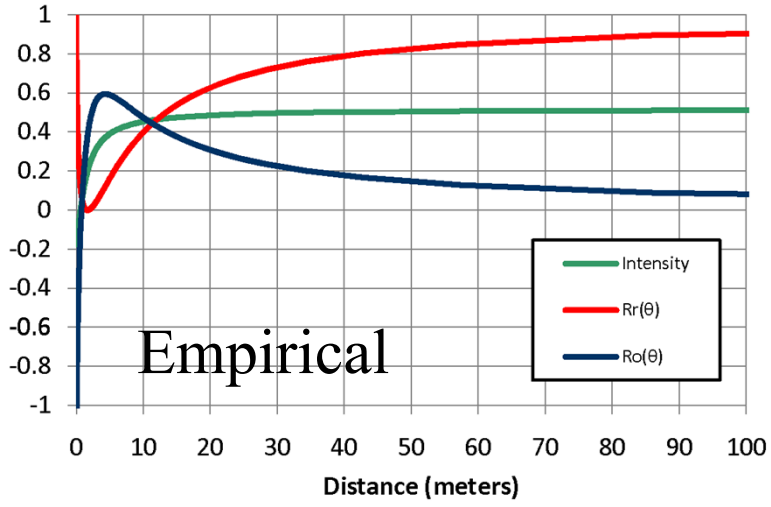
# Surface Reflection Coefficient

The fraction of the incident power that is reflected from an air/water interface is given by Fresnel equations:

$$R_{r,\parallel}(\theta) = \left[ \frac{n_1 \sqrt{1 - \left( \frac{n_1}{n_2} \sin\theta \right)^2} - n_2 \cos\theta}{n_1 \sqrt{1 - \left( \frac{n_1}{n_2} \sin\theta \right)^2} + n_2 \cos\theta} \right]^2$$

$$R_{r,\perp}(\theta) = \left[ \frac{n_1 \cos\theta - n_2 \sqrt{1 - \left( \frac{n_1}{n_2} \sin\theta \right)^2}}{n_1 \cos\theta + n_2 \sqrt{1 - \left( \frac{n_1}{n_2} \sin\theta \right)^2}} \right]^2$$

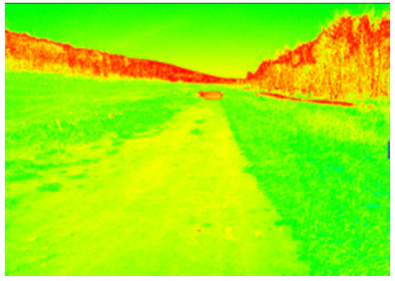
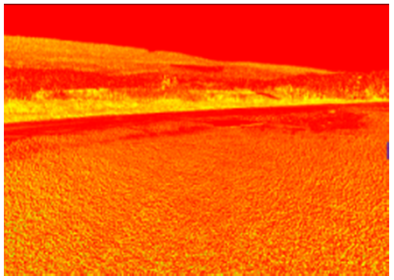
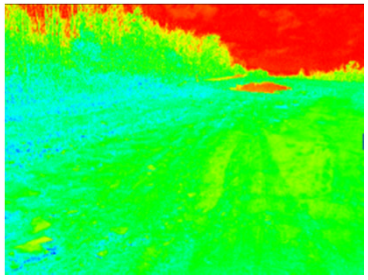
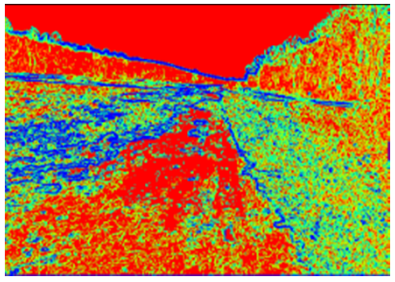
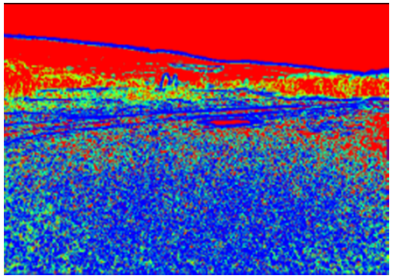
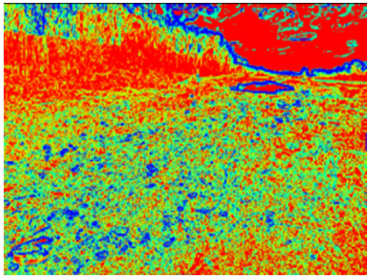
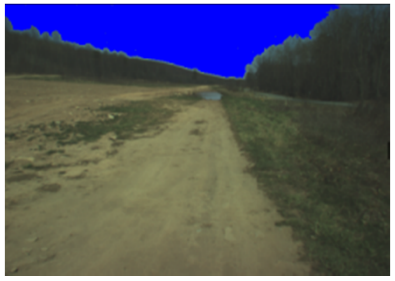



## Assumptions:

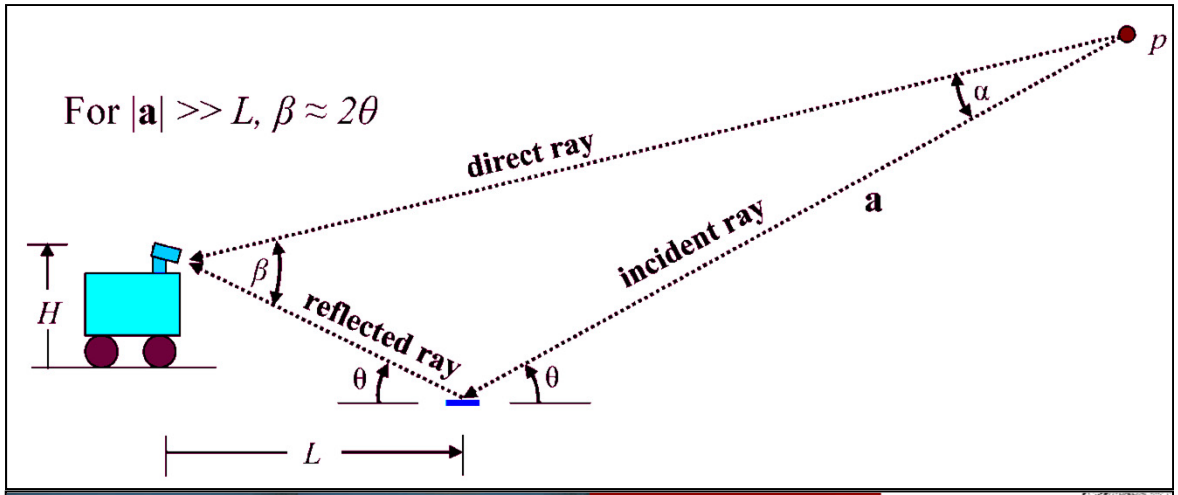
- Sensor height of 1.5 meters
- Water refractive index of 1.03, air refractive index of 1.33

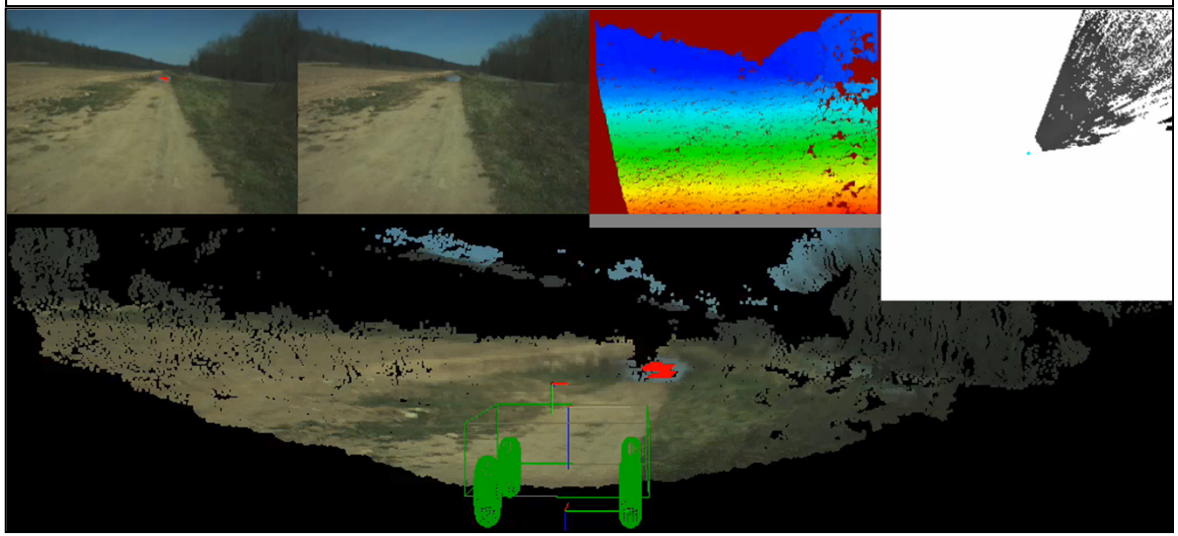
# Sky Detection

| | Clear | Overcast | Cloudy |
|---|---|---|---|
| RGB Image |  |  |  |
| Sat/Bri |  |  |  |
| Edge Magnitude |  |  |  |
| Sky detection |  |  |  |

# Water Detection based on Sky Reflections

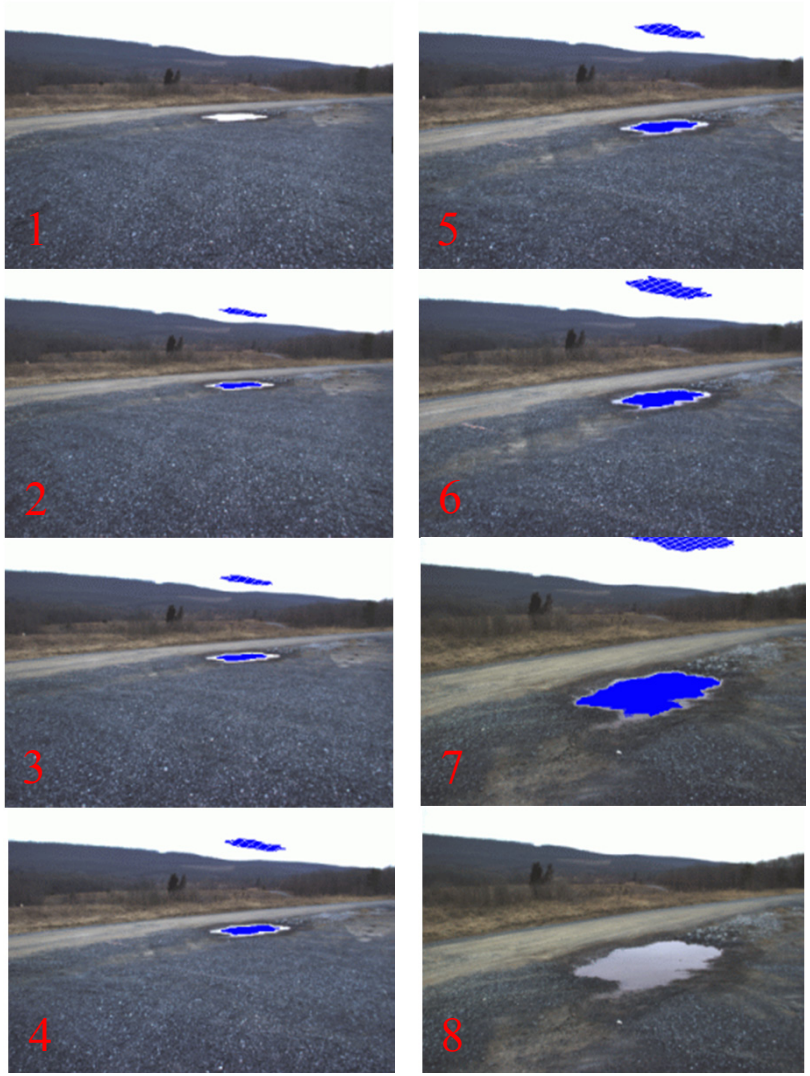
- Locate the sky pixel reflecting on a candidate water pixel
- Do they have a similar color?

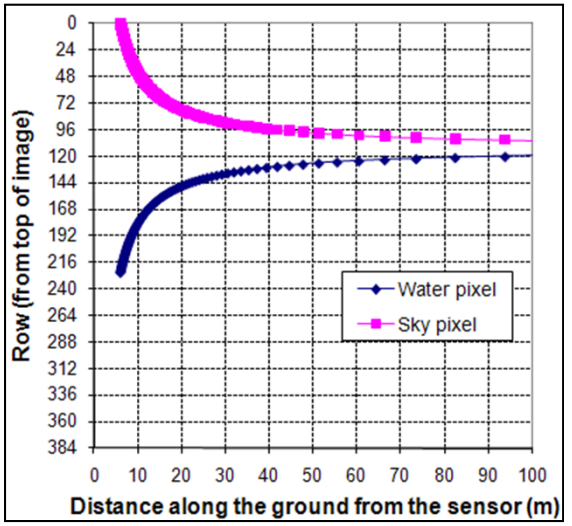


# Sky Pixels Reflecting on Water

- **At close range, the region of the sky reflecting on a water body moves outside a camera's FOV**



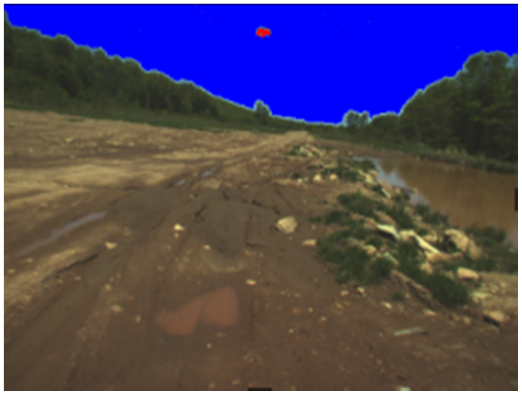




Assumptions:
1) Sensor height =1.5m
2) 10° sensor downtilt
3) 48° VFOV
4) 384 image rows

# False Detection Rejection

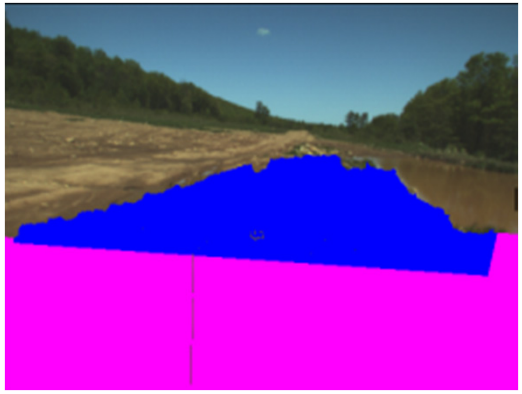
Sky detection can be used to determine which pixels on the ground are directly reflected on by the sky pixels in the FOV.

Scene with water body



Sky Detection

- Clear sky
- Cloud

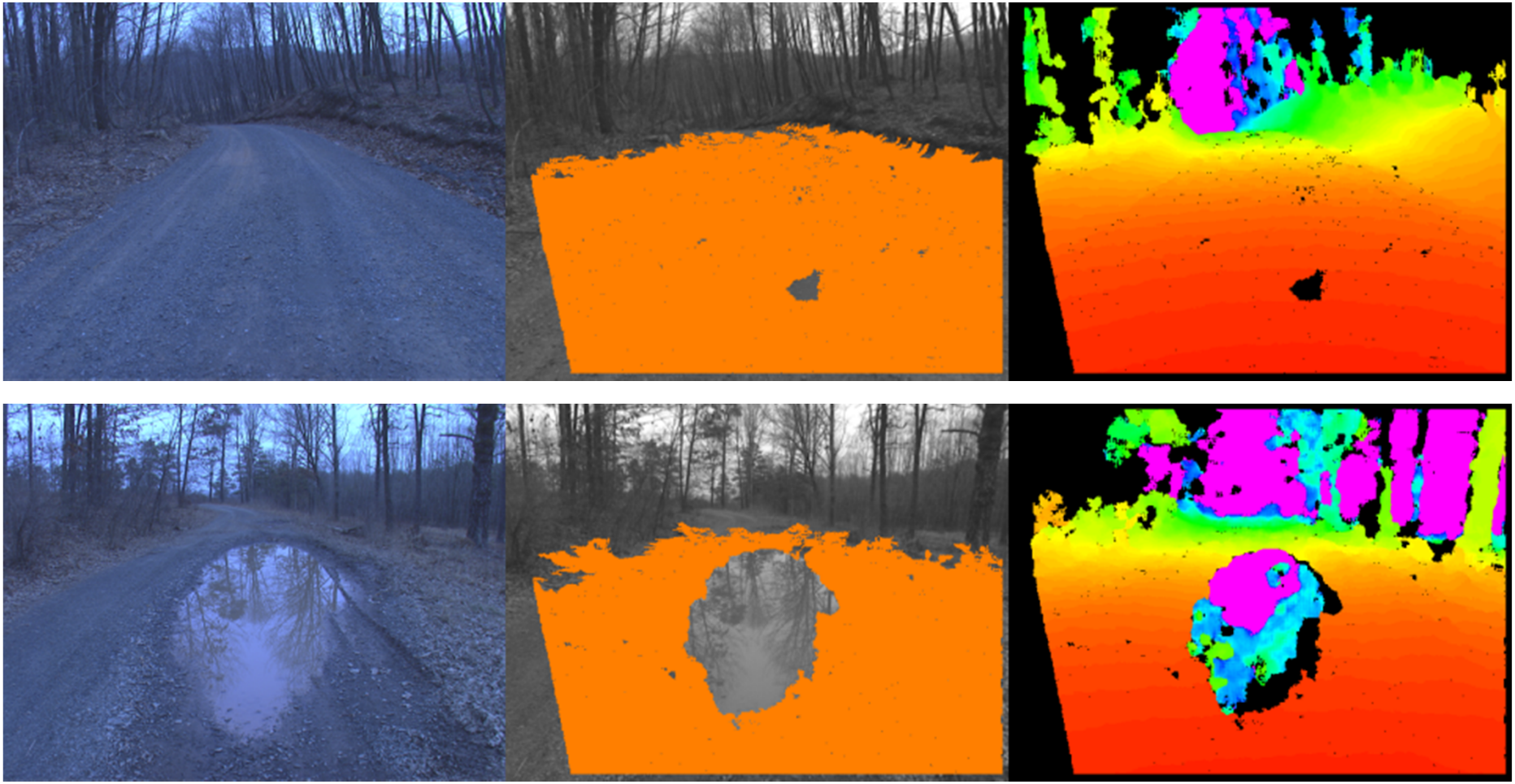


Ground pixels reflecting the sky

- Calculated
- Assumed

# False Detection Rejection

If its part of the ground surface, then it can't be water



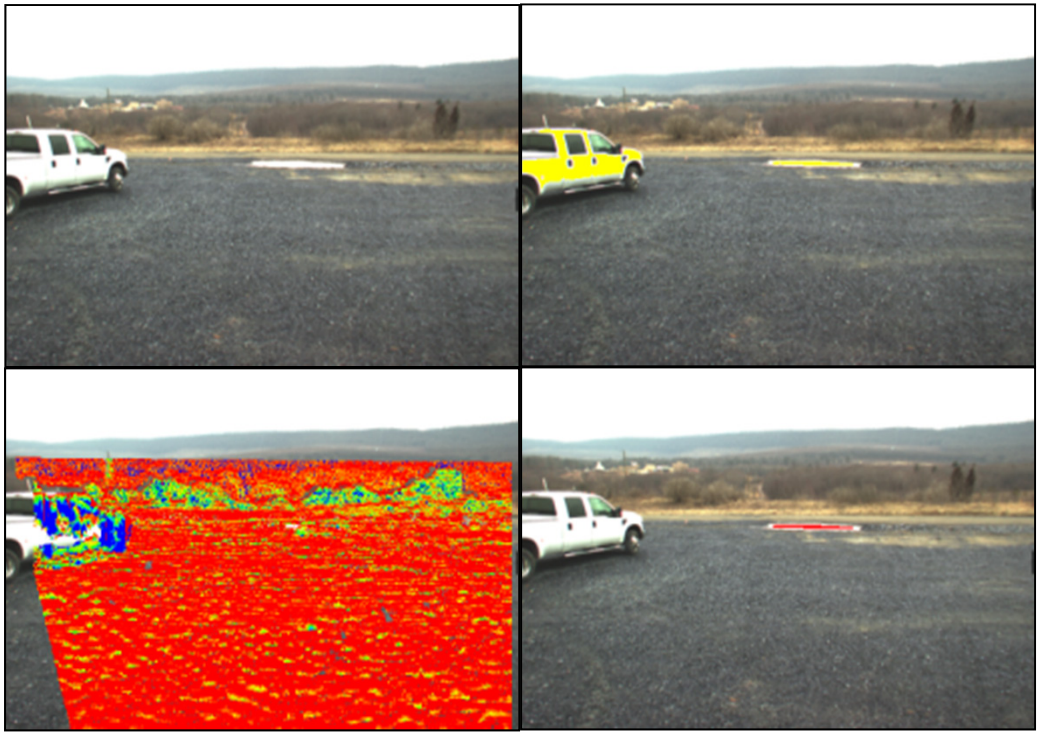
Scenes from FITG *forever loop* Ground detection Stereo range image

# False Detection Rejection

If its not level, then it can't be water

RGB image

Slope image



Color/ texture based detection

Final water detection

# False Detection Rejection

If its above the horizon, then it can't be a water body

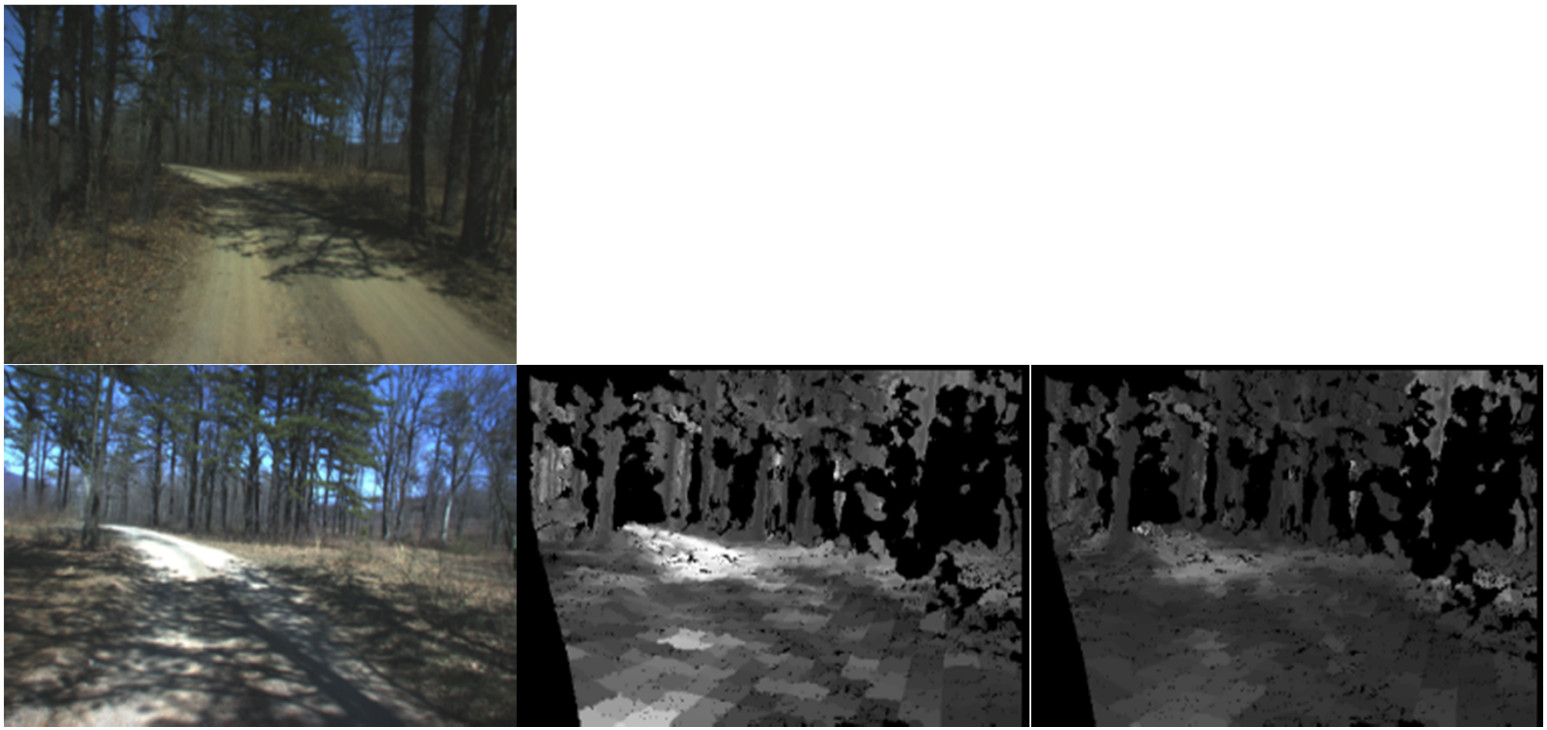
Horizon line located using UGV attitude data from IMU

# False Detection Rejection

If the brightness of a region increases as you approach it, then it's probably not water

Approaching a shadowed region

After driving into the shadowed region



RGB image

Current map cell color

Reference map cell color

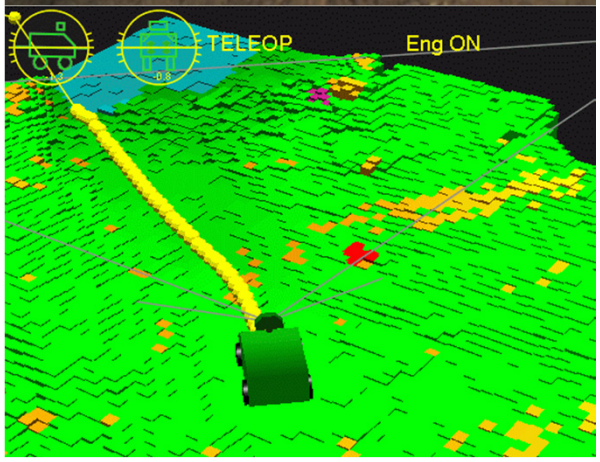
# Sample Results


| | 1st/Last Det | Num frames | True Pos | False Pos | Avg time |
|---|---|---|---|---|---|
| Clear | 64m<br>11.4 m | 265 | 100% | 0% | 105ms |
| Overcast | 51m<br>9.7m | 435 | 100% | 0% | 111ms |
| Cloudy | 47m<br>1.9m | 173 | 100% > 7m<br>4.4% < 7m | 0.58% | 99ms |

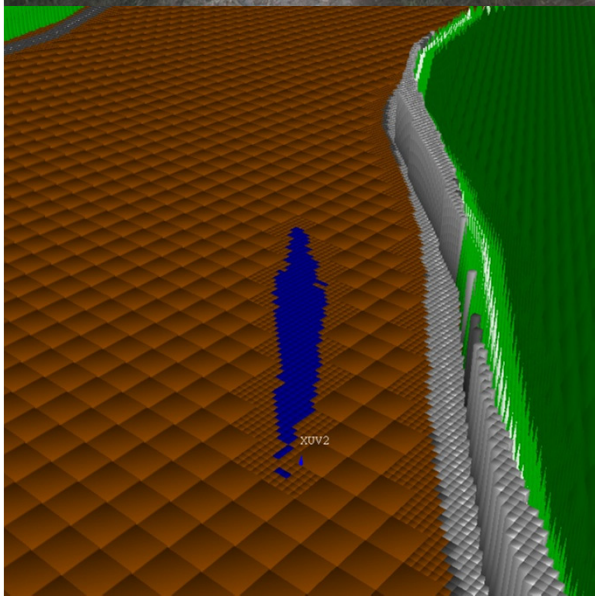
# Integration and Field Testing

Water detection sensors: stereo pair of color cameras

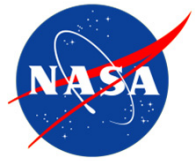

Integrated with XUV autonomous mobility (AM) map/planner



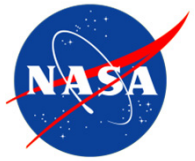

Integrated with XUV mid-range "C2" map



# Summary




- A water body's surface can be modeled as a horizontal mirror
- Water detection based on sky reflections and color variation are complementary
- A reflection coefficient model suggests sky reflections dominate the color of water at ranges > 12 meters
- Water detection based on sky reflections:
  - geometrically locates the pixel in the sky that is reflecting on a candidate water pixel on the ground
  - predicts if the ground pixel is water based on color similarity and local terrain features
- Water detection has been integrated on XUVs




# Questions?