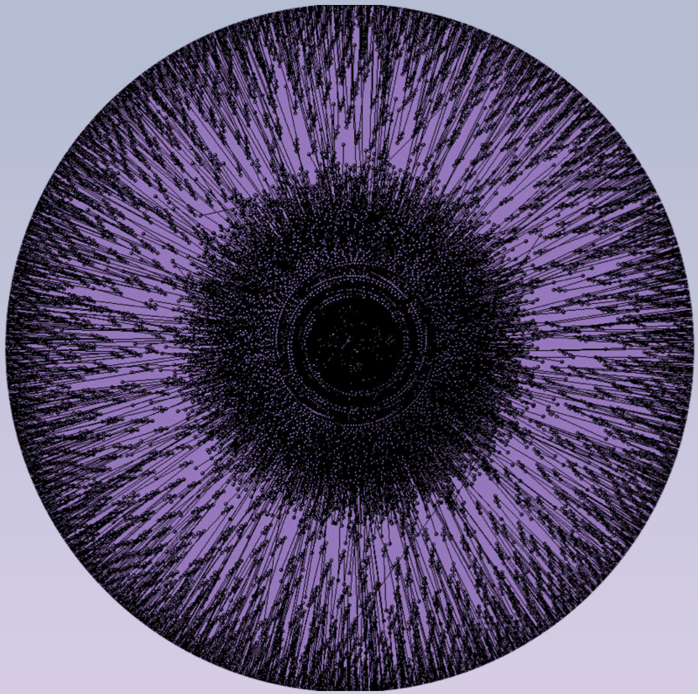
Fusing Optical Flow and Stereo in a Spherical Depth Panorama Using a Single-Camera Folded Catadioptric Rig



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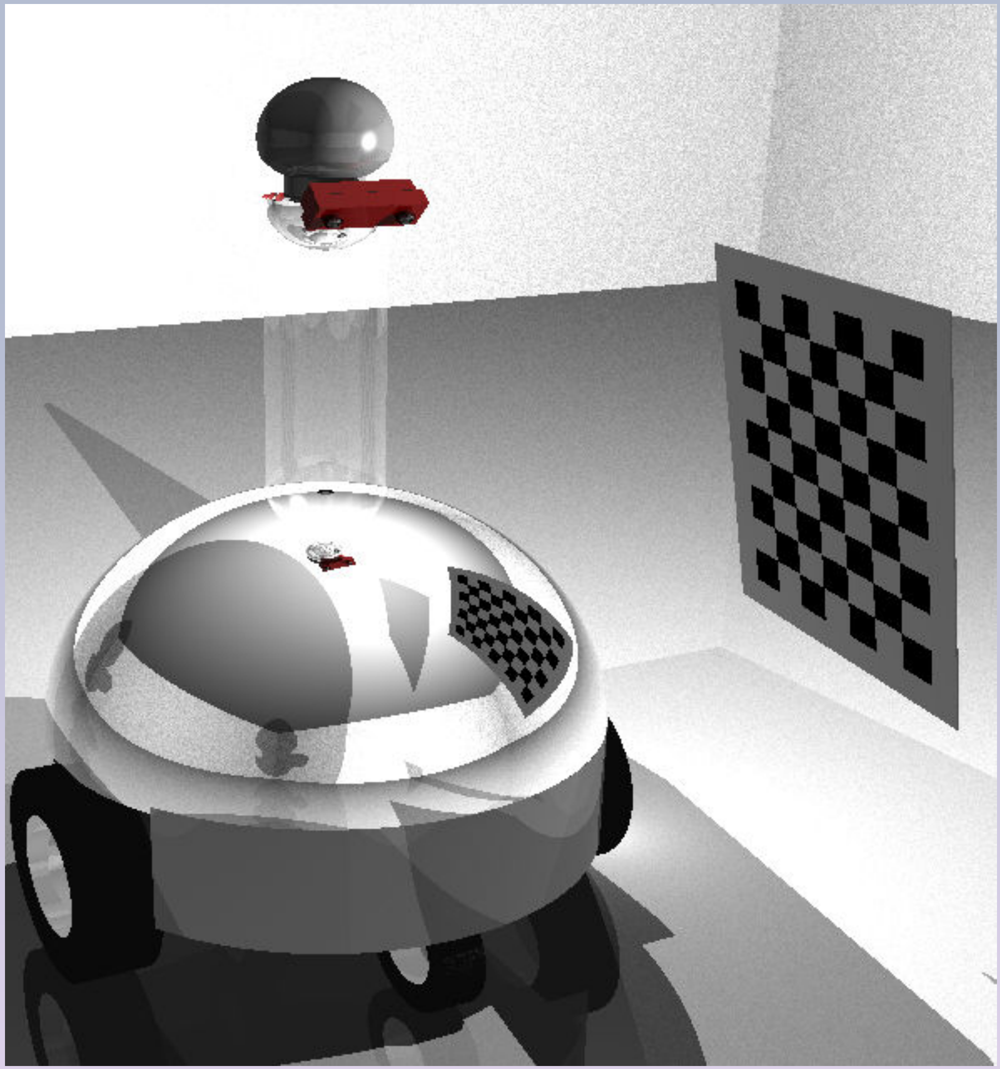
Robotics Lab

City College of New York

ICRA 2011

Presentation Outline



POV-Ray Robot Model

- **Introduction**
- **Rig Design (Model)**
- **Omnidirectional Stereo Geometry (*Sphereo*)**
- **Depth from Omnidirectional Optical Flow**
  - 3-D De-rotaion
- **Fusion of the 2 Modalities**
- **Results and Conclusion**

Introduction

- **3-D world = Surround Vision**
- **Eye geometry of insects**

  360° azimuthal field of view.
- **Catadioptric Sensors**

  Catoptrics (Mirror) + Dioptric (Lenses)
- **Guiding Visuall… e**
- **Guiding Robots**
  - Ground
  - Aerial

Omnidirectional

Motivation of Spherical Catadioptrics

- **Coaxial Alignment:**

Standard monocular web-camera

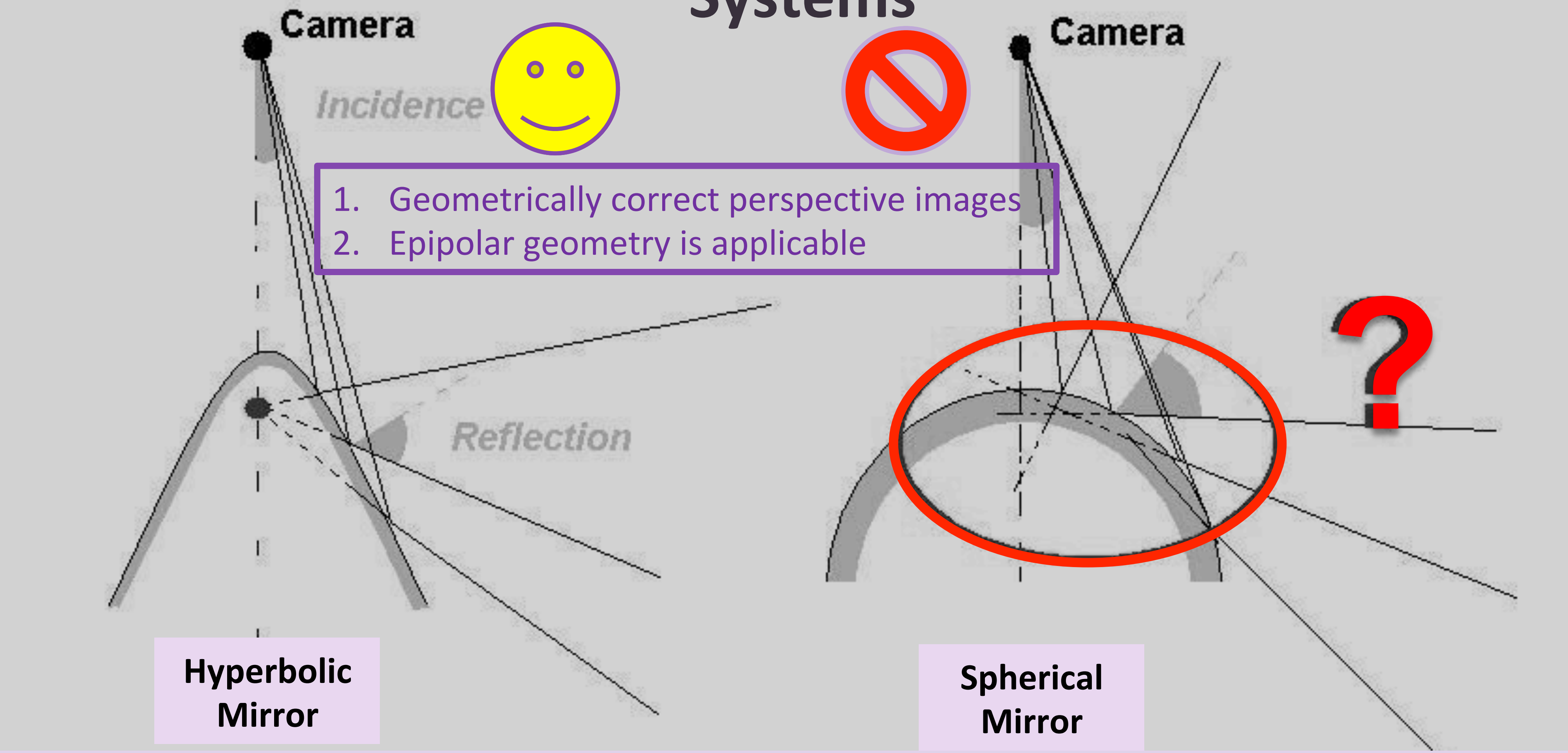
+

2 *spherical* mirrors???

- **Spherical Mirrors Cons:**
    - No Single ViewPoint (SVP)

SVP constraint = Only with Central Projection Systems

1. Geometrically correct perspective images
2. Epipolar geometry is applicable



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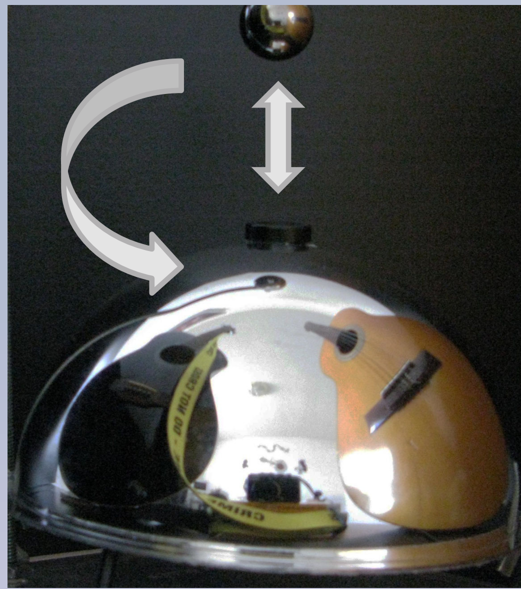
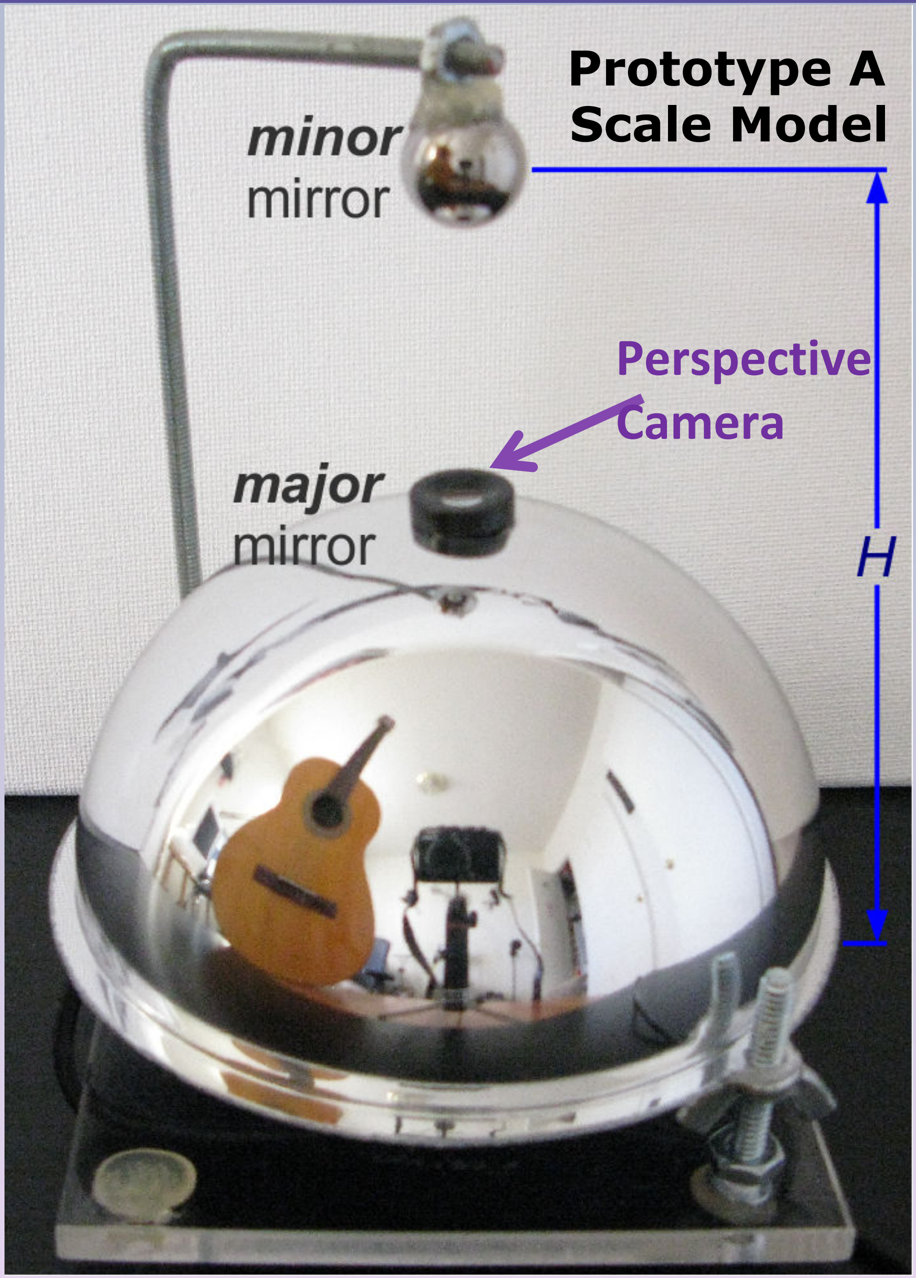
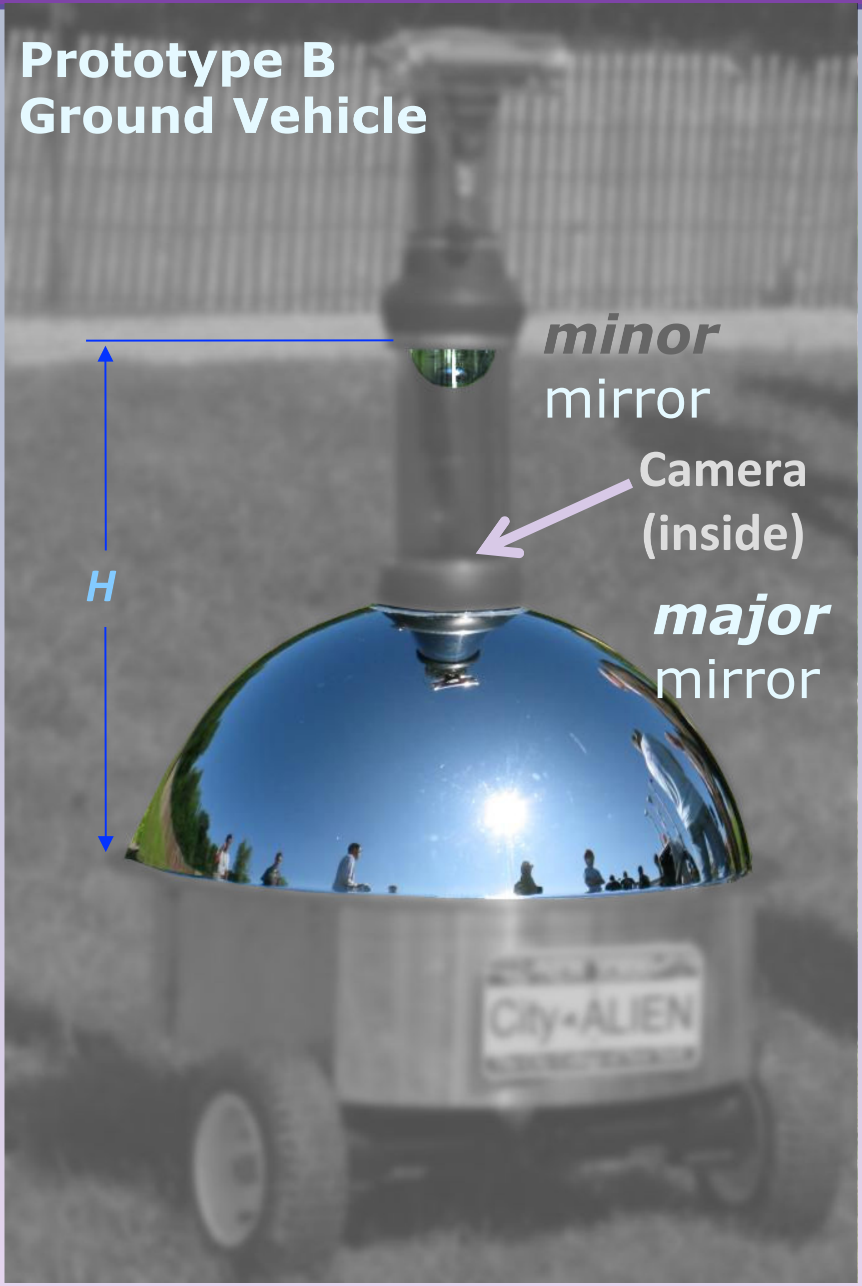


- **Spherical Mirrors Cons:**
  - No Single ViewPoint (SVP)
  - Lower resolution + Higher distortion (true for all mirrors)
- **Spherical Mirrors Pros:**
  - **Cheaper** to build and **low weight**
  - No multi-calibration issues (1 single camera to calibrate)
  - No synchronization problems + **No misalignments**
  - **Larger vertical FOV**

Folded-Configuration Models





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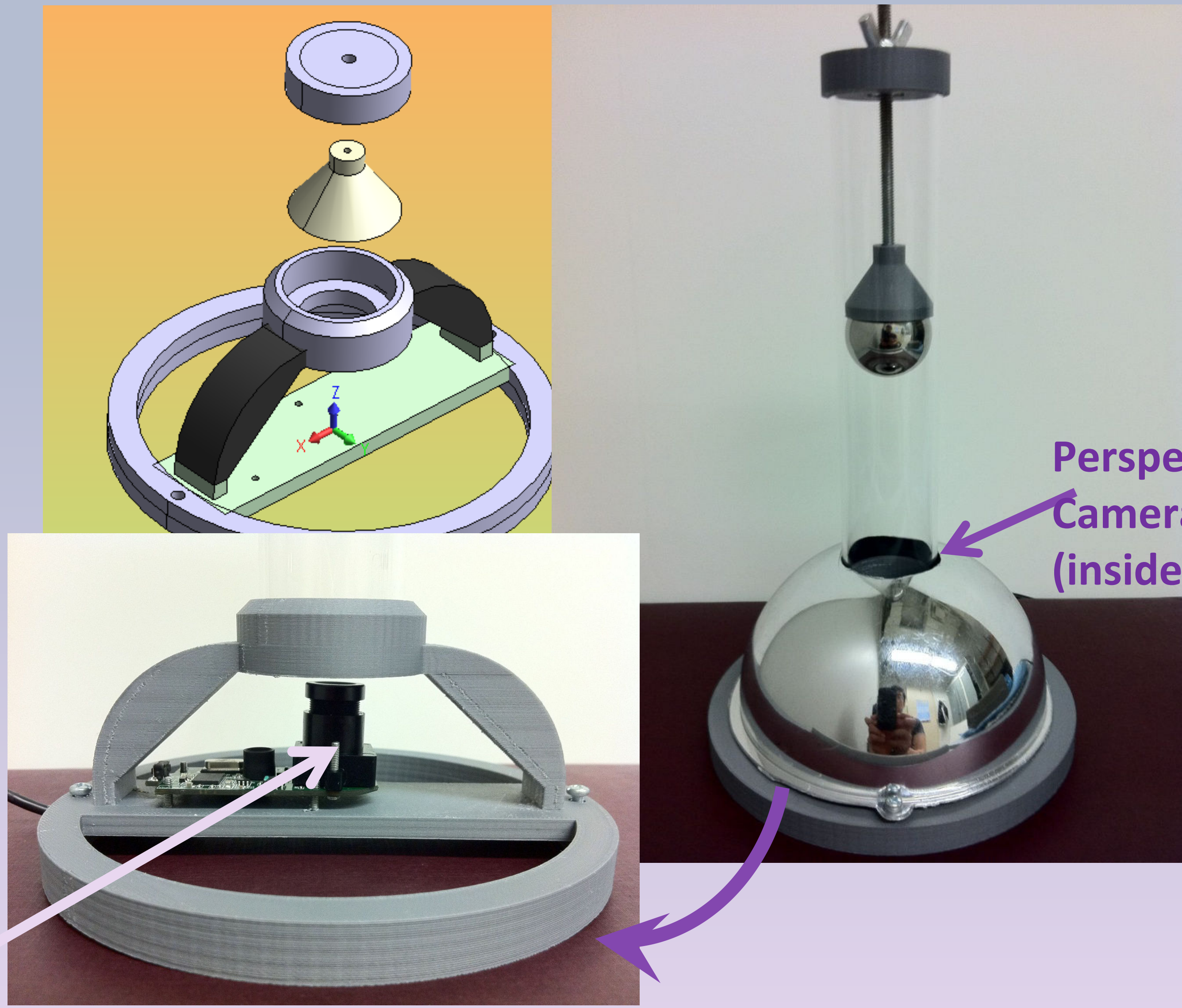
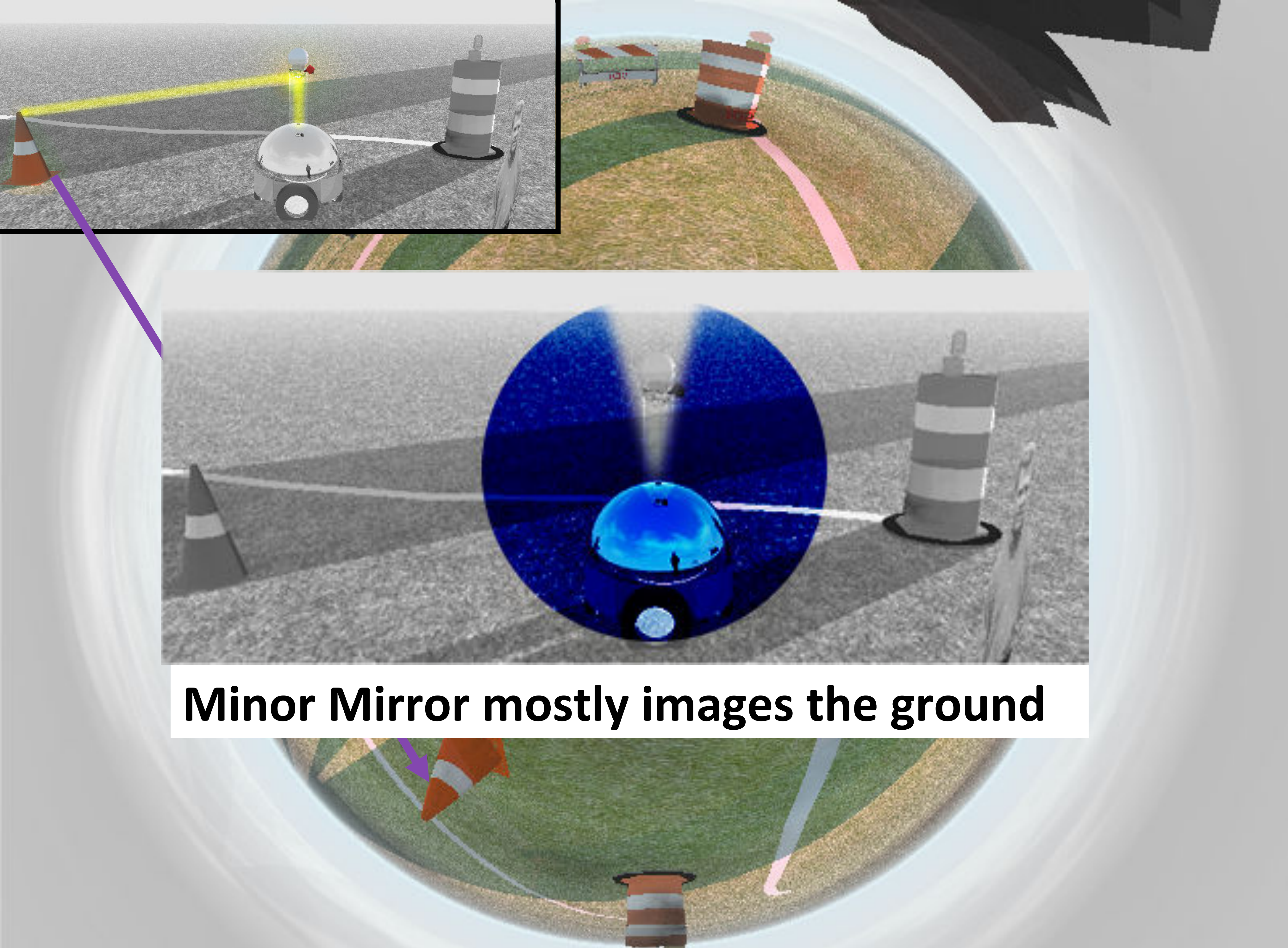
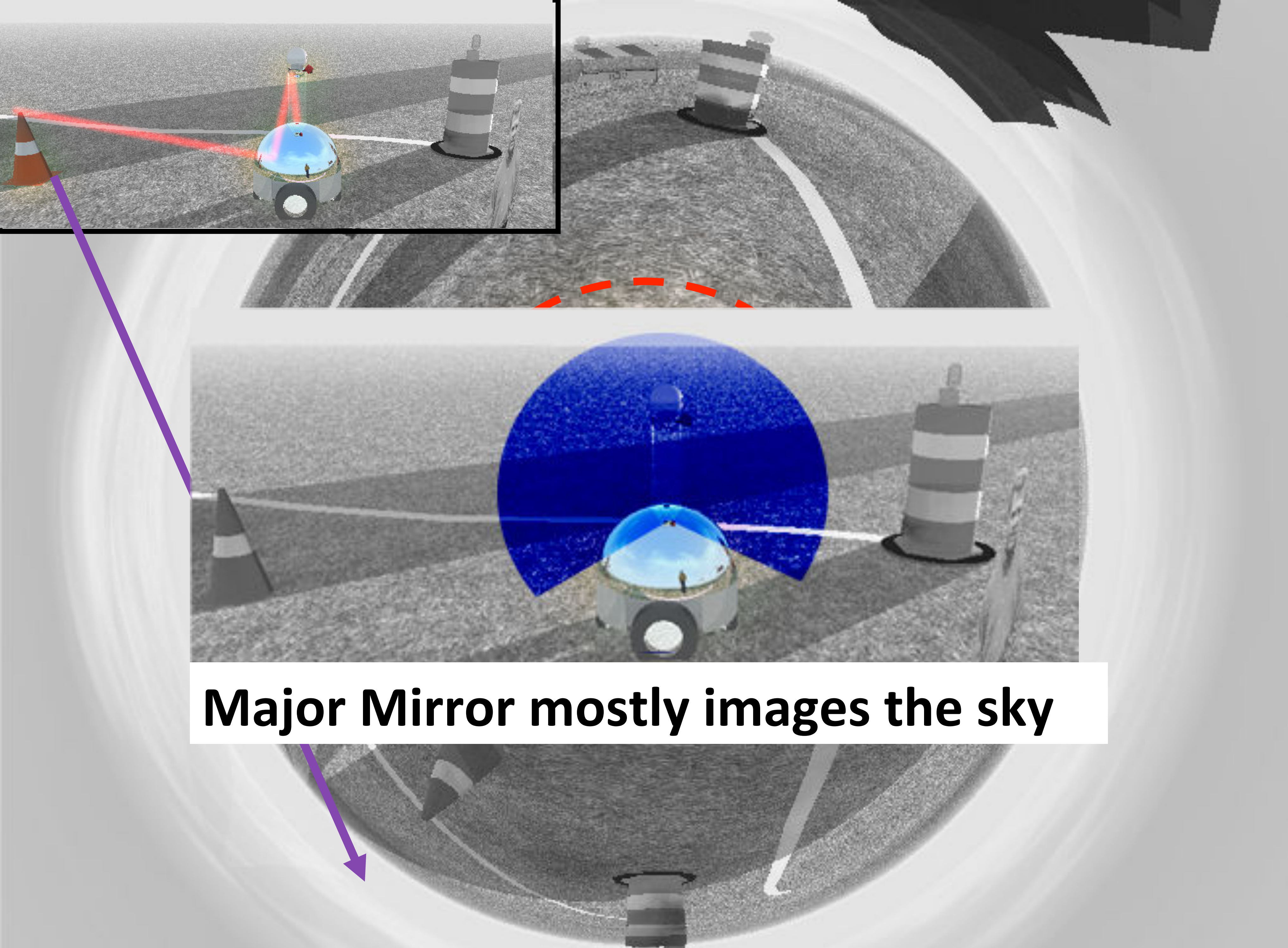


Introduction > **Rig Design** > Stereo Geometry > Optical Flow > Fusion > Results and Conclusion

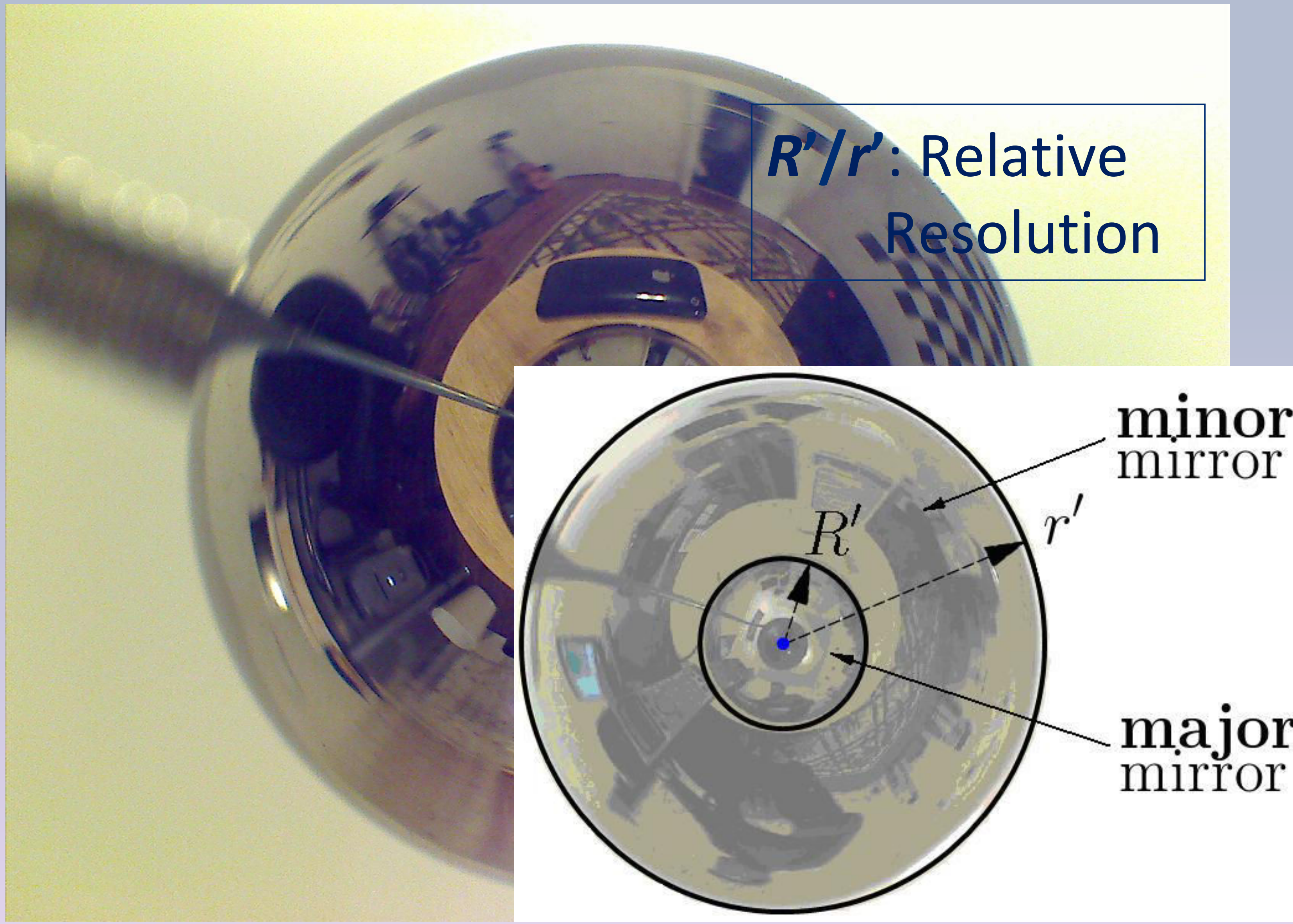


Minor Mirror mostly images the ground



Major Mirror mostly images the sky

Image Acquisition



R'/r' : Relative Resolution

Introduction > **Rig Design** > Stereo Geometry > Optical Flow > Fusion > Results and Conclusion

Design Parameters

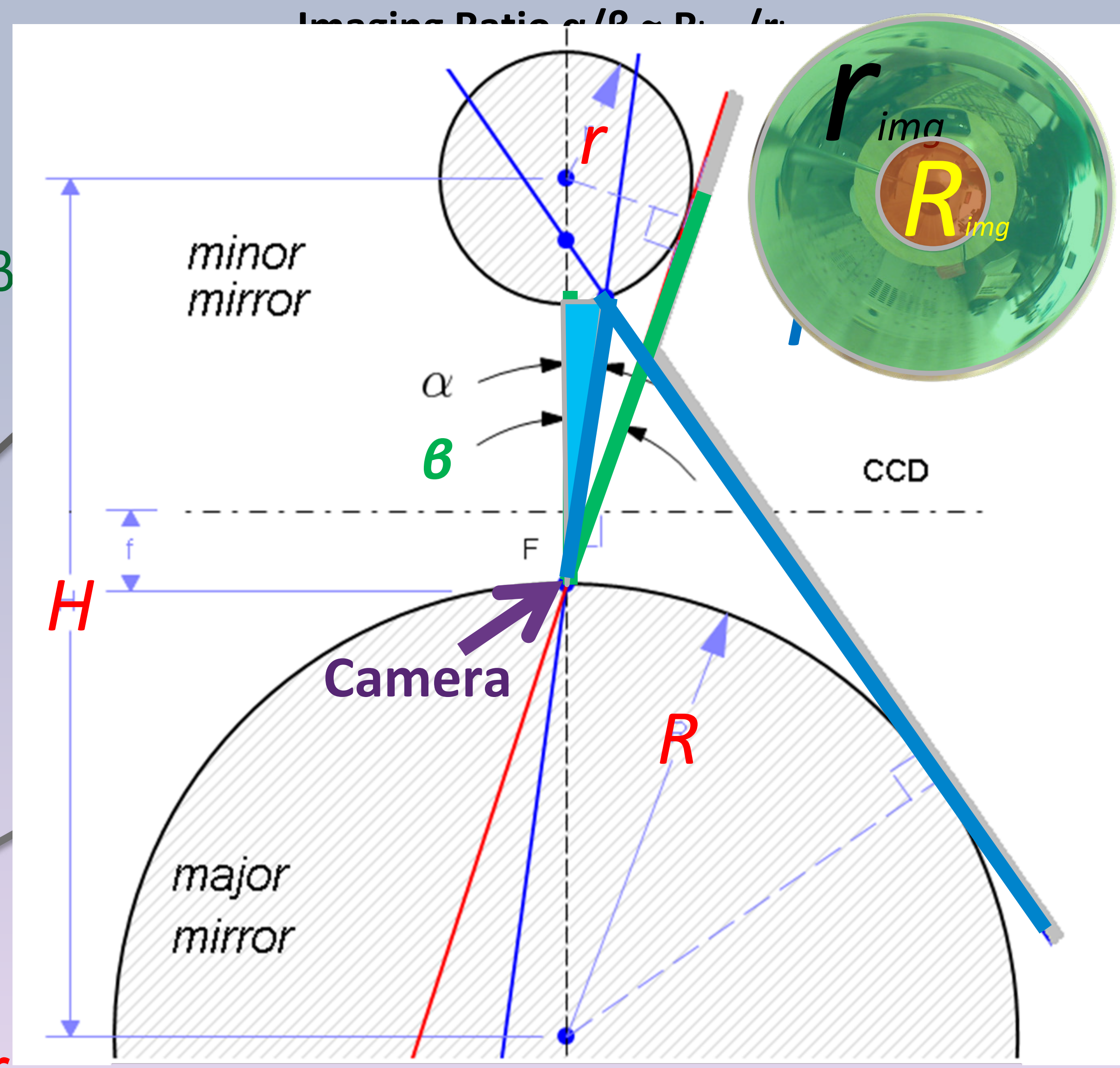
- **Assumptions**
  - Single Viewpoint
  - FOV of **camera F** is < 2β
- **Linearization Constraints**

H >> r and R >> r

$$\frac{R_{img}}{r_{img}} \approx \frac{\alpha}{\beta} = \frac{R}{H\sqrt{2}}$$

$$FOV = \pi - \frac{R}{H}$$

Less than 10% deviation when H > 2 R and R > 2 r



Modality 1: SPHEREO (Stereo Vision with Mirror Spheres)

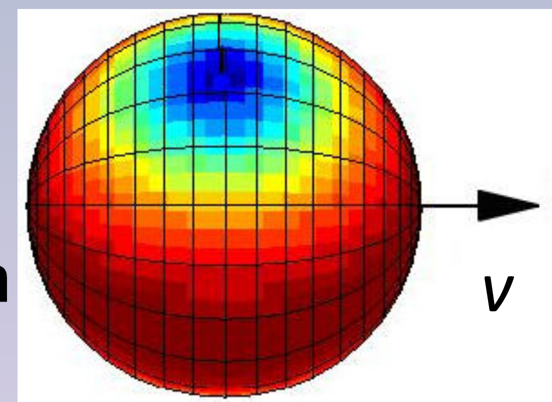
- Has been attempted MANY times

- **Problem:**
  Depth may be recovered only in a **NARROW** (<30 degrees) **band** around the equator of the view-sphere

Depth From Optical Flow

Modality 2:
OPTICAL FLOW = Visual Features + Motion

Has been attempted too!



Problem 1 - Provides depth everywhere except in the direction of your own motion

Problem 2 - Only **RELATIVE depth** (Scale Factor needed)

Problem 3 - Needs motion!!!

Our Solution

SPHEREO + OPTICAL FLOW

Has NOT been attempted in catadioptrics

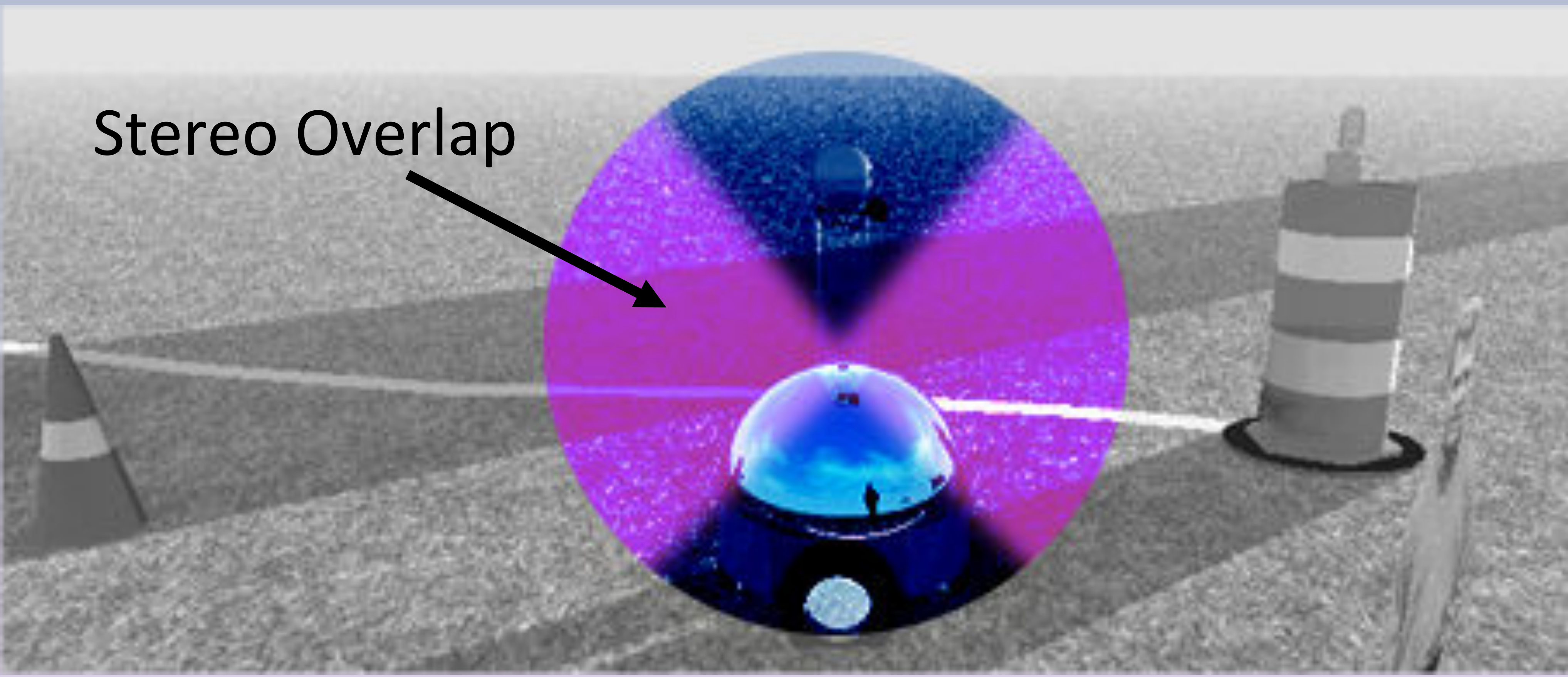
Goal: To take advantage of 2 Modalities:

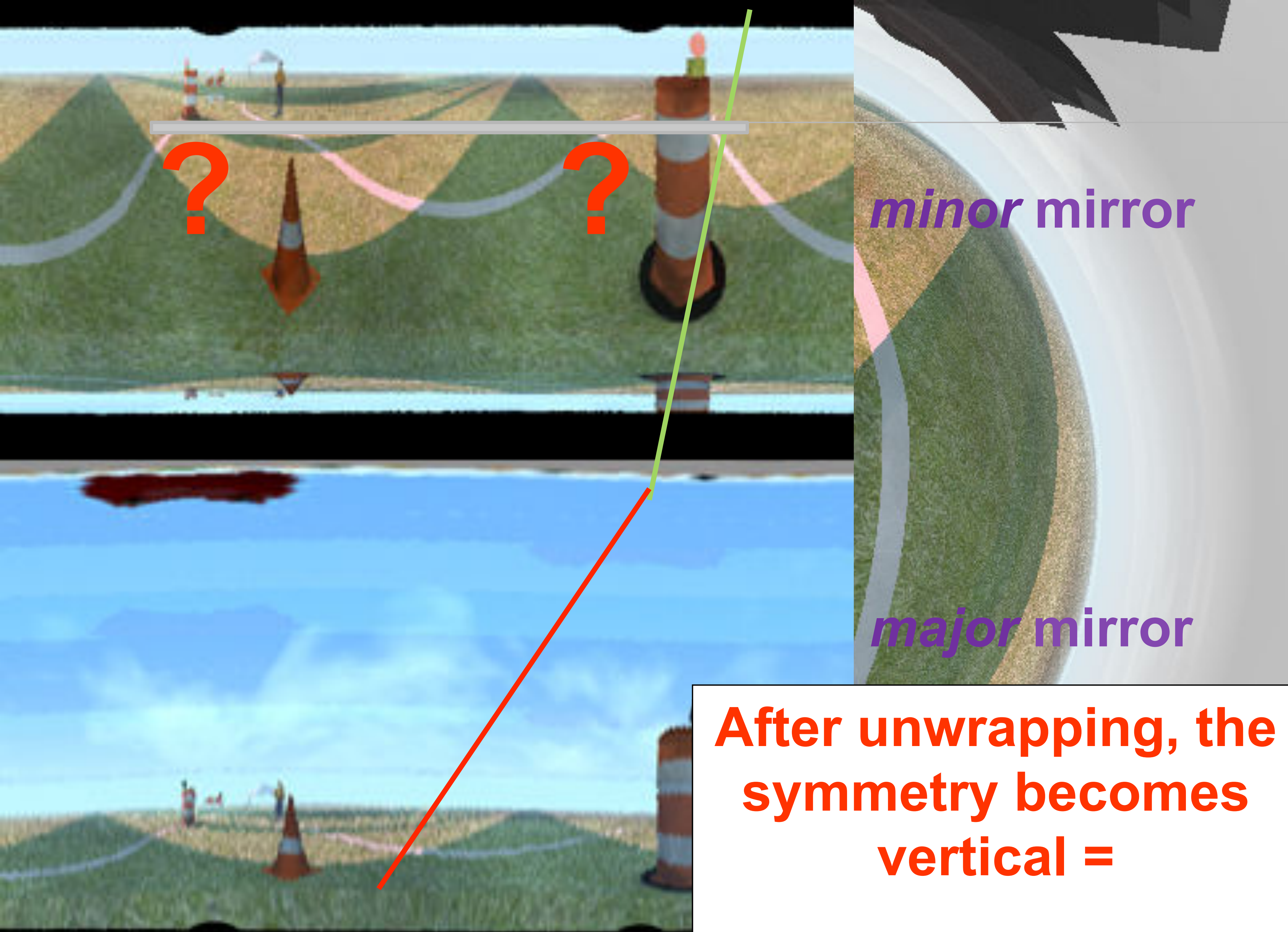
* **Stereo:** higher resolution on equator

* **Optical Flow:** better around poles

=> **Fusion** solves problem of relativism (***scale factor***) of depth from Optical Flow

Omnidirectional Sphereo

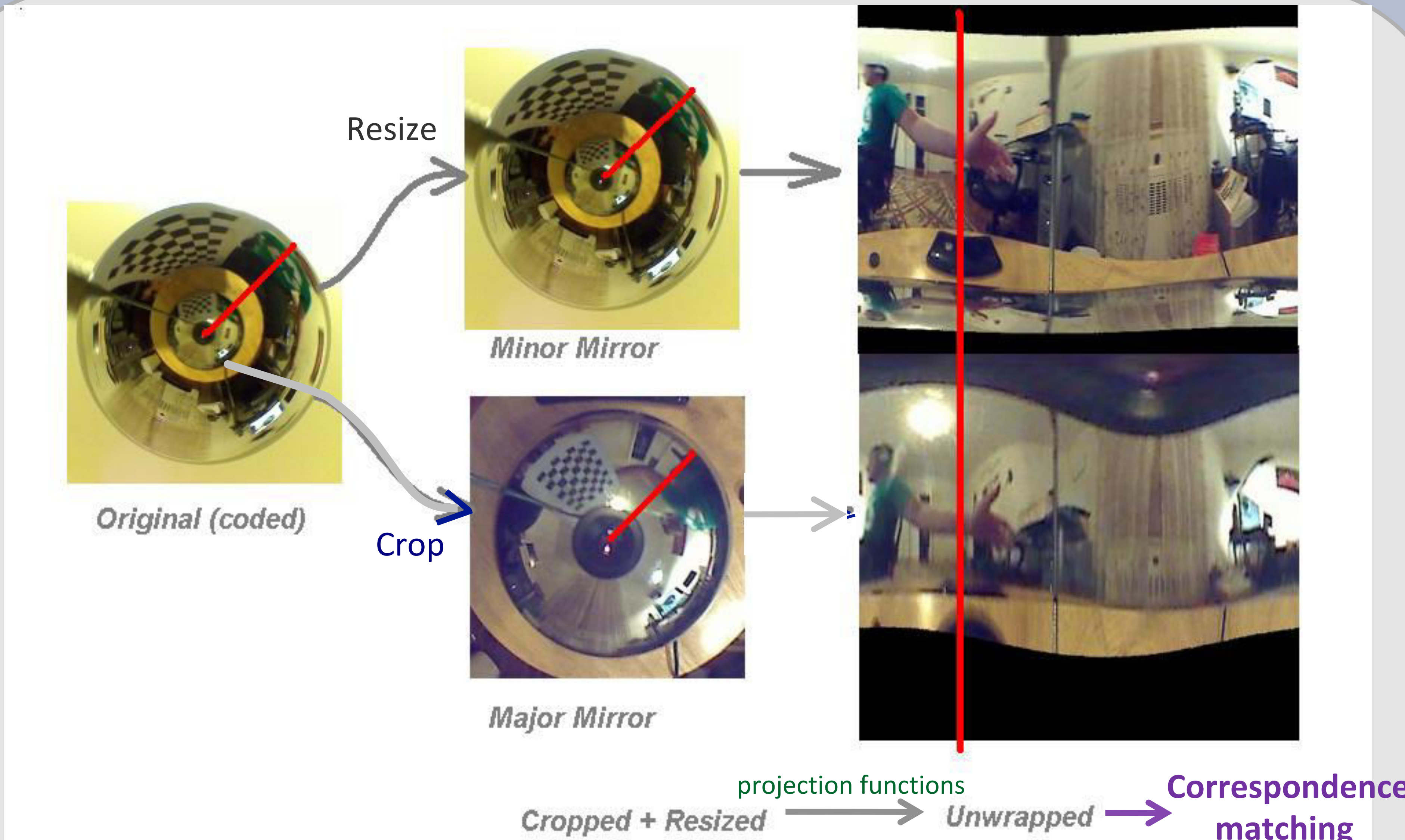




After unwrapping, the symmetry becomes vertical =

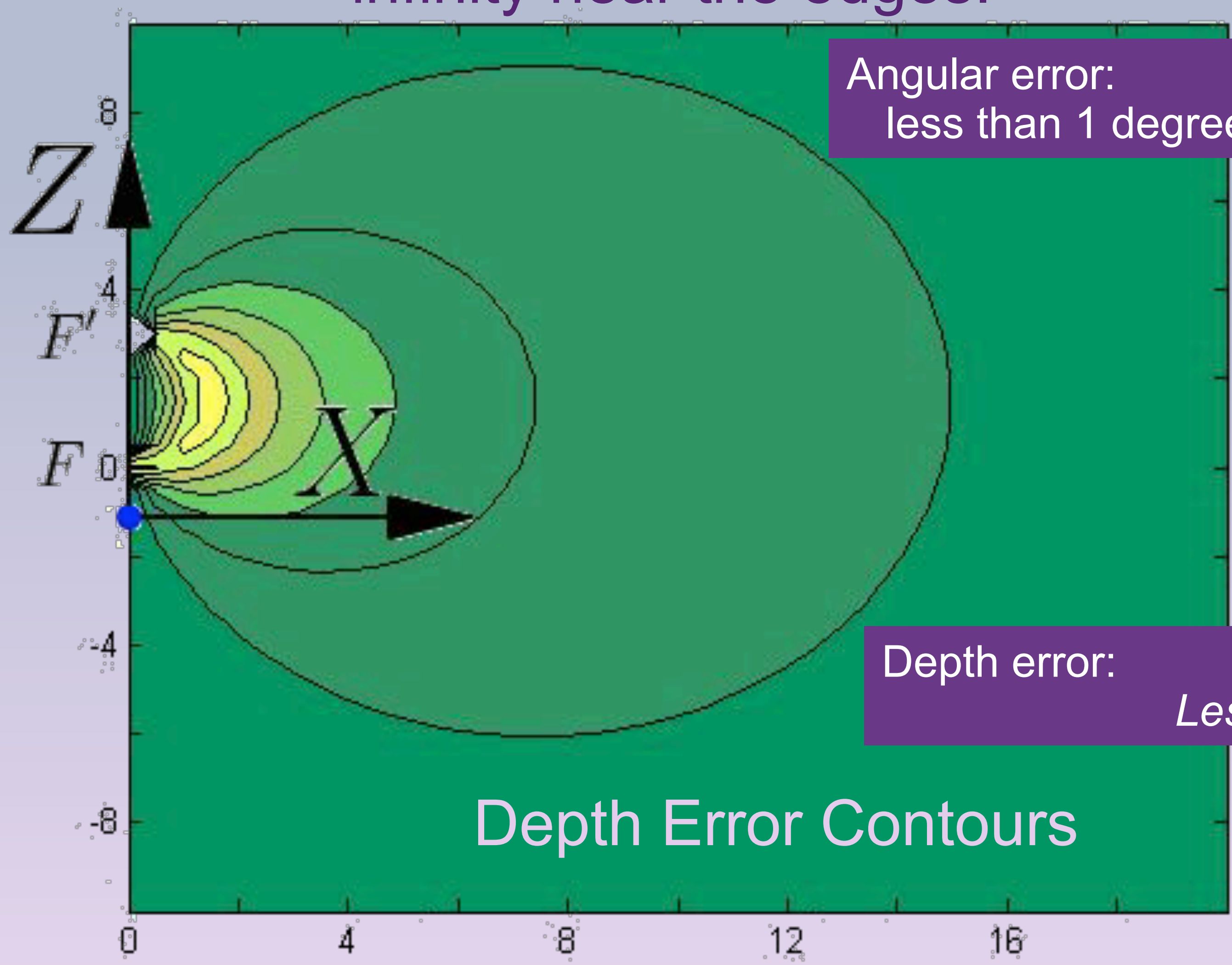
SIMPLE MATCHING

Stereo Pipeline



Triangulation Uncertainty

Derivative of projection function **f**(u) goes to infinity near the edges.



Angular error:
less than 1 degree for points at *d>3h*

Depth error:
Less than 5% at *d=3h*

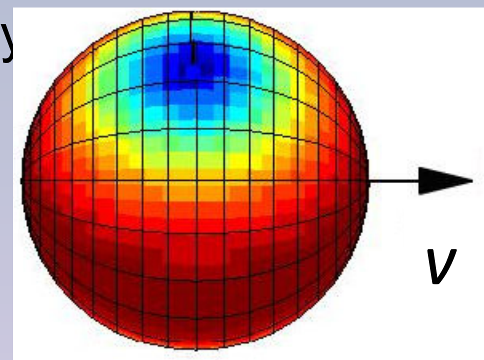
Depth Error Contours

Modality 2: Optical Flow

ADVANTAGES:

For *horizontal motion (e.g.)*, strongest optical flow occurs ABOVE and BELOW the rig

+ Compensates for STEREO which is mostly best near the EQUATOR



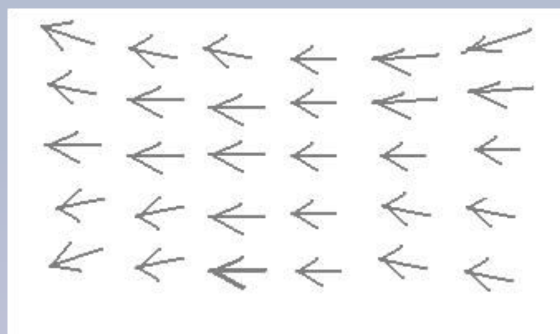
...BUT 2 DISADVANTAGES:

1. Optical Flow field **must be de-rotated** first
2. Depth can **only** be recovered up to scale factor

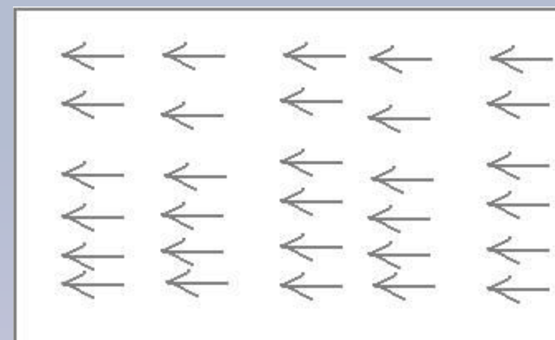
De-Rotation of Optical Flow

- **De-rotation with single (narrow field-of-view) camera:**

Rotation



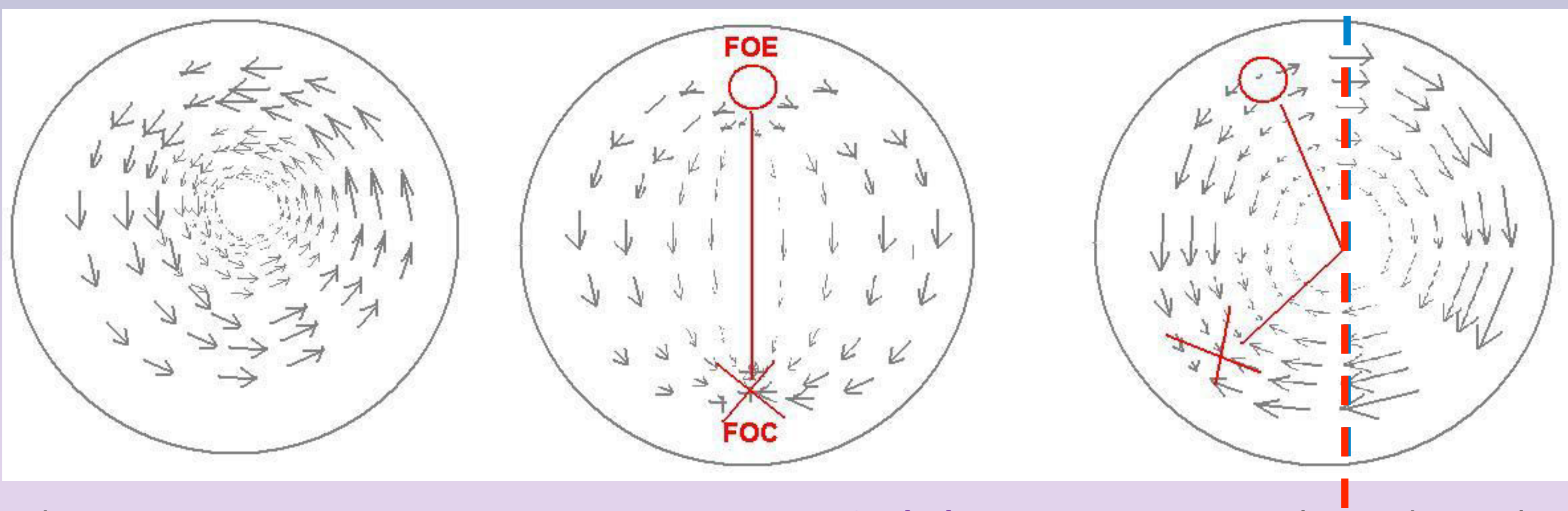
Translation



HARD!!!!

- **De-rotation with Omnidirectional Catadioptric Rig**

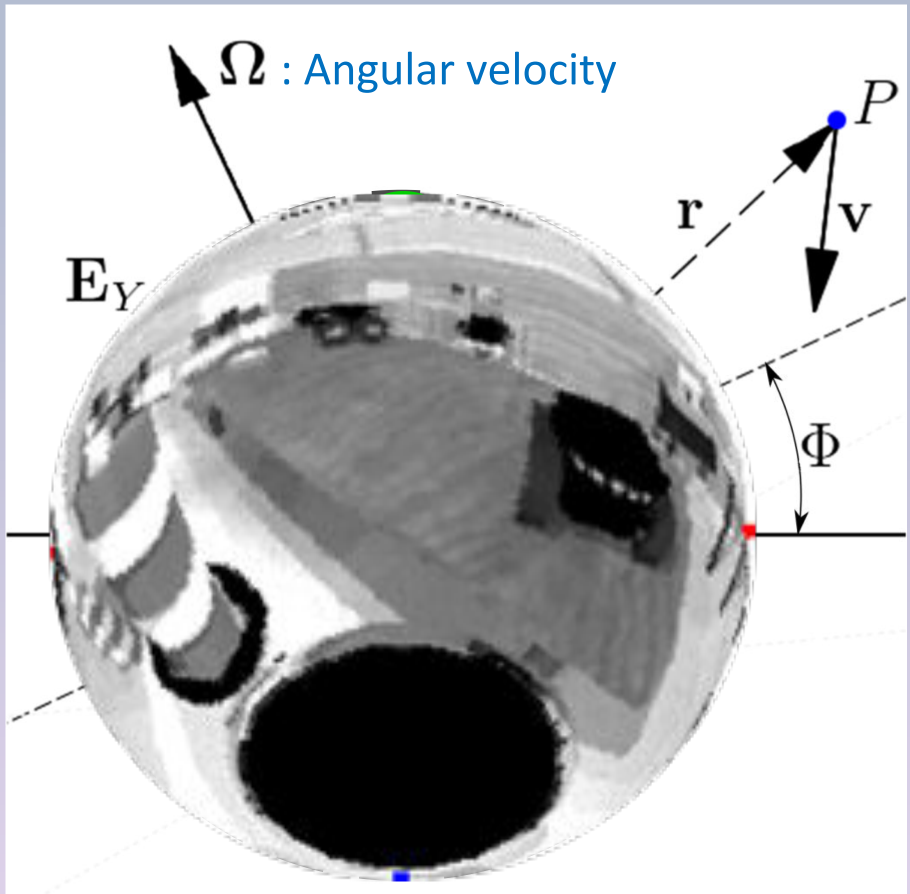
Pure Rotation | Pure Translation | Rotation + Translation



De-rotation (cont.)

DE-ROTATION of omnidirectional images has only been attempted* onto a plane using **Nelson-Aloimonos Algorithm**

- exploits the distinct global rotational and translational flow patterns
- recover components using a simple 2D search along ANY three great circles (Ex, Ey, Ez)



*C. McCarthy, N. Barnes, and M. Srinivasan, "Real time biologically-inspired depth maps from spherical flow," 2007 IEEE International Conference on Robotics and Automation, 2007,

De-rotation (cont.)

Projection bands (e_x, e_y, e_z) of the 3 Great circles:

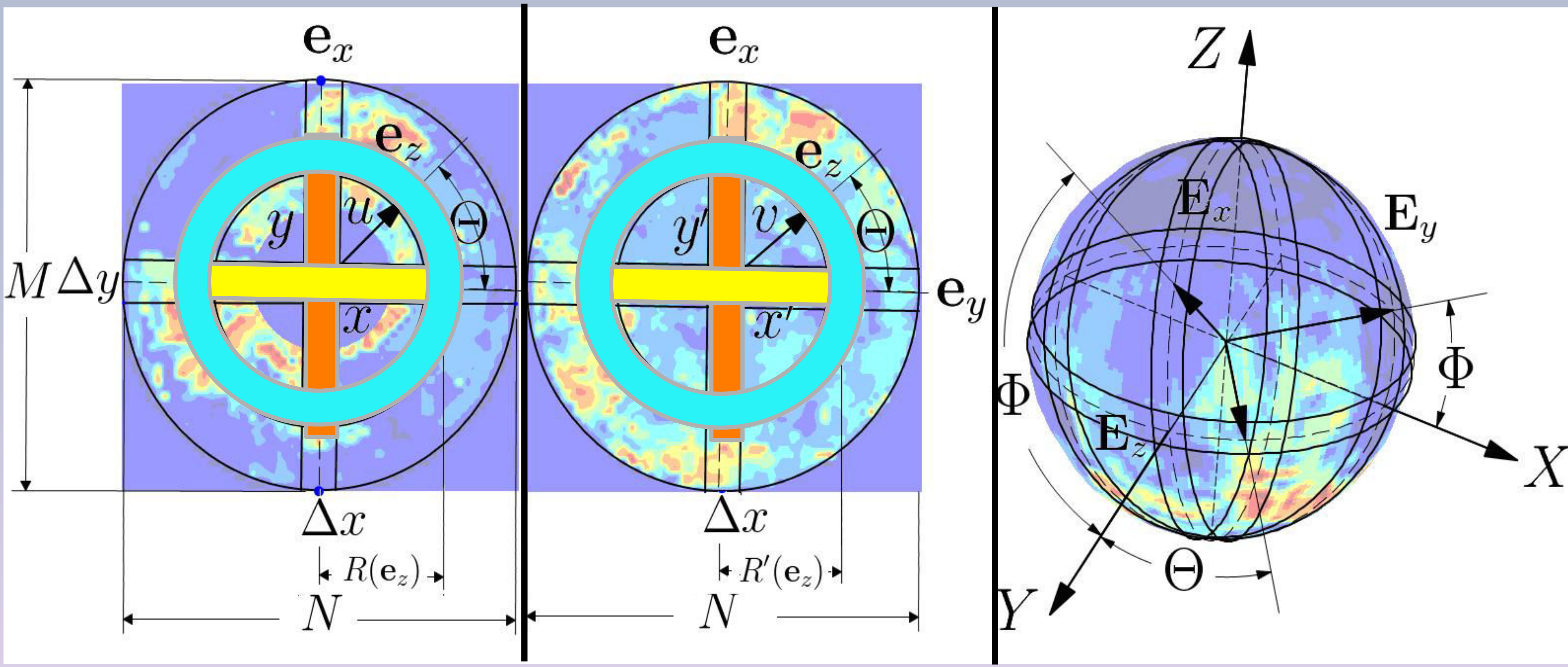


Image of ***minor*** mirror

Image of ***major*** mirror

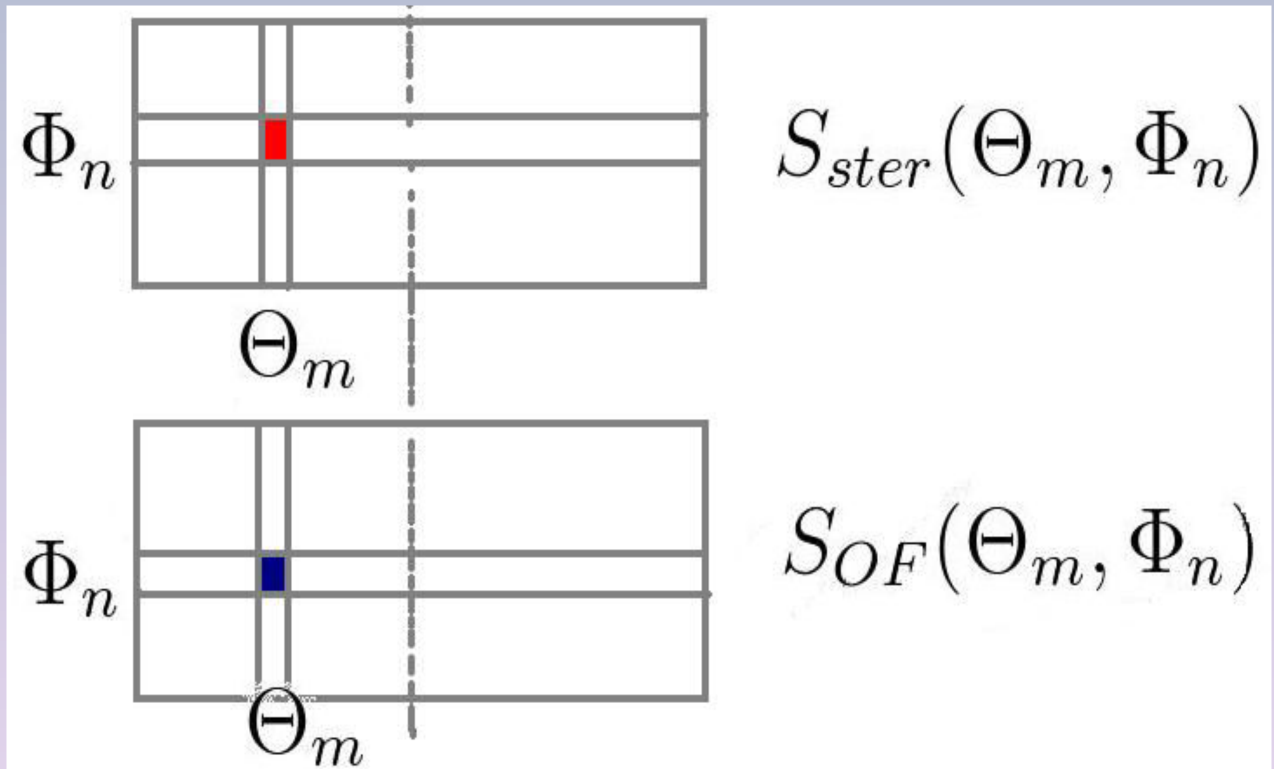
Images projected onto **Viewsphere**

Depth Scale of Optical Flow

Minimization with Weighted Least Squared on overlaps

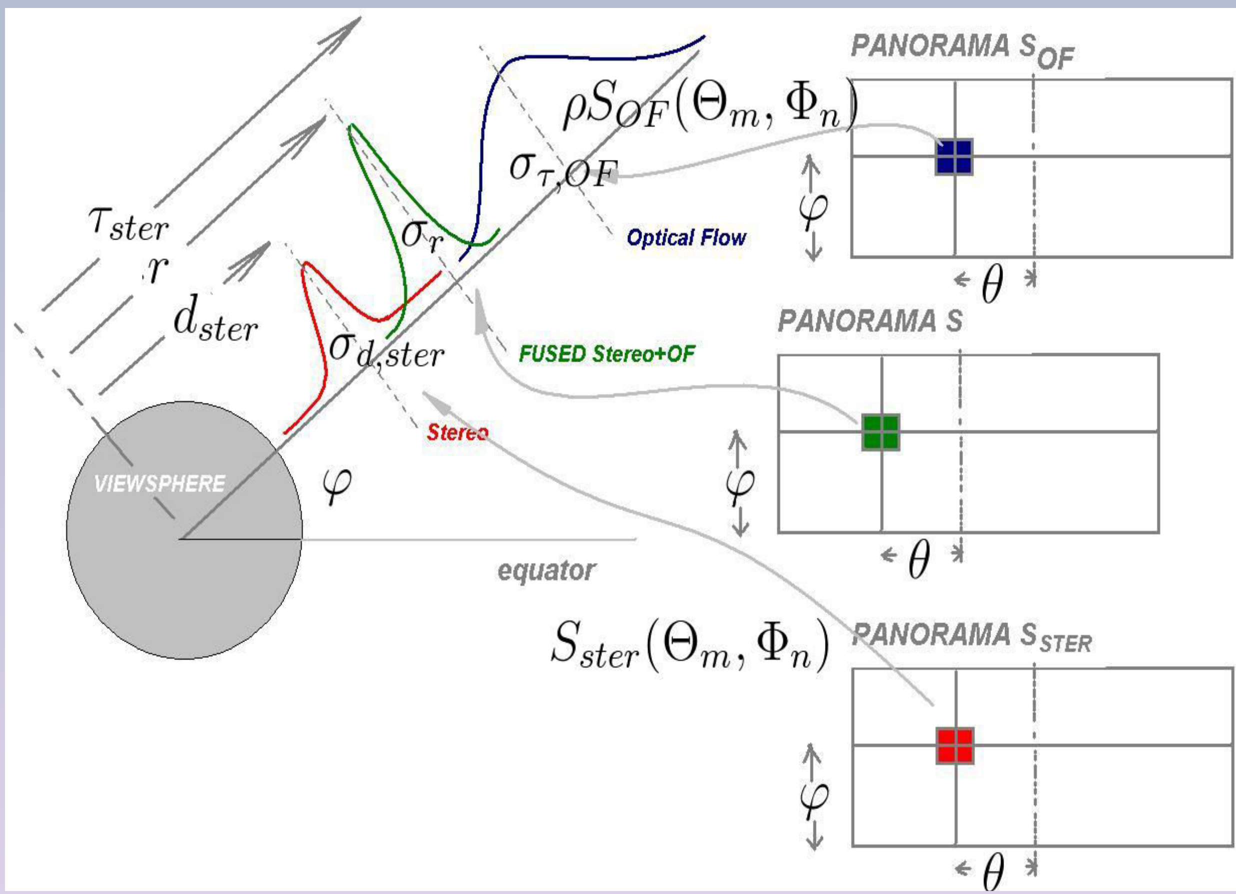
$$\rho = \arg\min_{\rho} \sum_{\Theta_m}^{M} \sum_{\Phi_n}^{N} d^2_{\Theta_m,\Phi_n}(\rho)$$

$$d_{\Theta_m,\Phi_n} = \frac{S_{ster}(\Theta_m,\Phi_n) - \rho S_{OF}(\Theta_m,\Phi_n)}{\sigma^2_{ster}(\Theta_m,\Phi_n)\,\sigma^2_{OF}(\Theta_m,\Phi_n)}$$



Fusing Depth from Modalities

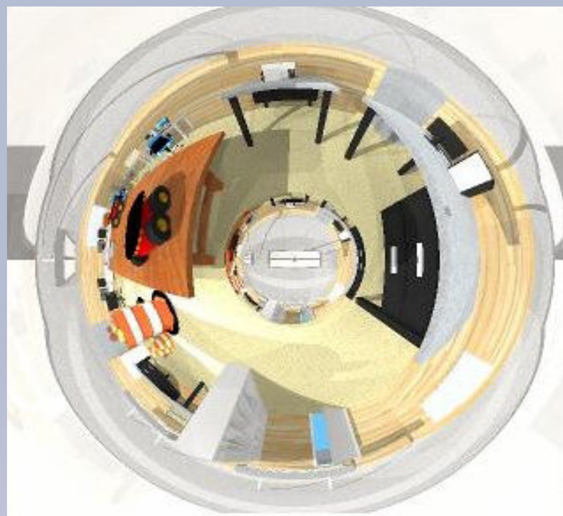
Performed in a panoramic image *S*
using standard **linear sensor fusion equations**

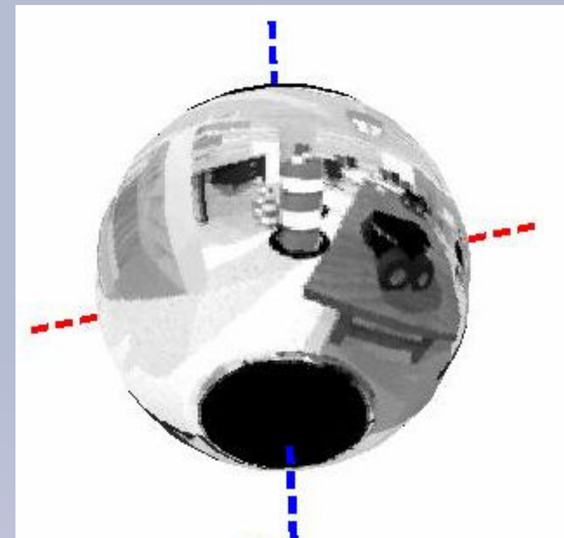


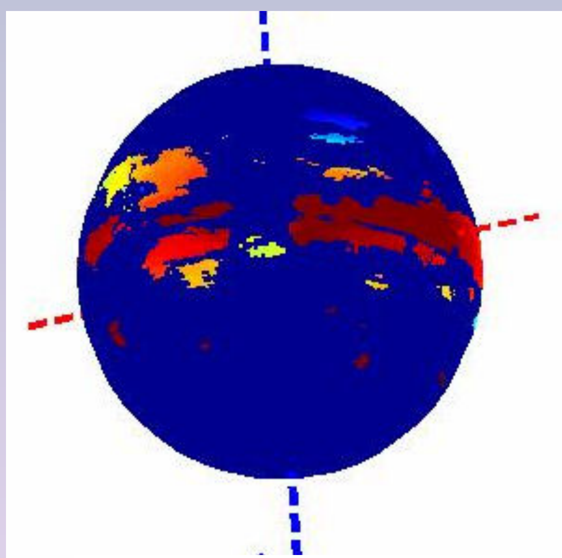
$$r = \frac{d_{ster}\sigma^2_{\tau,OF} + \tau_{OF}\rho^2\sigma^2_{d,ster}}{\sigma^2_{d,ster} + \rho^2\sigma^2_{\tau,OF}}$$

$$\sigma^2_r = \frac{1}{\sigma^{-2}_{d,ster} + \rho^{-2}\sigma^{-2}_{\tau,OF}}$$

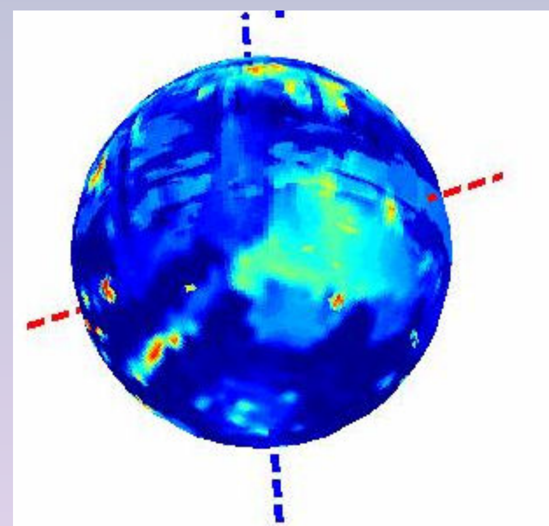
Experiments - Simulations



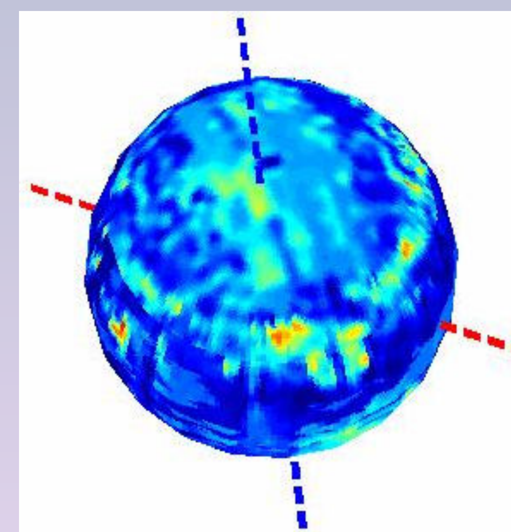




Disparity Panorama



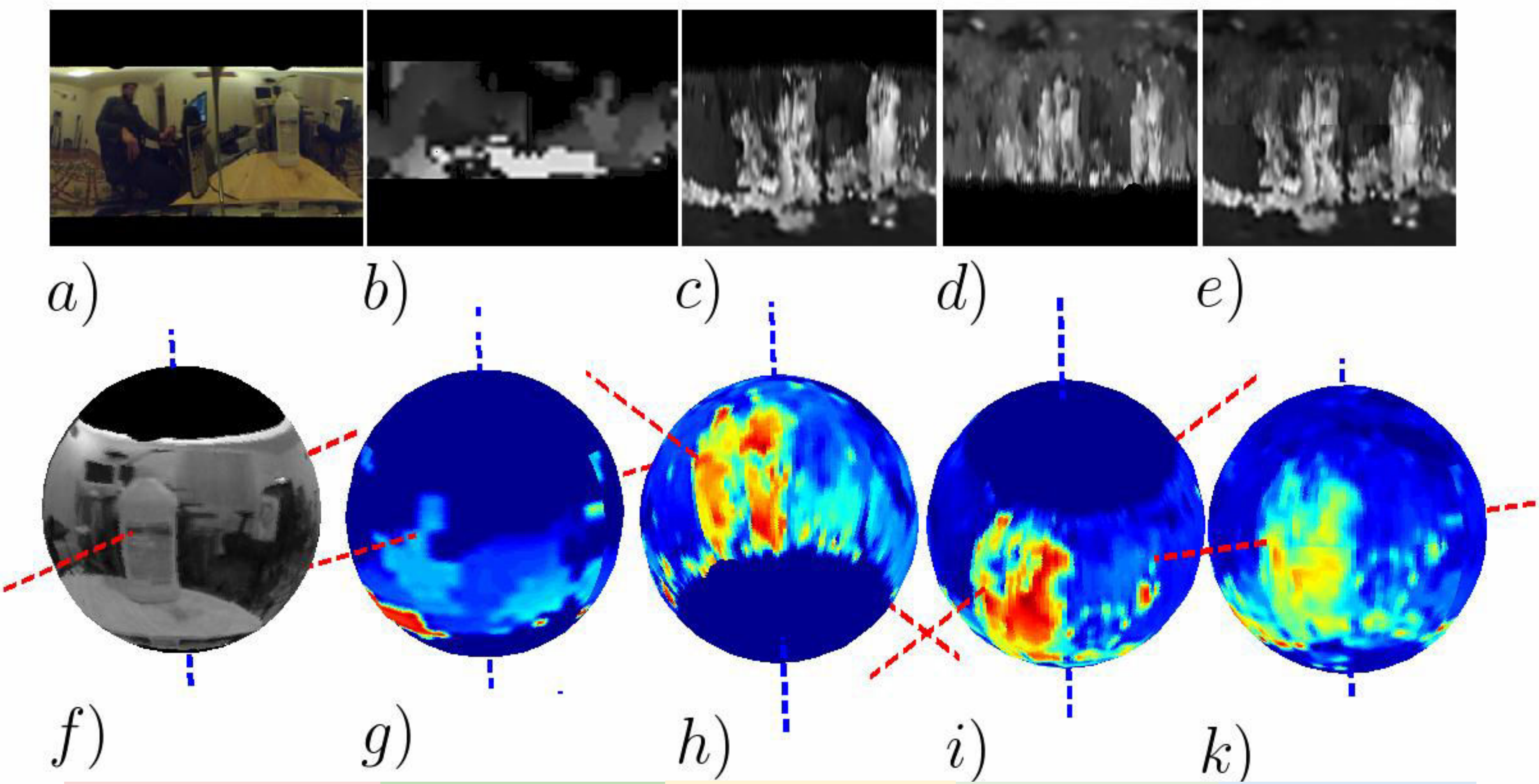
Disp+OF Panorama (S)



Disp+OF Panorama (N)

Experiments – Real World

Major Pan | Sster | SOF from F | SOF from F | fused S



projections of (a,b,c,d,e) on the view-sphere

Summary of Contribution

1. **We use spherical mirrors in a folded configuration to maximize image resolution near the poles of the viewsphere.**
   - For robots moving in a horizontal plane, this generates high-resolution relative depth from optical flow above and below the robot.
2. **We exploit radial epipolar geometry of the spherical mirrors to compute dense metric-depth in the equatorial region of the view-sphere.**
3. **We fuse depth from optical-flow (poles) and stereo (equator) in a dense probabilistic depth panorama to obtain comparable depth resolution in every direction.**
   - The scale factor for depth-from-optical-flow is recovered by using weighted least-squares in regions where depth from optical flow and stereo overlap.

Remarks and Future Work

- Theoretically demonstrated with off-line imagery
- The fusion of these two modalities (stereo and optical flow) can generate an almost-entire view-sphere of probabilistic range information
- Exceptions are self-occluded areas on the poles.
- Greater errors in areas where neither modality provides sufficient depth resolution (no-overlapping regions and near the edges → high distortion and low resolution).

FUTURE:

- Deeper analysis of uncertainty in each modality
- Real-time performance of the system.
  - Try sparse optical flow (feature correspondences) with the Nelson-Aloimonos' de-rotation algorithm.

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Thank you!