Meteor Trajectory Estimation using Multiple Unsynchronized Video Cameras

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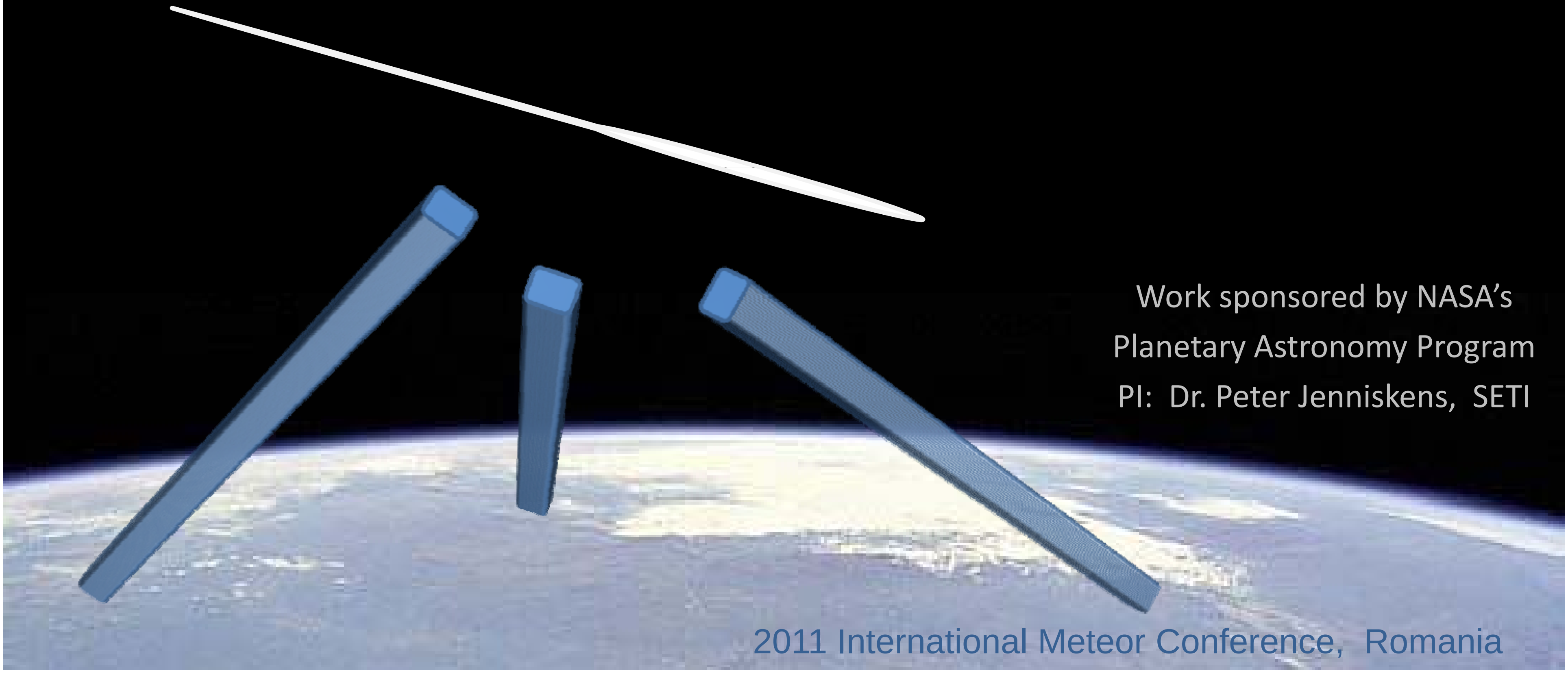
Presented by Damir Segon



Work sponsored by NASA’s
Planetary Astronomy Program
PI: Dr. Peter Jenniskens, SETI

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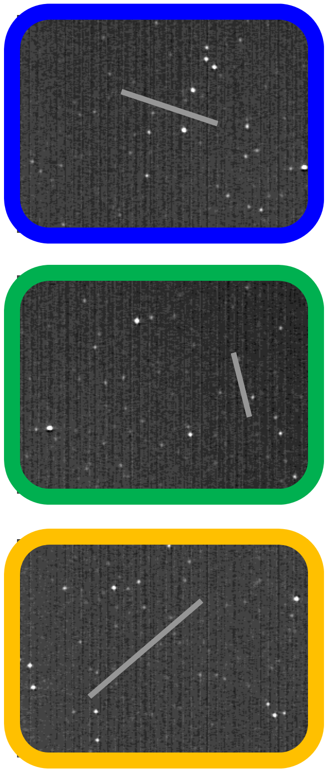
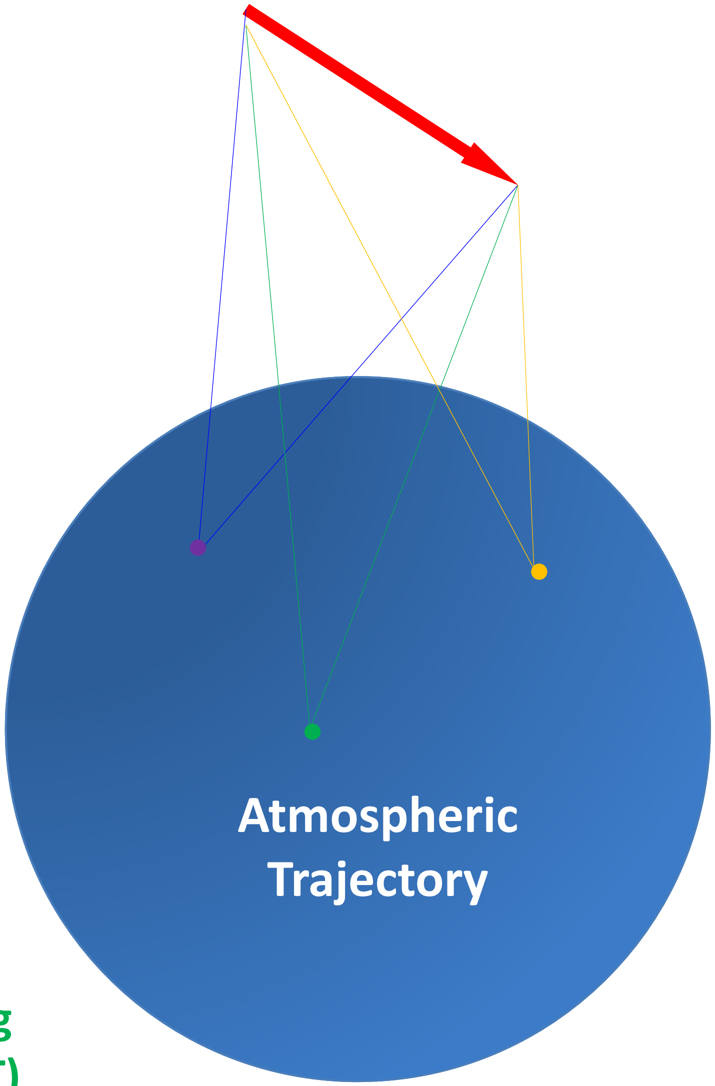
Problem: Obtain Atmospheric Trajectory via Video Triangulation

Multi-Site Video Measurements

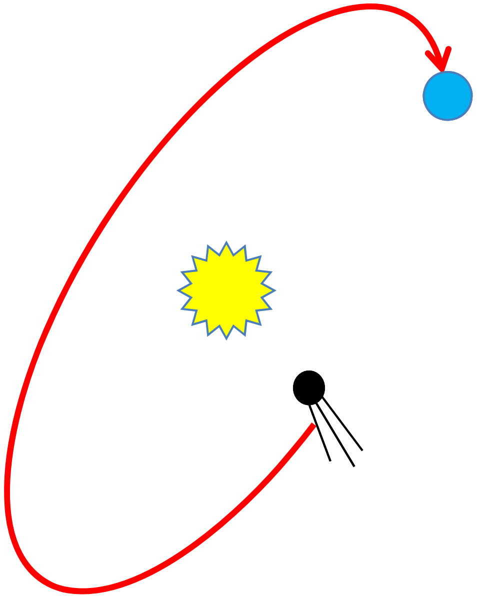


Knowns:

Camera position/pointing
Date and approx time (UT)
FOV astrometry
Sample rate



Solar System Orbit



Unknowns:

Radiant direction α, δ
Meteor position, V_∞, deceleration
Camera timing offsets

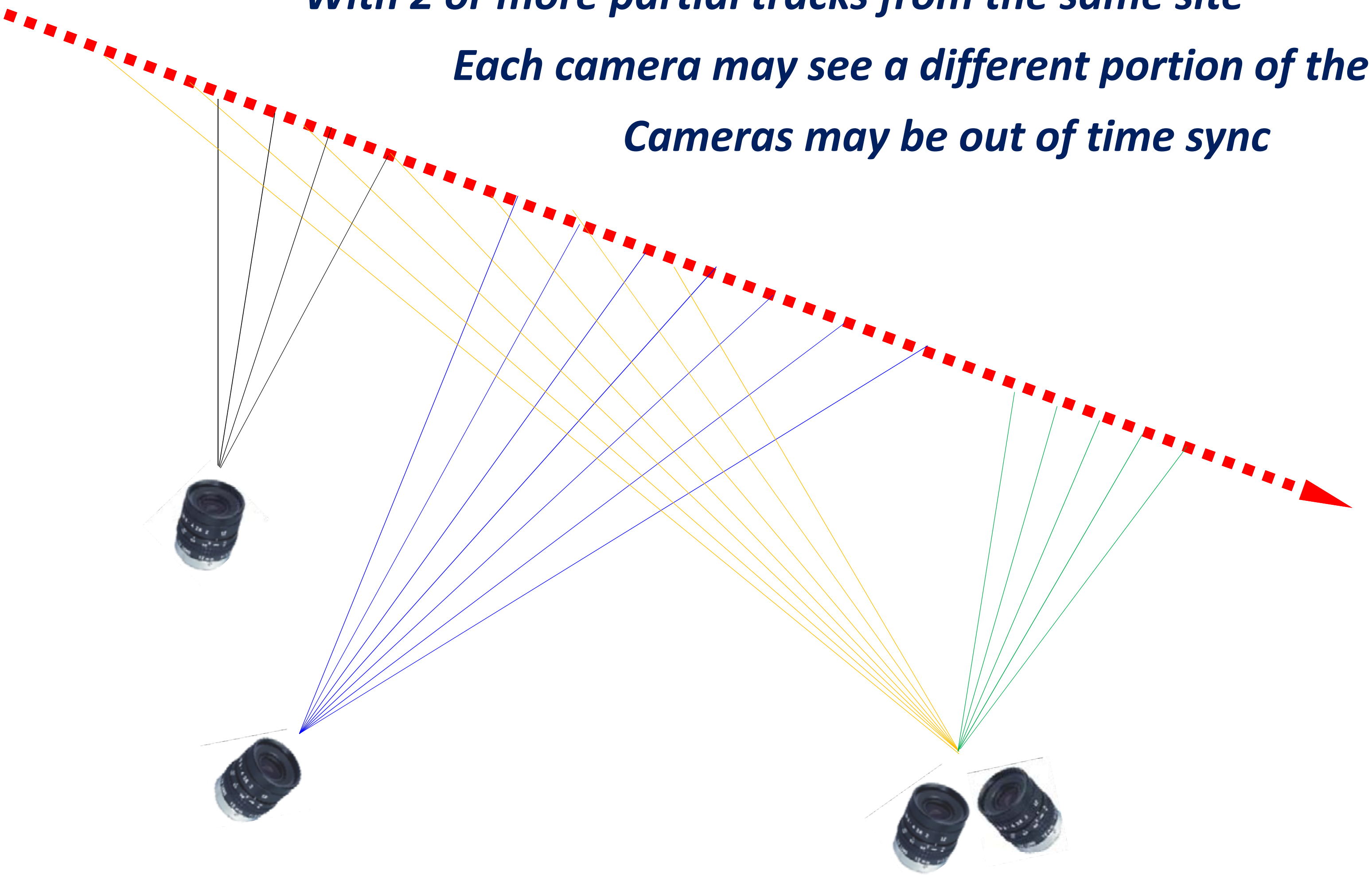
Several deployed systems capture meteors from multiple cameras:

From 2 or more sites

With 2 or more partial tracks from the same site

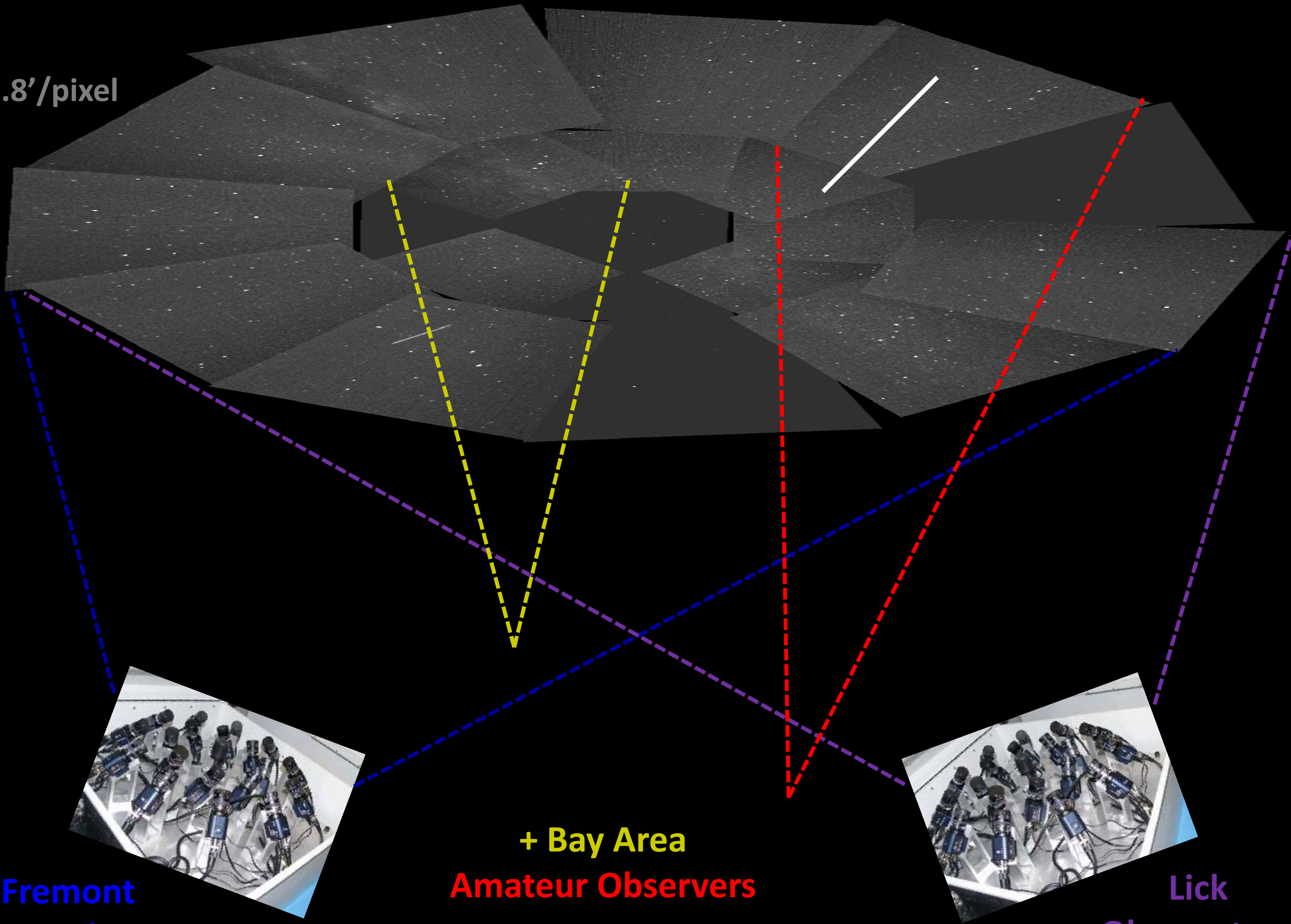
Each camera may see a different portion of the track

Cameras may be out of time sync



But given space-time coincidence – it is all the same <u>single</u> track !

Example: CAMS All-Sky Coverage from Multiple Video CCDs



2.8’/pixel

+ Bay Area

Amateur Observers

Fremont
Peak

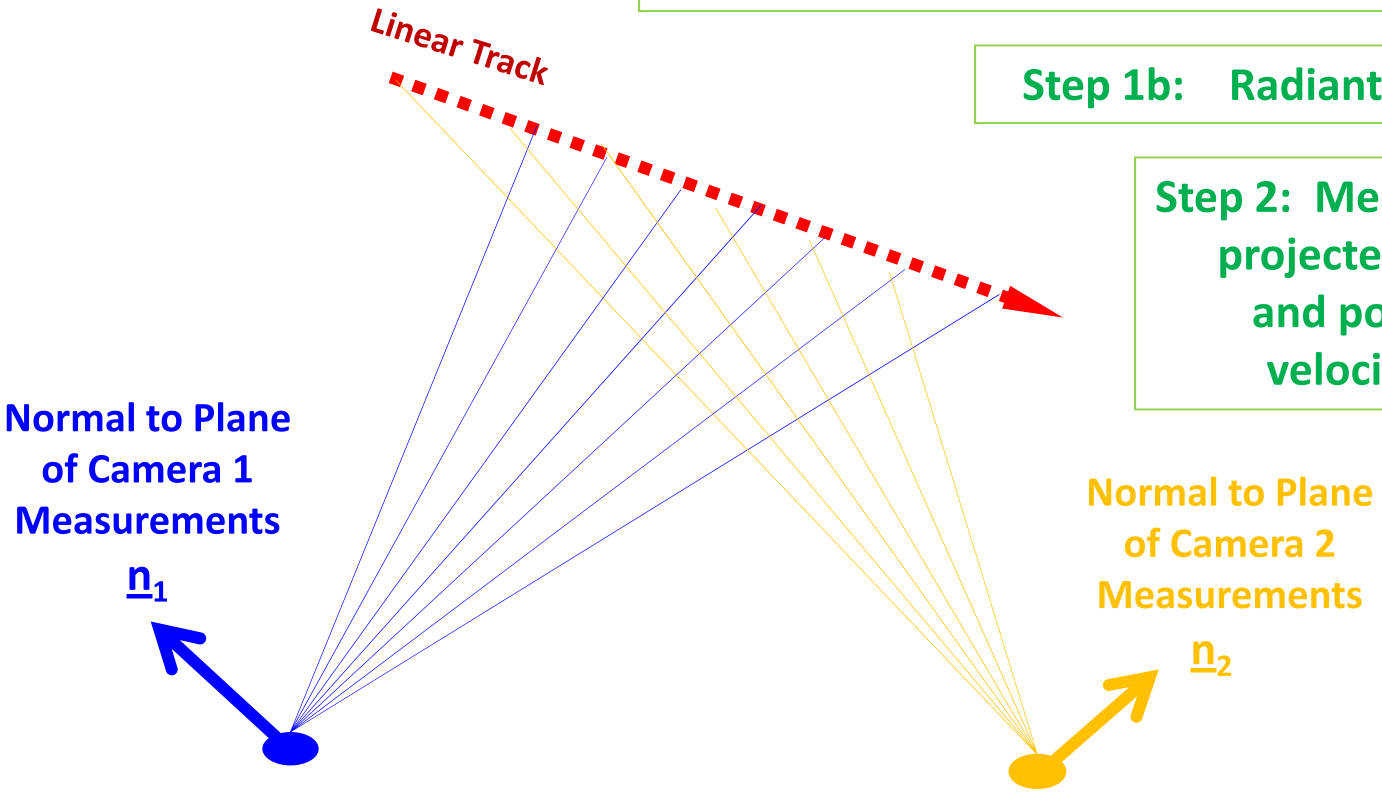
Lick
Observatory

Ceplecha 1987: Intersecting Planes *followed by* LMS fit to Velocity

Step 1a: Find normal to best fitting plane per camera = $\underline{n}_k$

Step 1b: Radiant Direction = $\underline{n}_1 \times \underline{n}_2$

Step 2: Measurement vectors are projected to CPA of the line and positions are fit for velocity / deceleration

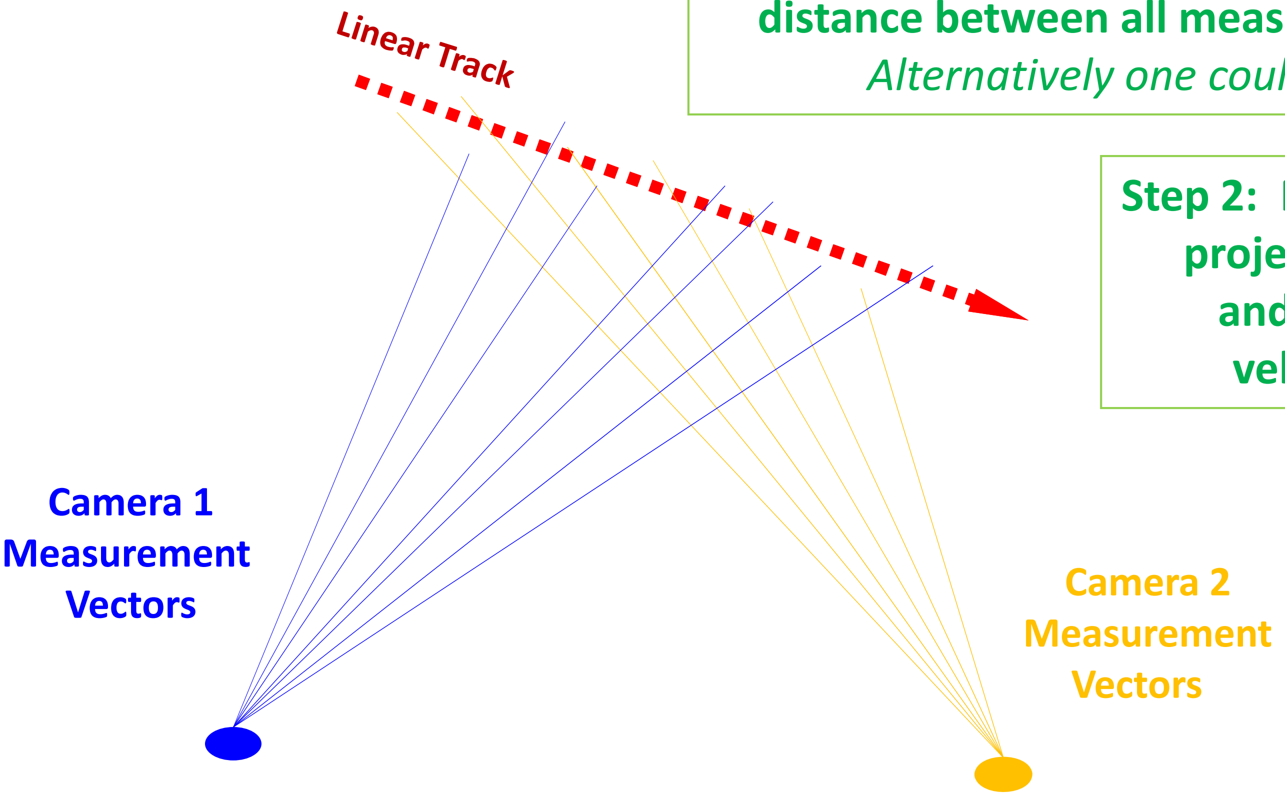


**When there are more than two cameras,
several directions are obtained through all possible unique pairings,
and an ad hoc weighting is applied to get a single radiant solution !**

Jiri Borovicka 1990: Straight Least Squares Method

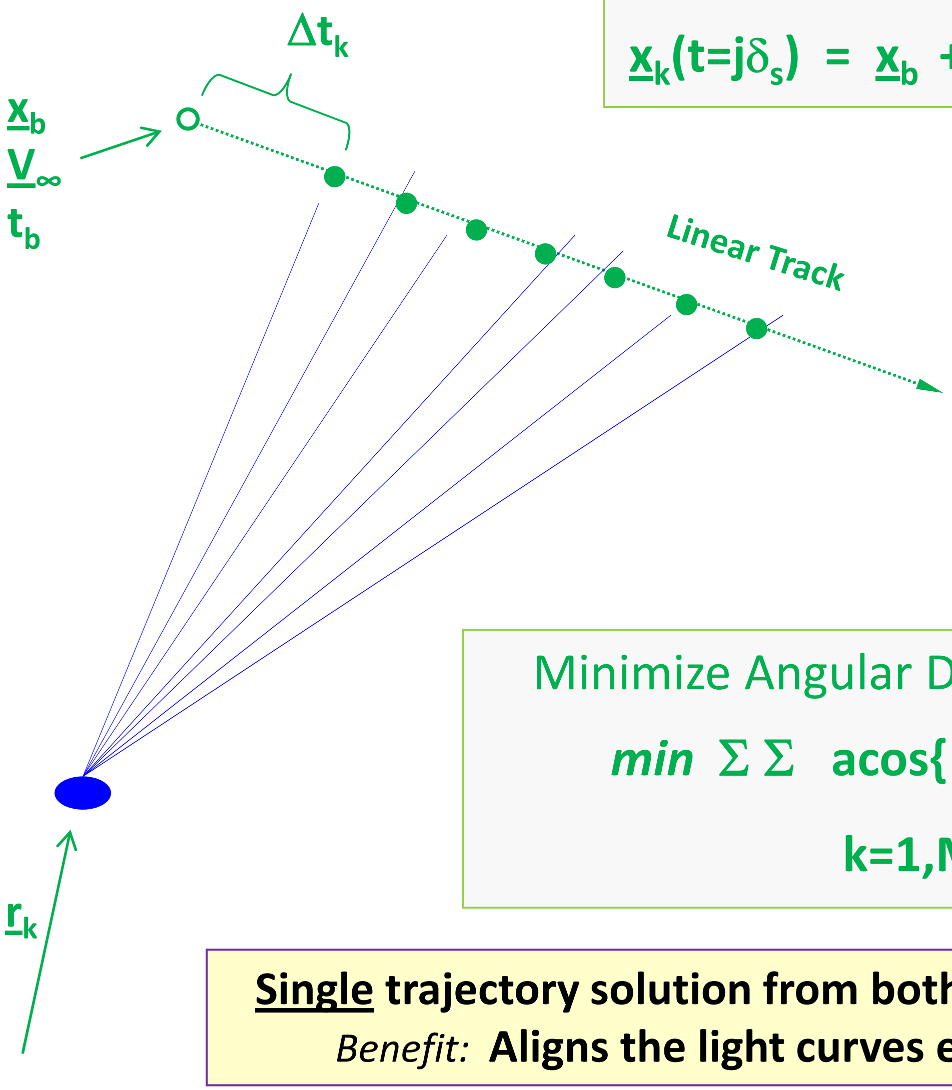
Step 1: Solve for a line in 3D space that minimizes the distance between all measurements and that line.
Alternatively one could minimize angle.

Step 2: Measurement vectors are projected to CPA of the line and positions are fit for velocity / deceleration



This method more naturally handles more than two cameras.
However, it produced equivalent radiant accuracy to intersecting planes !

New Solution: Fit a Multi-Parameter Motion Model to **all** Measurements



Single k^{th} Camera Motion Model:

$$\underline{x}_k(t=j\delta_s) = \underline{x}_b + \underline{V}_\infty * [t + \Delta t_k - t_b] + a(t + \Delta t_k - t_b)$$

Number of Unknowns

$\underline{x}_b$ = 3 for position
$\underline{V}_\infty$ = 3 for velocity
a = 0, 1, or 2 for deceleration
Δt_k = #cameras for time offsets

Constrain t to be uniformly spaced δ_s
(NTSC F_s = 29.97 Hz)

Minimize Angular Distance: Measurement to Model

$$\min \sum \sum \operatorname{acos}\{ \underline{meas}(j,k)^\wedge \cdot [\, \underline{x}_k(j\delta_s) - \underline{r}_k \,]^\wedge \}$$

$$k=1,M_{cams} \qquad j=1,N_{meas}(k)$$

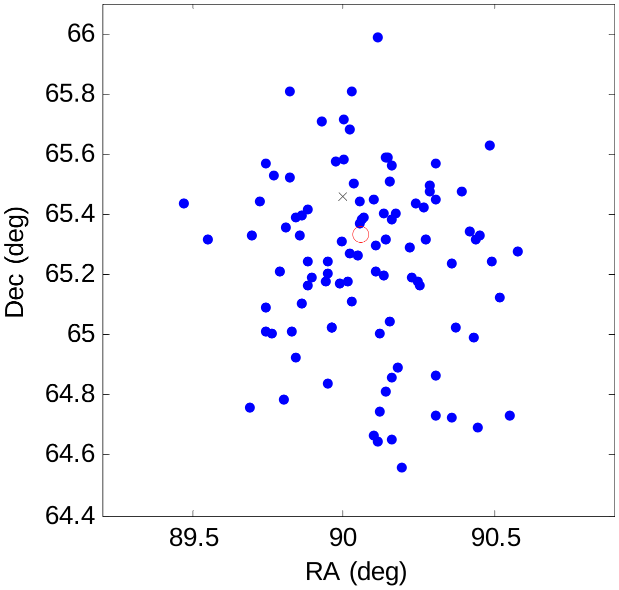
Single trajectory solution from both same-site and disparate-site cameras !
Benefit: **Aligns the light curves even for unsynchronized cameras !**

Currently employs a Nelder-Mead, Downhill Simplex, Amoeba minimization

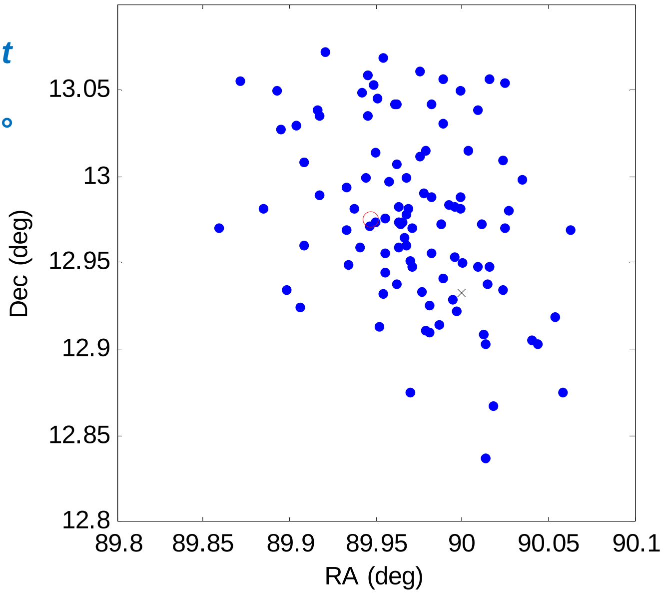
Function Also Provide State Vector Error Estimation

- **Error estimates generated for the begin point position and velocity**
  - ***Existing methods try to propagate errors and formulate closed forms expressions***
  - ***New algorithm adds a Monte-Carlo Gaussian distributed error to each measurement***
  - ***Solve over many trials with the baseline solution as the starting parameters***
  - ***Resultant variances are obtained for say 100 trials***
  - ***Feeds into the orbit estimation error analysis***

Low Radiant
RA σ = 0.25°
Dec σ = 0.32°

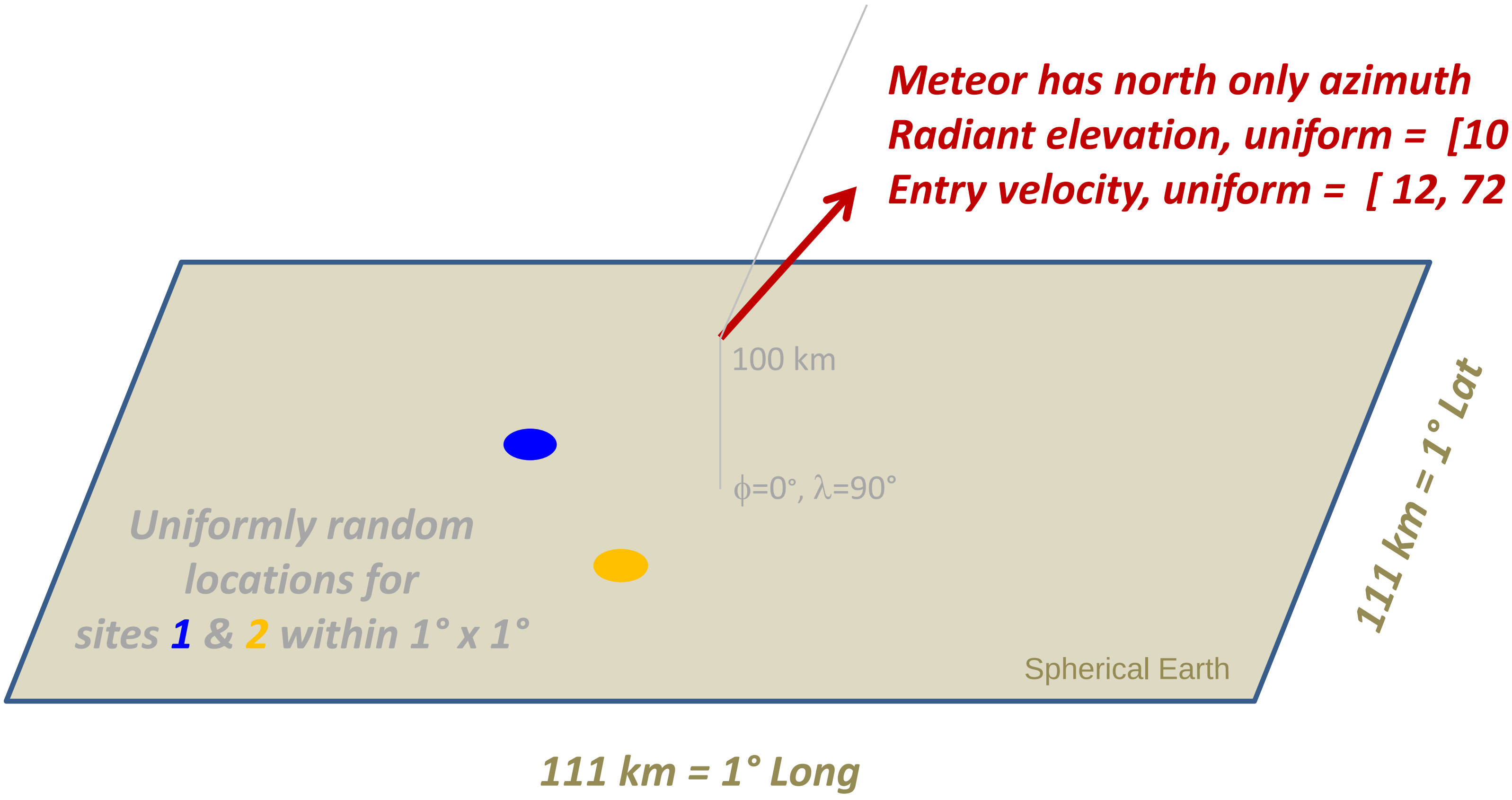


High Radiant
RA σ = 0.05°
Dec σ = 0.05°



Simulation to Examine Performance

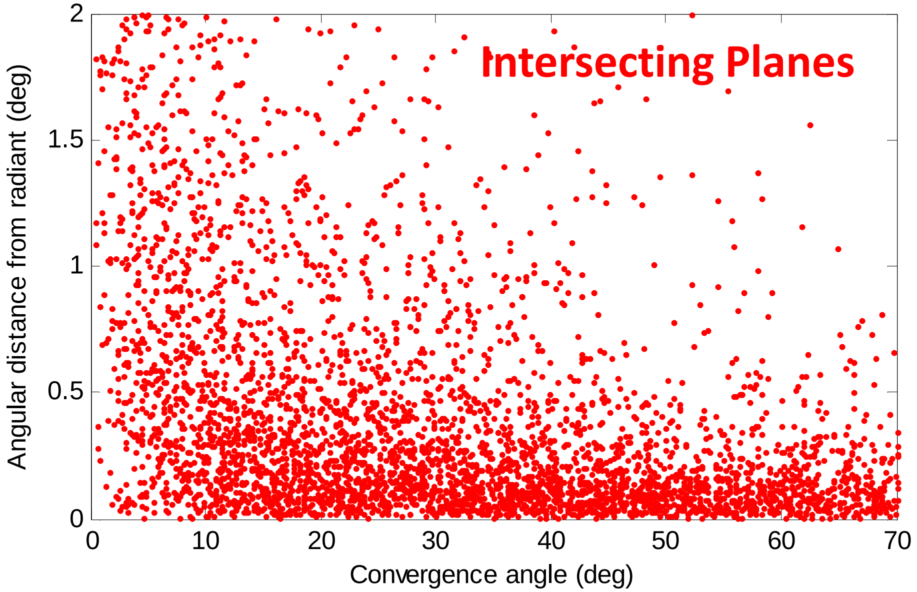
- ***Measurement frame rate = 60 Hz*** *(interleaved row centroids for NTSC)*
- ***Pixel angular extent = 0.28, 2.8, 10, and 20 arc-minutes***
- ***Measurement error Gaussian σ = 0.3 and 1.0 pixels, 3σ limit***
- ***Number of measurements uniformly distributed (integer) = [10, 30]***
- ***20,000 Monte-Carlo trials***

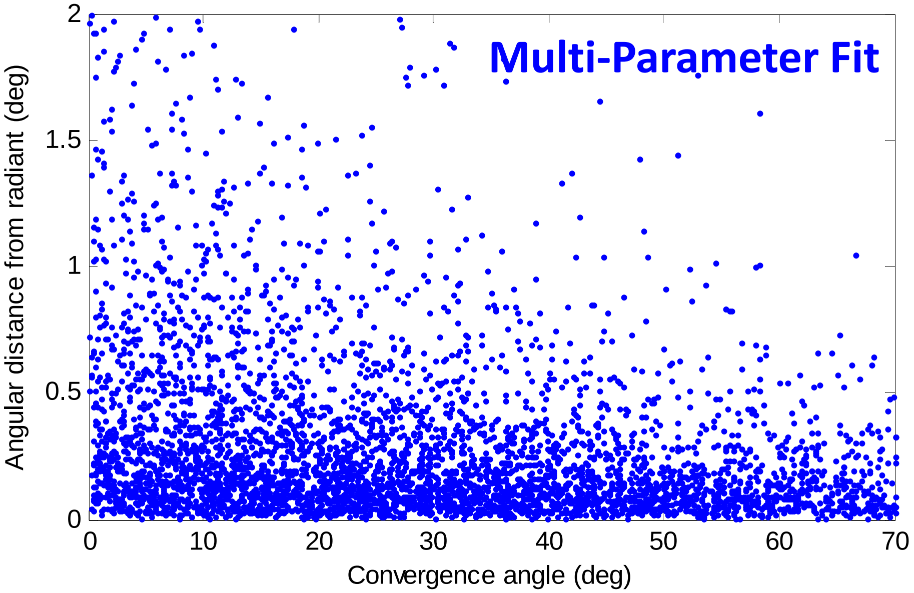


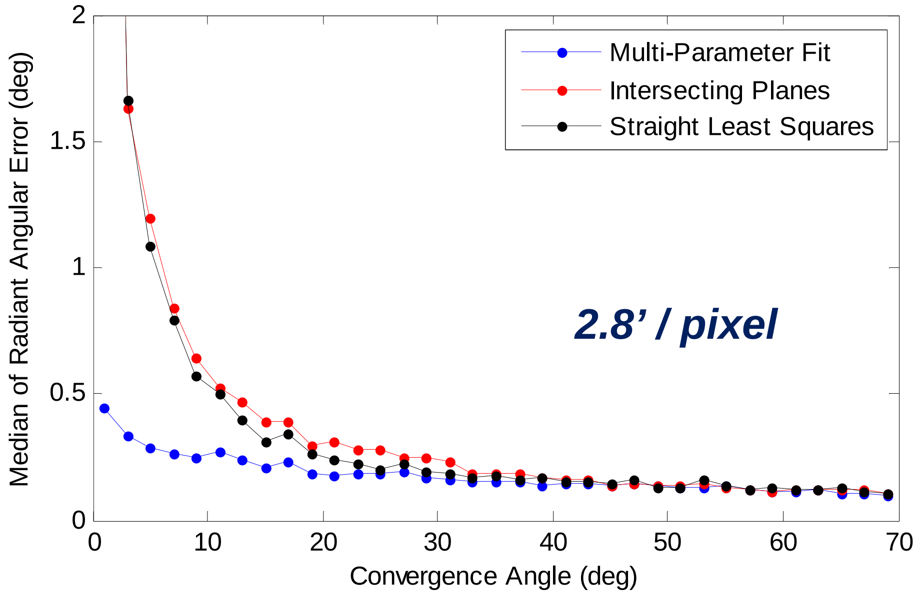
Meteor has north only azimuth
Radiant elevation, uniform = [10°, 80°]
Entry velocity, uniform = [12, 72] km/sec

Uniformly random locations for sites 1 & 2 within 1° x 1°

Radiant Error versus Convergence Angle





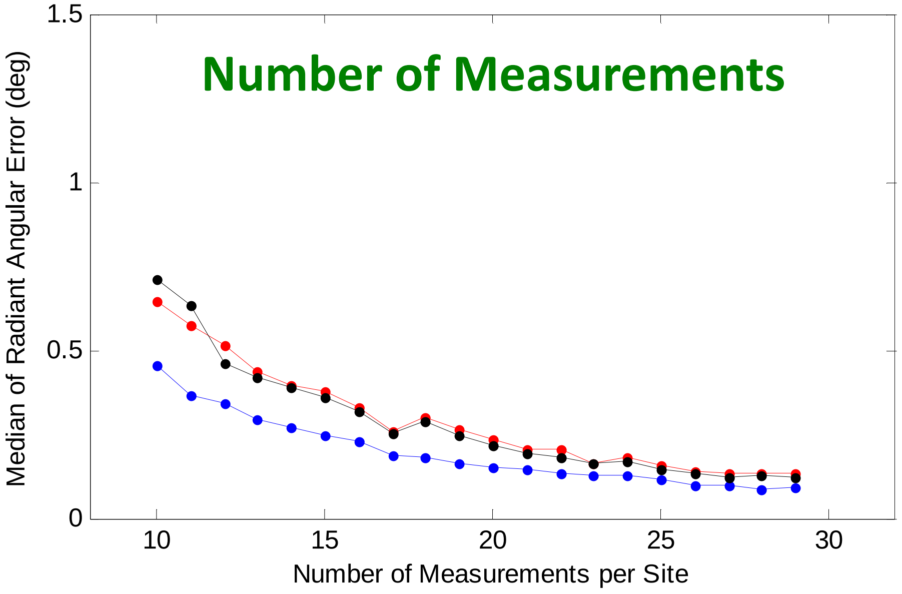


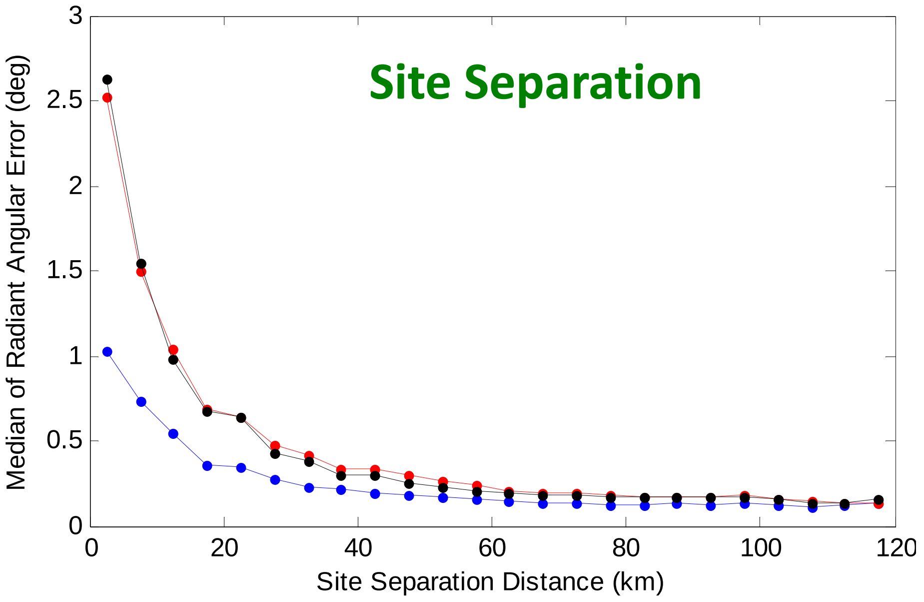
Dr. Jenniskens noticed in CAMS data:

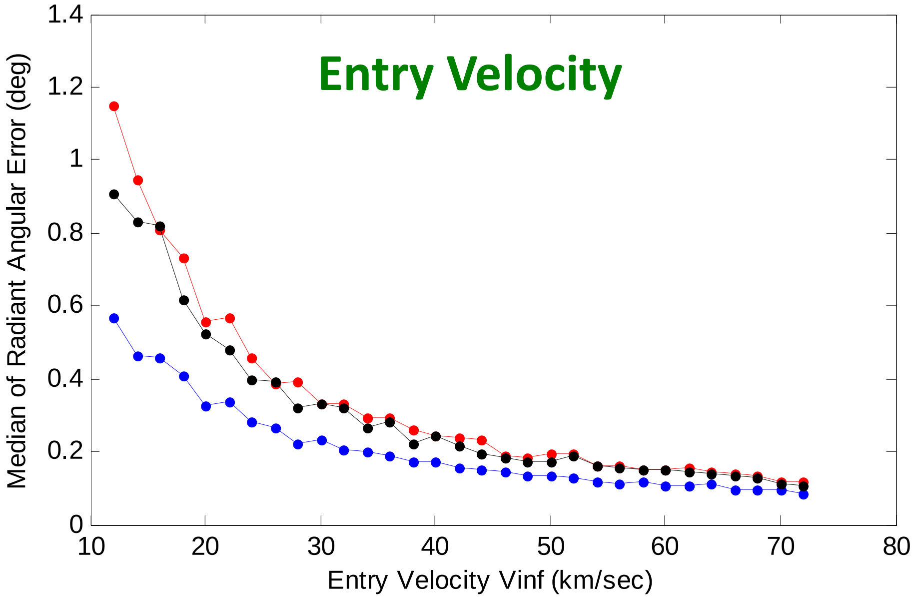
One can obtain quality solutions under 30° convergence angle !

Explanation: Addition of implicit range to the angle-angle measurements arising from the angle subtended over the video time step.

Radiant Error Sensitivities to:


Number of Measurements


Site Separation


Entry Velocity

It is well known to:

Separate your observing stations.

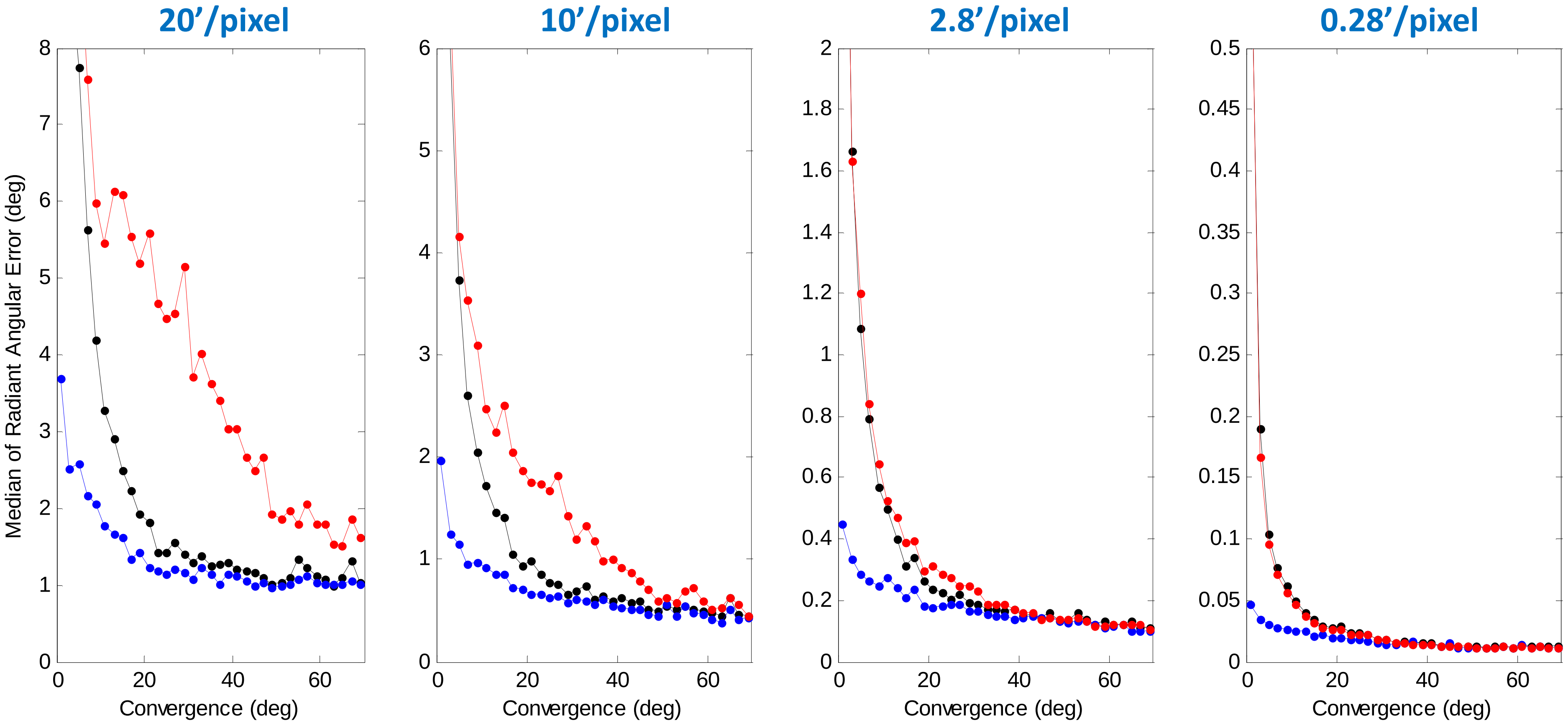
Maximize track length for orientation.

Plots for angular resolution = 2.8'/pixel

Meas σ = 0.3 pixels

60 Hz interleaved row centroid measurements

Radiant Error for Various Sensor Resolutions (Fixed Measurement σ = 0.3 pixels)


20’/pixel

10’/pixel

2.8’/pixel

0.28’/pixel

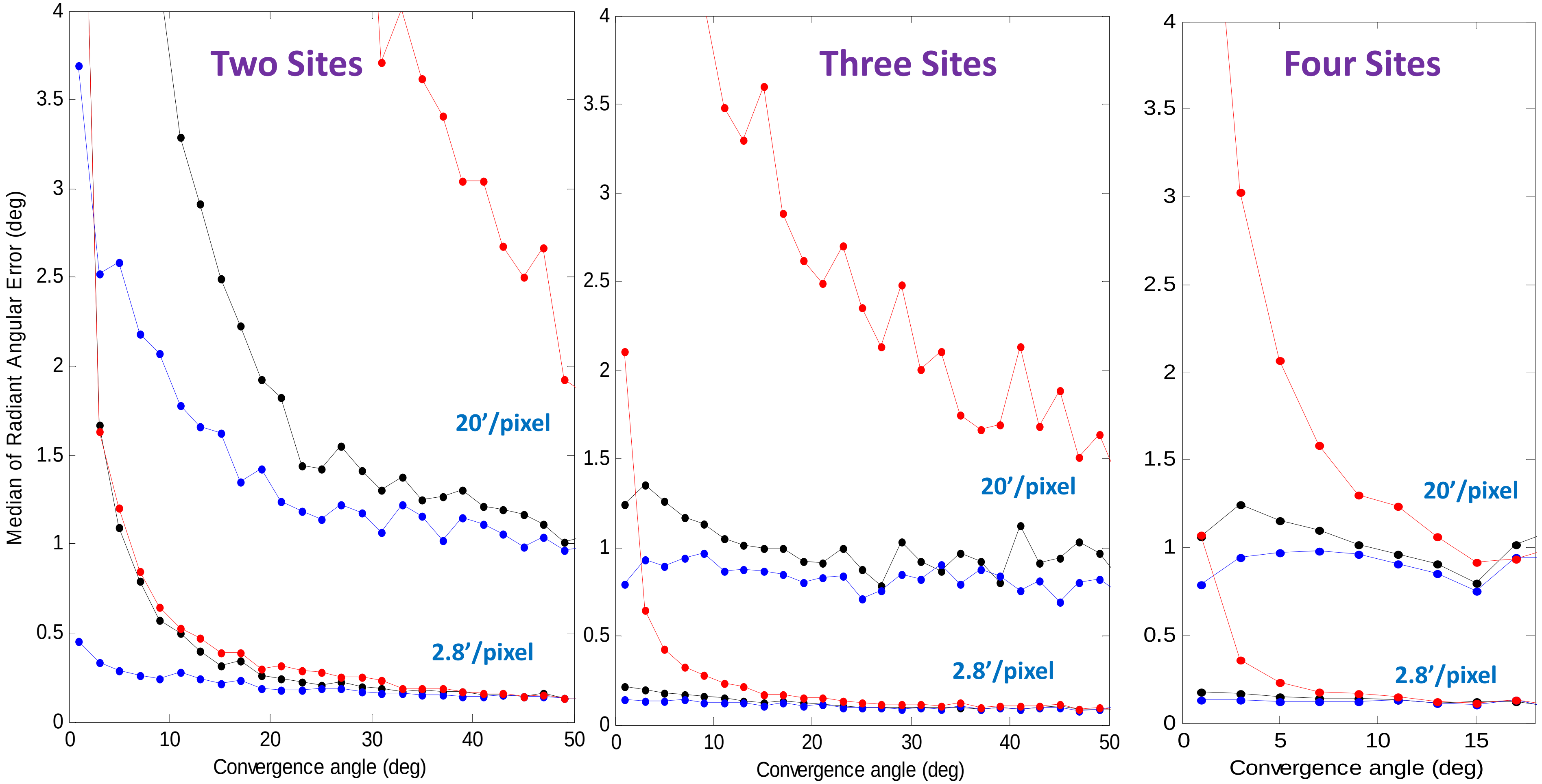
FOV	**Sensor Resolution (arcmin / pixel)**
160° x 213°	**20**
80° x 107°	**10**
22° x 30°	**2.8**
2.2° x 3°	**0.28**

Wide field and all-sky cameras can improve

their radiant estimation performance !

Note change in vertical scale

Radiant Error Comparing 2, 3, and 4 Observation Sites



Site separation always ≥ 10 km
Measurement error σ = 0.3 pixels
IP equally weighted average of radiants

With 3 or more sites, the least squares and parameter fit produce equivalent performance !

Summary

- **New trajectory estimation technique developed**
  - ***Multi-parameter fit of multiple un-synchronized cameras to a single-track motion model***
  - ***Provides improved accuracy for:***
    - Low convergence angle
    - Smaller site separation
  - ***Available as a self-contained C function file "TrajectorySolution.h"***

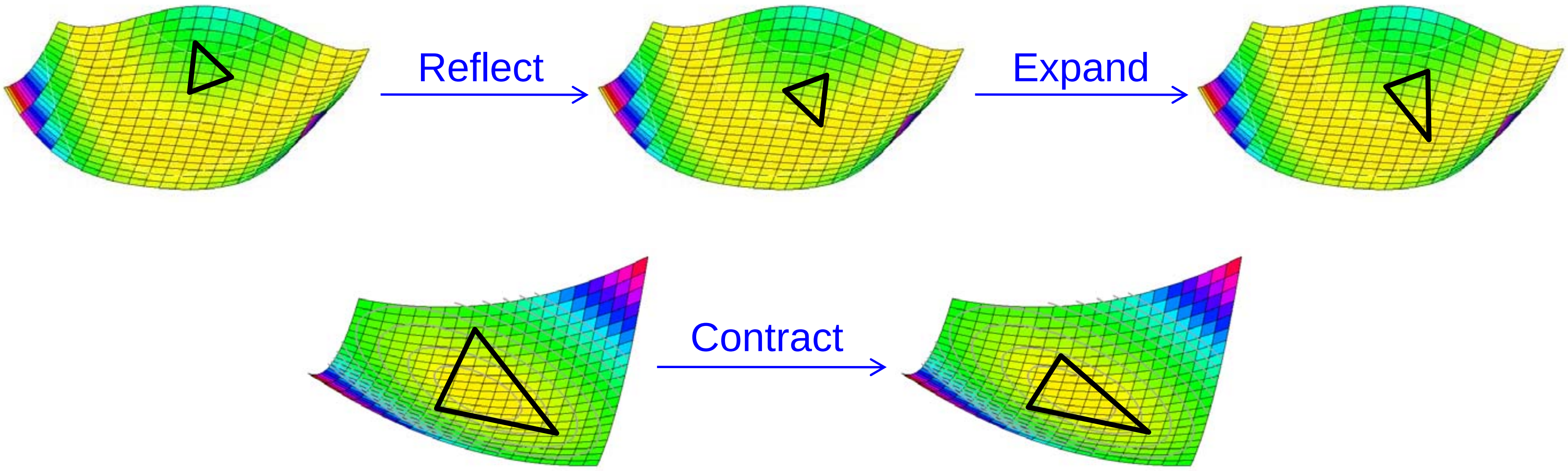
- **Potential Improvements**
  - ***Simulated Annealing minimization***
  - ***Add measurement specific error to minimization cost function***
  - ***Ingest Azim-N/Elev, Azim-S/ZenAng , versus Ra/Dec only***

Backup Charts

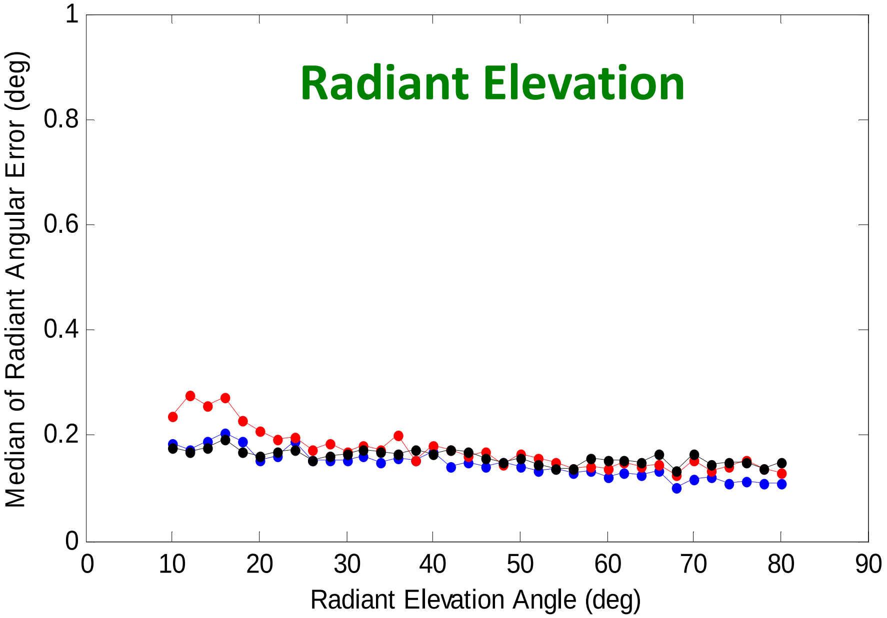
- Downhill Simplex function minimization
- Radiant error insensitivity to meteor geometry
- Radiant error for closely separated sites / 5° FOV
- Radiant error for various measurement error levels

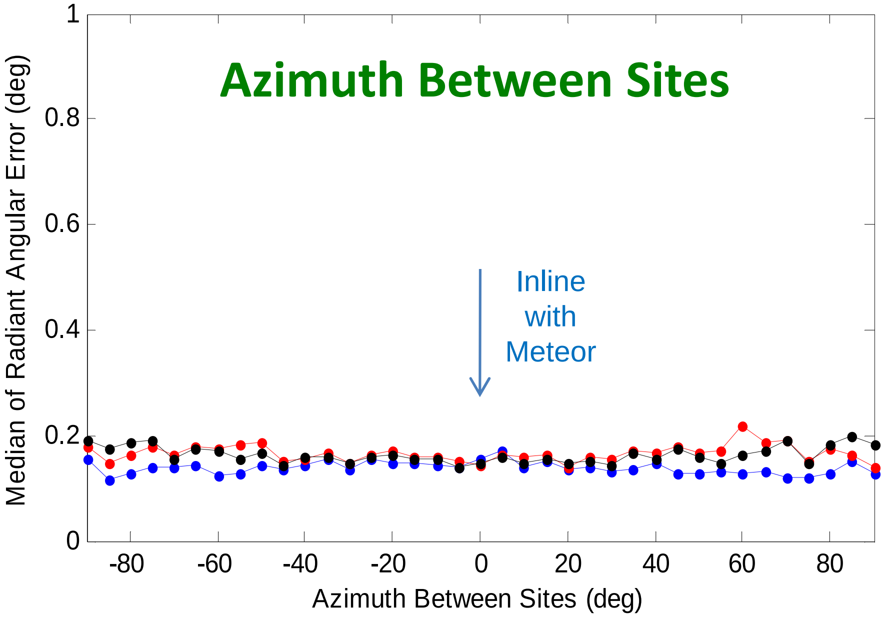
Trajectory Minimization Solver Implemented in C

- **Nelder-Mead, Downhill Simplex, or Amoeba minimization**
  - *Function evaluations only, no gradients*
  - *Requires good initial guesses to find global minimum*
  - *Intersecting planes, LMS velocity fit, time offsets solved with others constrained*
  - *Final iterative solution includes all parameters with no constraints*



Radiant Error Insensitive to Meteor Geometry





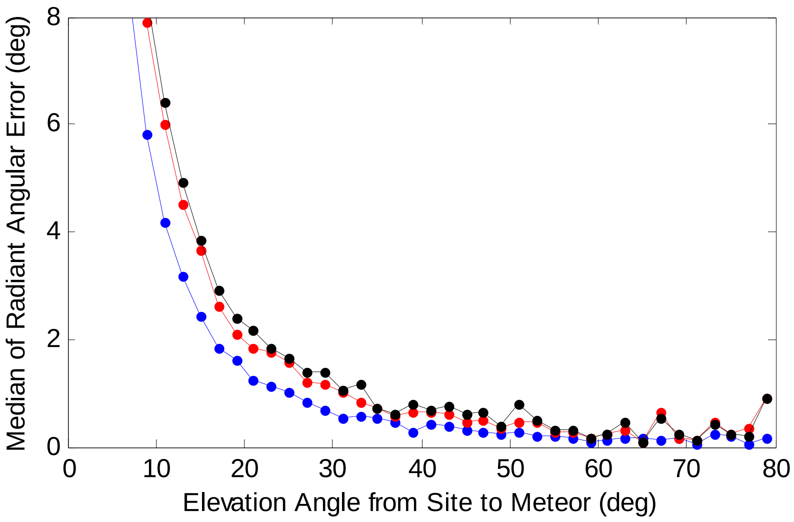
No obvious dependency on

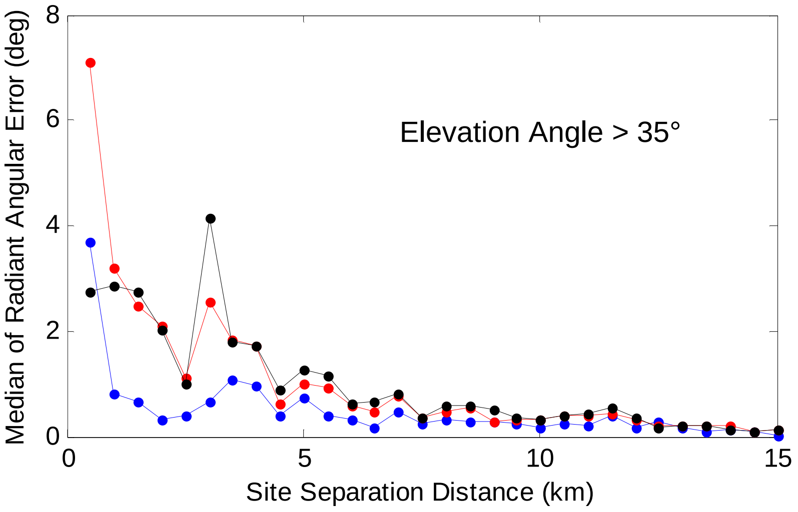
meteor geometry and site positioning:

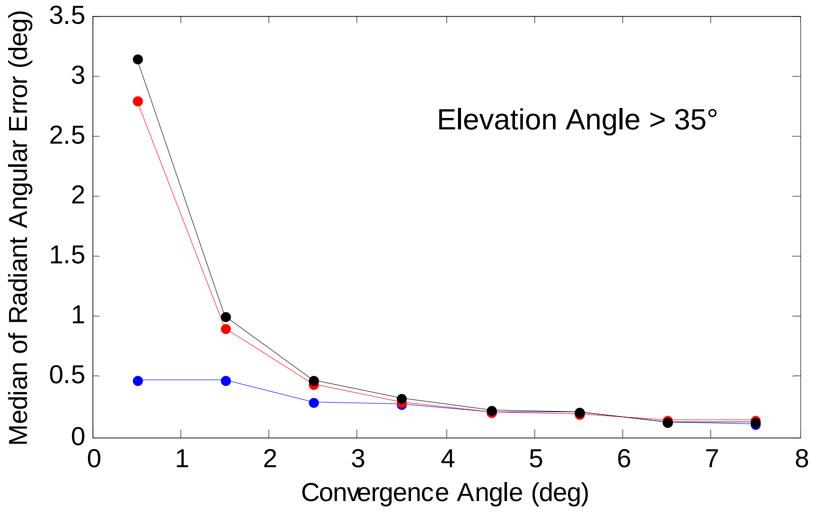
Plots for angular resolution = 2.8'/pixel, meas σ = 0.3 pixels

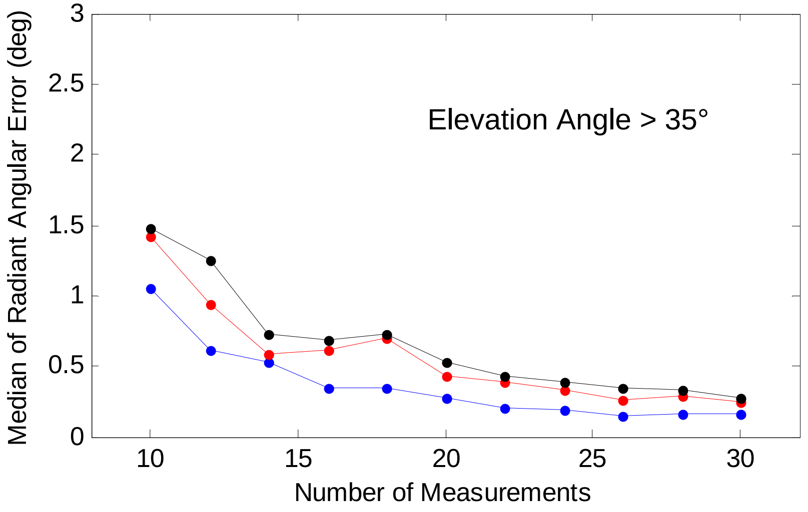
Convergence angle > 20°

Radiant Error for Closely Separated Sites / 5° FOV





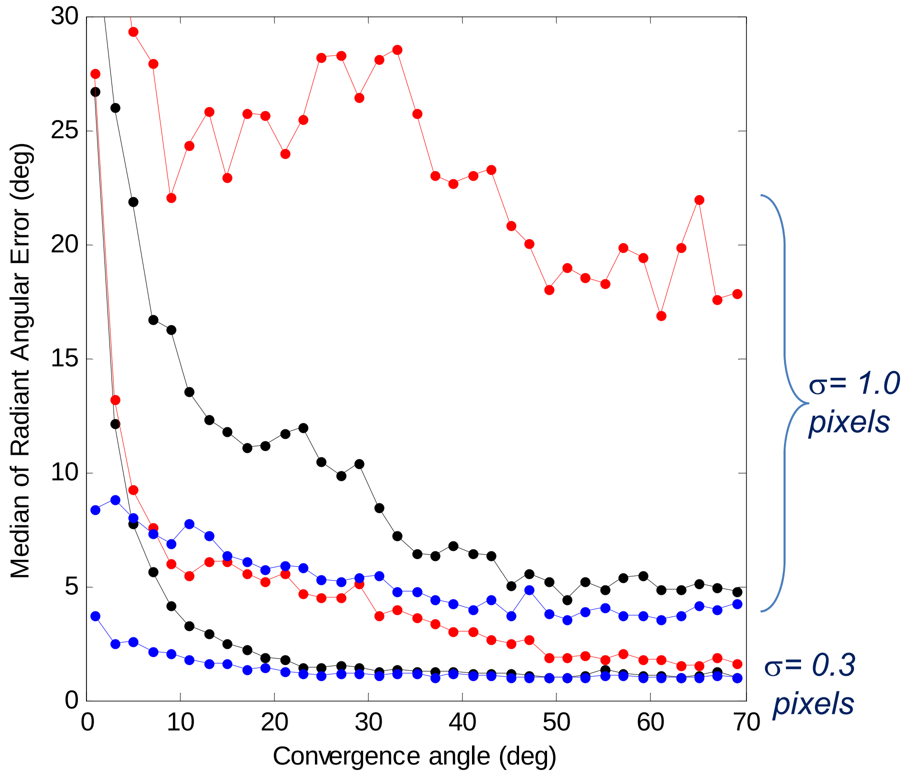


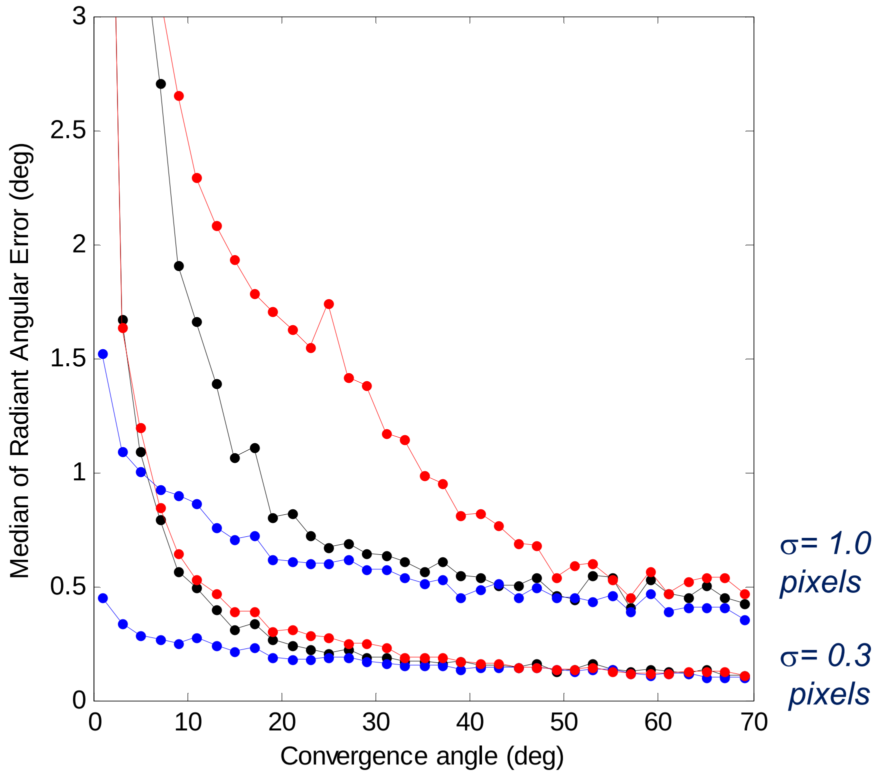


Avoid low elevation angles and hope for long meteors !

Plots for angular resolution = 0.5'/pixel, meas σ = 0.3 pixels

Radiant Error for Various Measurement Errors (Fixed Sensor Resolution)


Resolution = 20’/pixel


Resolution = 2.8’/pixel

FOV	Sensor Resolution (arcmin / pixel)
160° x 213°	20
80° x 107°	10
22° x 30°	2.8
2.2° x 3°	0.28

Radiant error directly proportional

to measurement accuracy

for all resolutions (except IP)