Preliminary Analysis of Double-Station Meteors Observation via CubeSat Cluster Flight

Hongru Chen*

Nicolas Rambaux

Robin Matha

Riad Chelil

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Background: Meteor and debris characterization

- Meteoroids: remnant of the formation of the solar system
- Space debris:
  - Environment model for space activities
  - Re-entry physics
- **Objective: Determination of fluxes of meteoroids and space debris entering the Earth atmosphere**
- Ongoing projects:
  - Ground: FRIPON, Canadian Network
  - Space: S3-CUBE (JP), Meteor (USA-JP)


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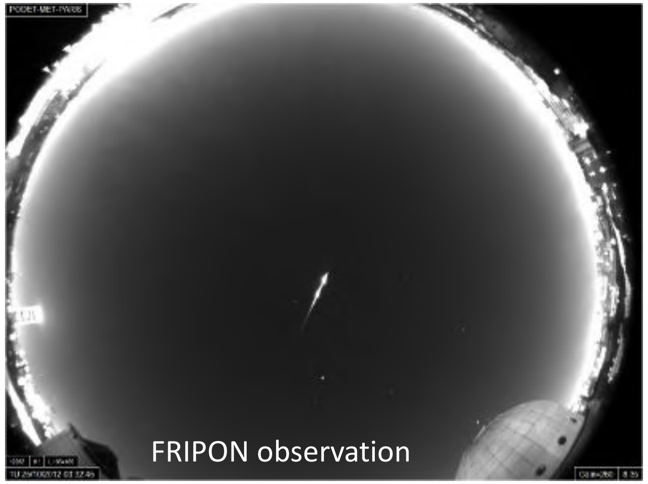
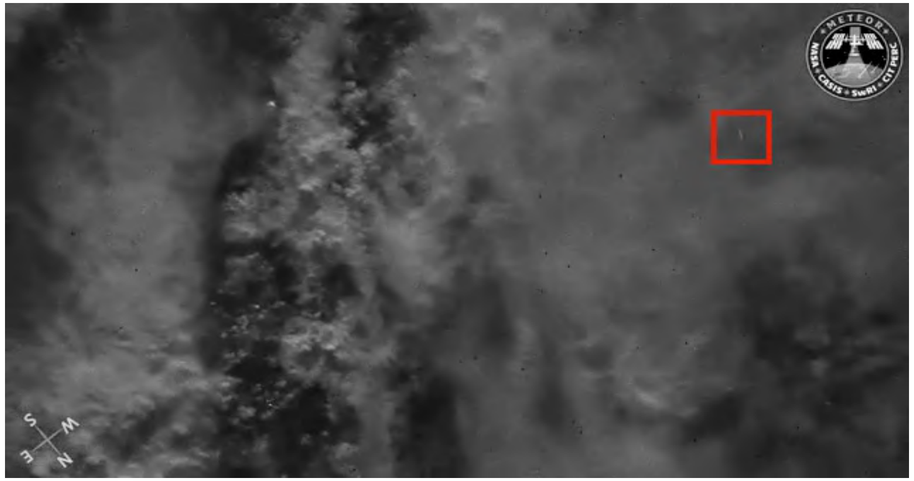

FRIPON observation

Meteorix: a CubeSat dedicated to meteors and debris detection

- Space-borne observation: no weather constraint, wide coverage
- Meteorix plans and objectives:
  - Photometric measurements of meteors to study their interaction with the atmosphere
  - Demonstration of meteor chain detection from a Cubesat with low power available
  - Enabling orbit determination of meteoroids and space debris (combining with Earth-ground data, e.g. Fripon)

Detection algorithm



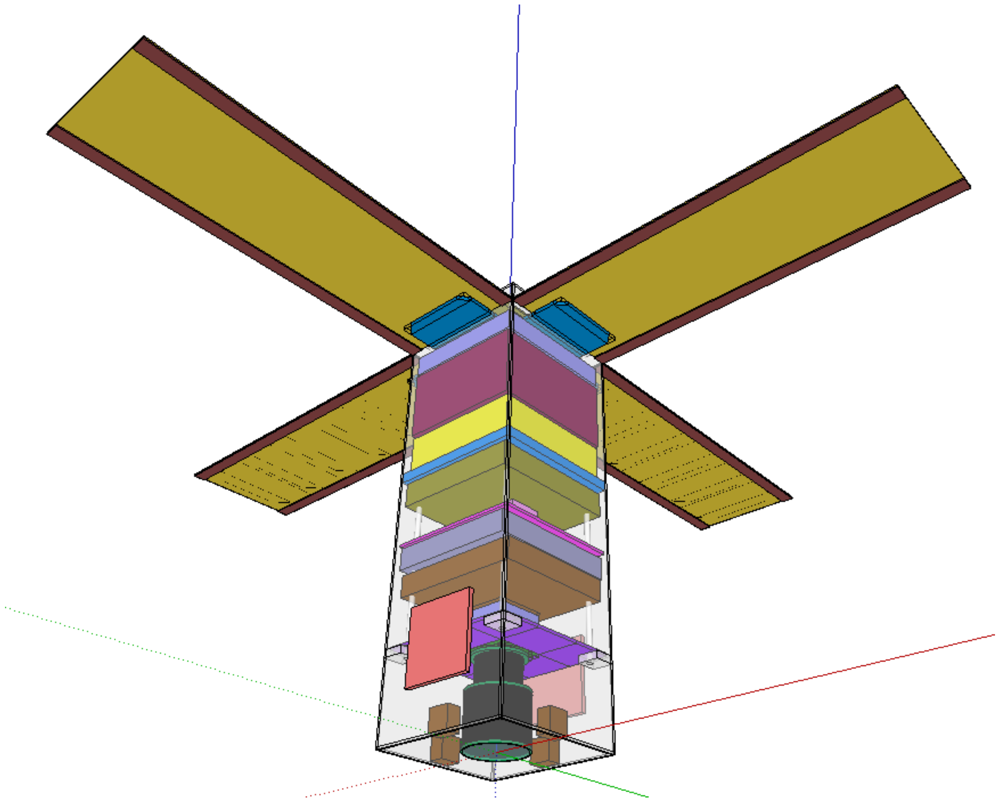
(a) Frame 106 of a grayscale sequence

(b) Frame 106 binarized: threshold = 72

(Image from Meteor experiment onboard of ISS, Univ. Chiba, Courtesy, T. Arai)

Meteorix project overview

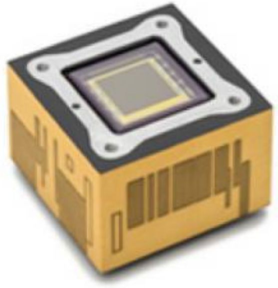
- Payload: camera (visible)
- Observation during local nights in nadir directions
- Mission lifetime: 1 year
- Detection ~100 events during the mission
- Orbit: 500 km Sun-synchronous (not constrained)
- Reviews:
  - Analysis of baseline mission (09/2015), feasibility (09/2017), currently Phase B
  - **Double CubeSat measurement analysis** (this work)



IDM-CIC CNES

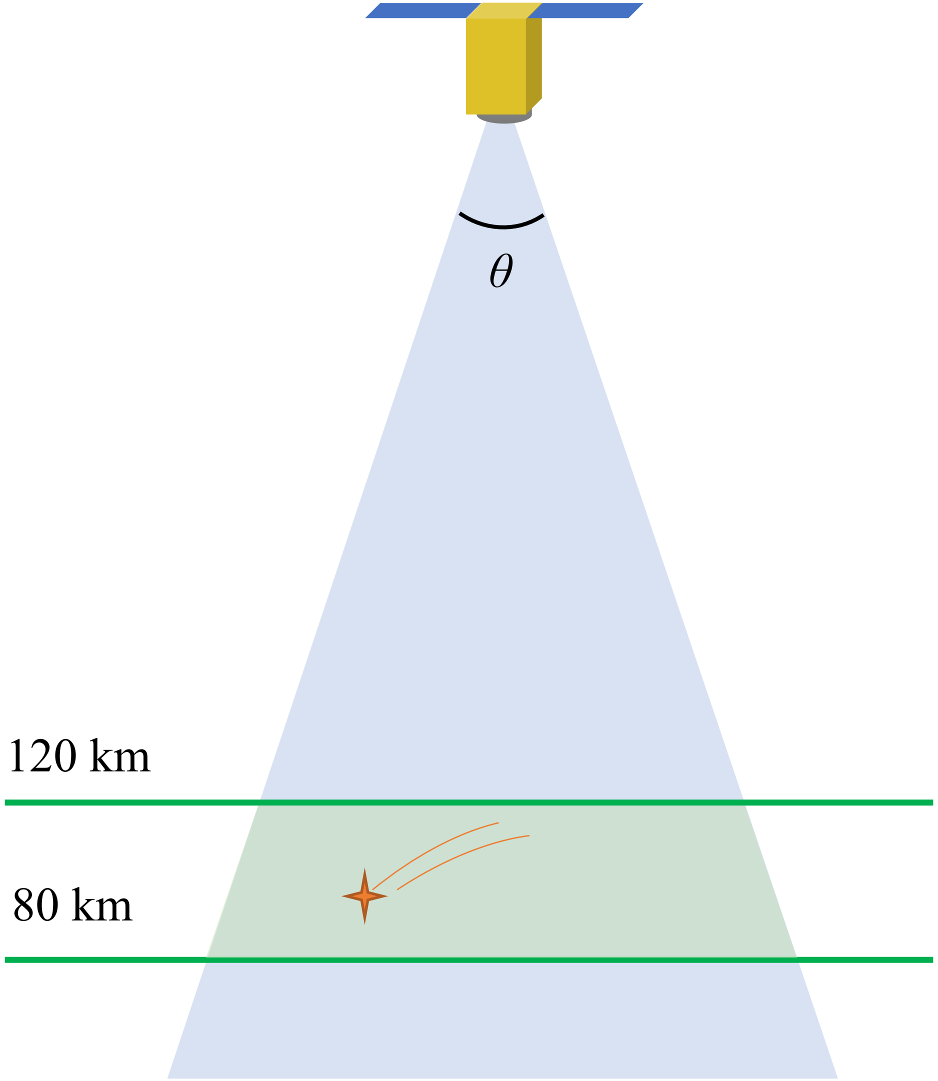
Payload: Camera

	Expected specifications	3D Plus
Name	-	3DCM681
Monochrome	Yes	Yes
Mass	-	64 gr (without optics)
Spatializable	Yes	Yes
Fps	10	12 or 16
Companding	8 to 12	12 or 10
Temperature	-30°C to 40°C	-40°C to 70°C
Size (mm*mm*mm)	97*97*100	35*35*23 (without optics)
Frame size (px*px)	640*512	2048*2048
Heritage	Yes if possible	EyeSat & Supercam



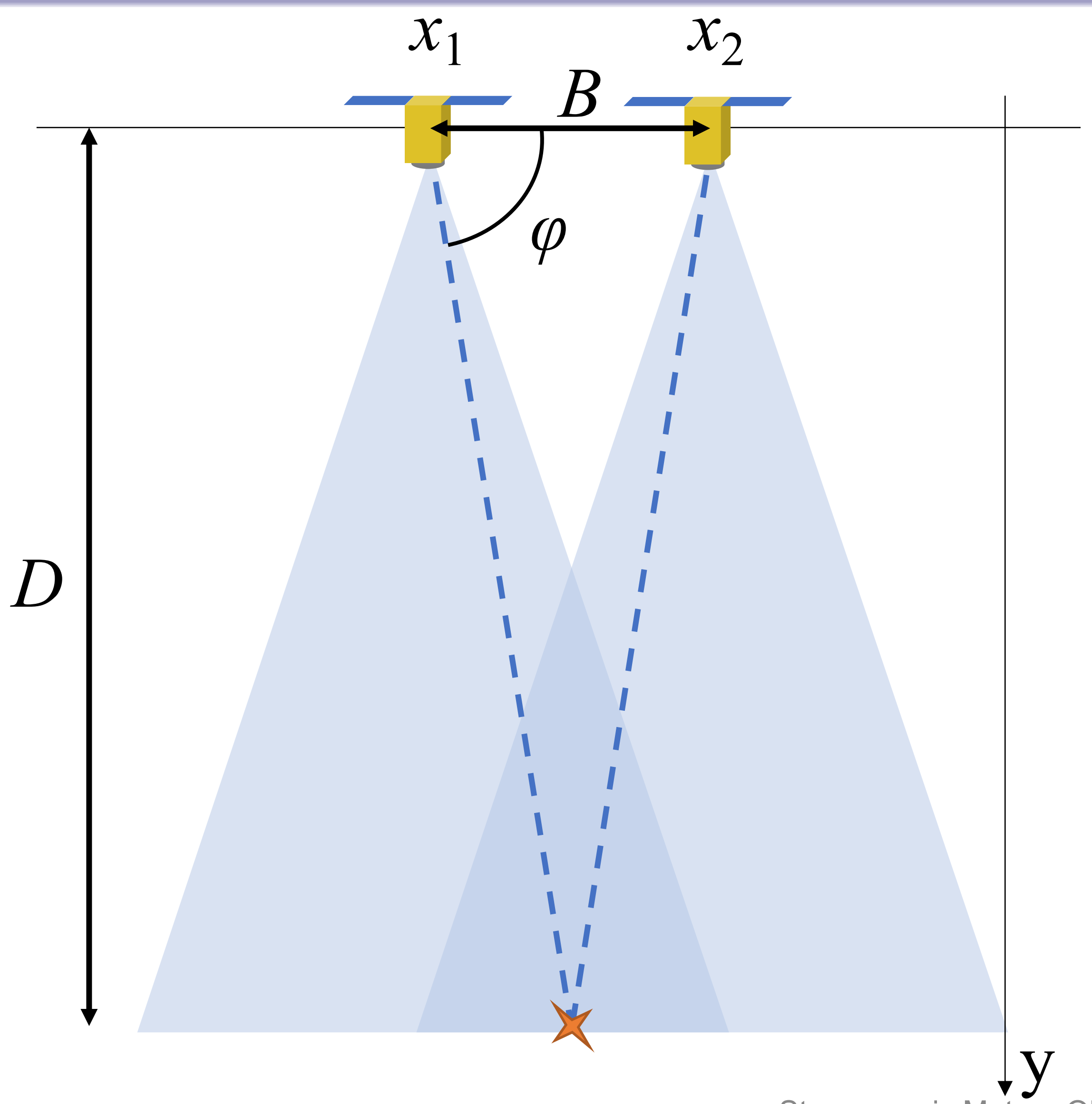
	Expected specifications	LEICA
Name	-	Summilux- M 24 mm
Field of view	30° to 40°	84°/ 74°/ 53°
Focal number	1-1.4	1.4
Price	-	7295 $
Mass	-	500 g
Size (mm*mm)	97*97*100 – Sensor size	58.5*75.6

Observation setting



- FoV of camera: 40º
- Resolution: 2048 x 2048 (px x px)
- Observation direction: nadir
- Observation altitude: [80, 120] km

Stereoscopic measurement enabled by dual-CubeSats



$$\delta x = \sqrt{\frac{1}{2}}\frac{D}{B}\delta x_1$$

$$\delta y = \sqrt{\frac{1}{2}\left(\frac{D}{B}\delta x_1\right)^2 + \left[\left(\frac{D^2}{B} + B\right)\delta\varphi\right]^2}$$

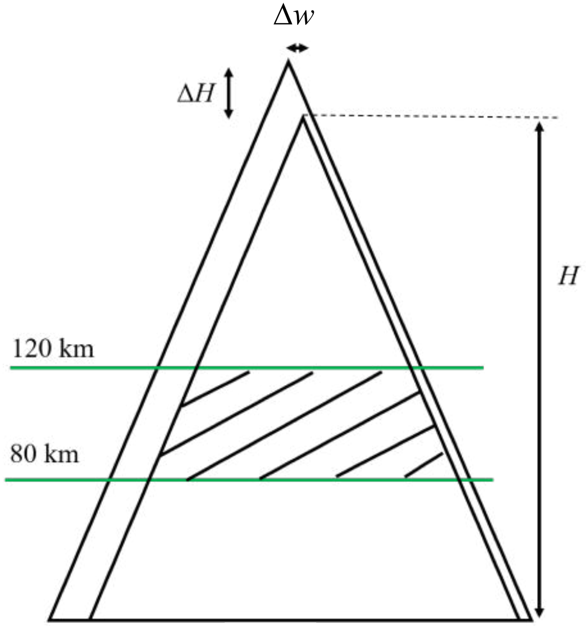
$$\delta z = \sqrt{B^2 + D^2}\,\delta\varphi$$

where

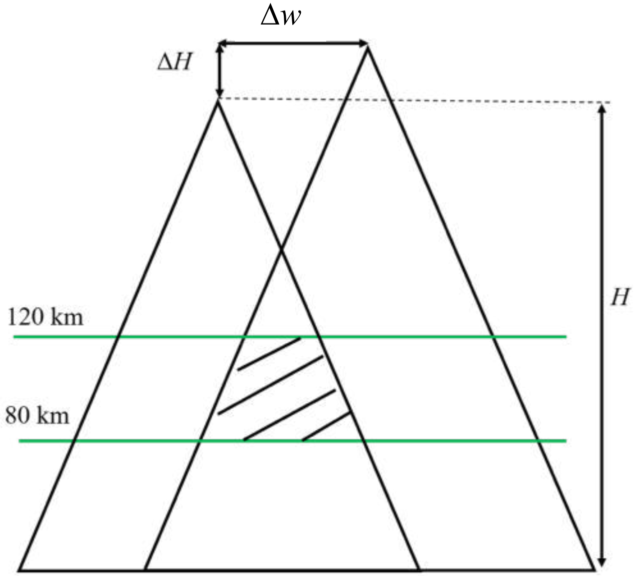
$\delta x_1 = \delta x_2 = 100\mathrm{m}$ Orbit determination error

$\delta\varphi = \frac{\theta}{px} = \frac{40^\circ}{2048}$ Frame resolution

Field intersection

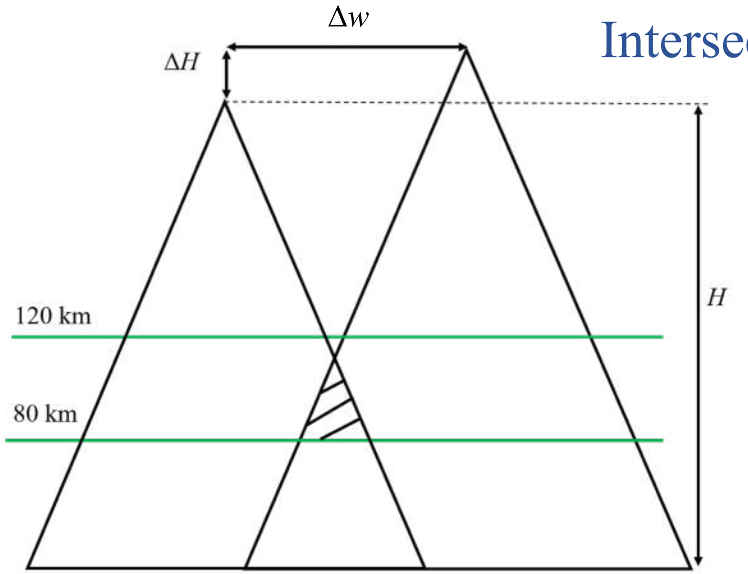


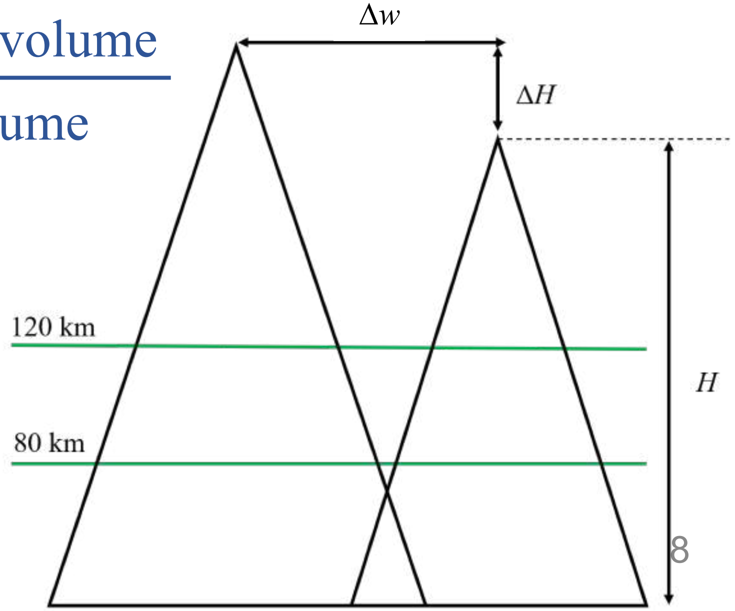
Considering all possible situations



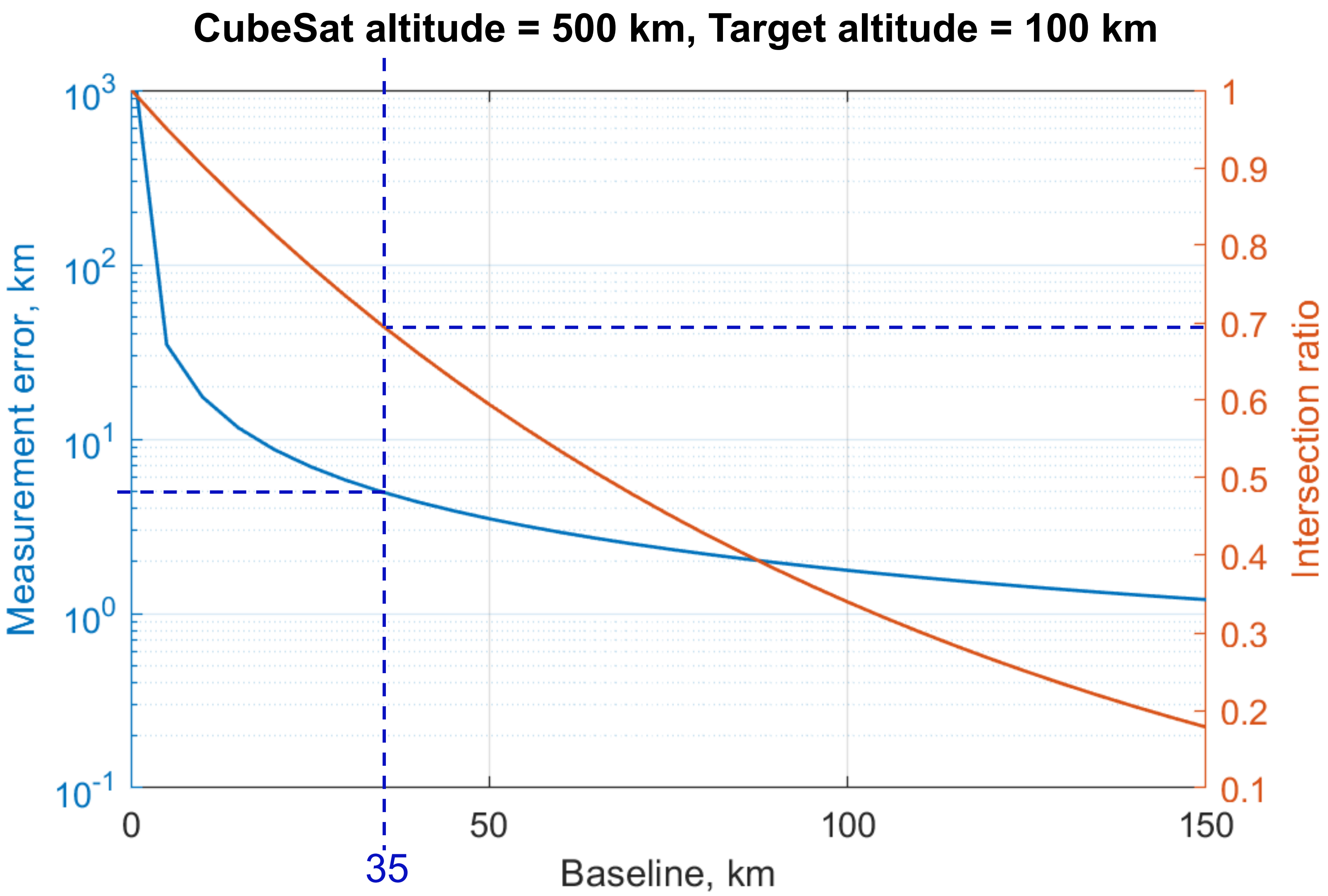
Define

$$\text{Intersection ratio} = \frac{\text{Overlapped observable volume}}{\text{Single observable volume}}$$





Relationship between baseline, measurement error, and intersection ratio

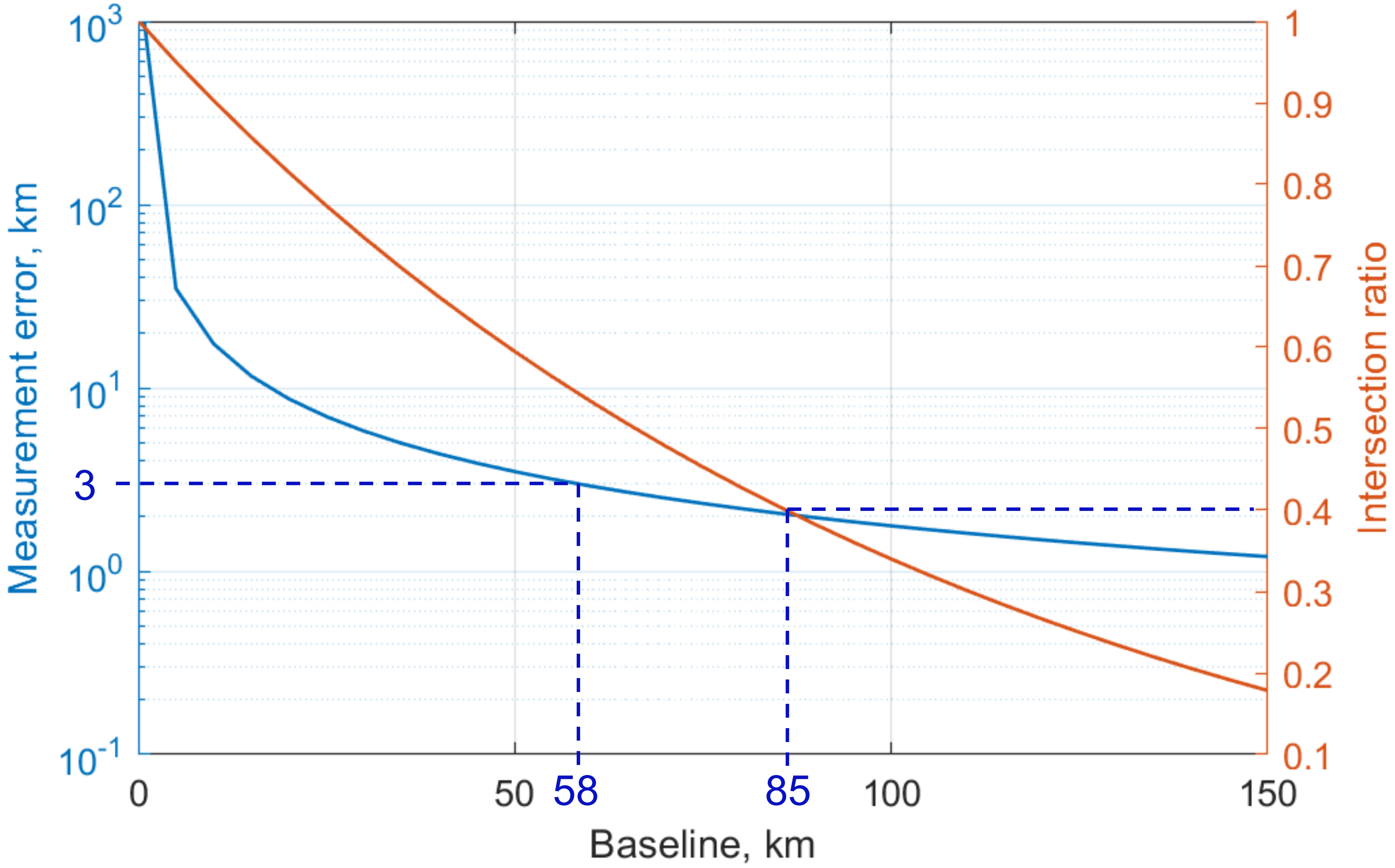


Remarks:

Measurement error too large (>> 5 km) when baseline < 35 km, though intersection ratio > 0.7

Relationship between baseline, measurement error, and intersection ratio

CubeSat altitude = 500 km, Target altitude = 100 km

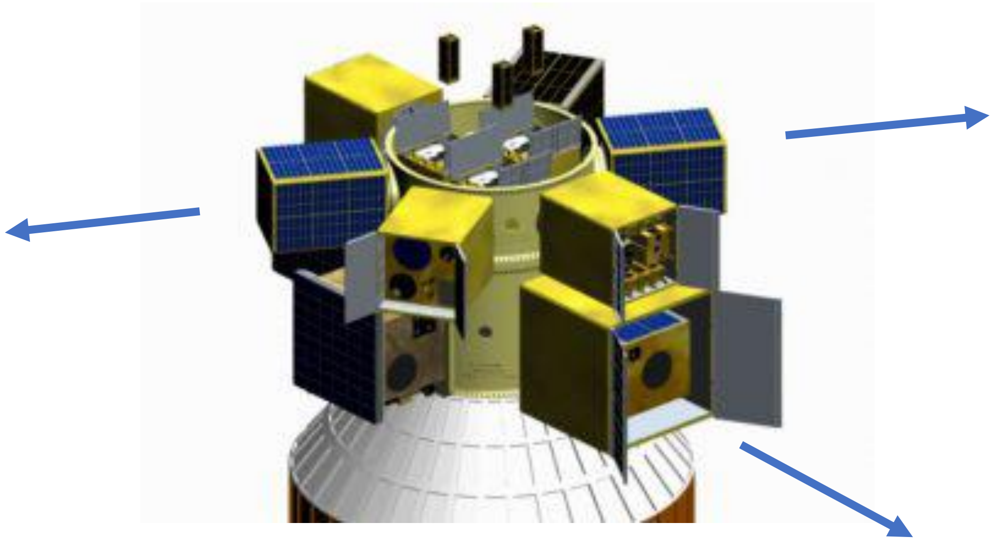


Remarks:

- When baseline > 60 km, error not efficiently decreases
- When baseline > 85 km, the intersected ratio < 0.4 not ensuring stereoscopic measurement

35 < optimal baseline < 85 km

Deployment Assumption:



FANTM-RiDE small spacecraft dispenser
© TriSept Corporation and Moog CSA

- Departure velocity 2 m/s
- Deployment directions can be chosen;

Orbit setting

Orbital elements of the deployer

a*, *km	6878.136
e	0.002
LTAN, hours	10.5
***i*, deg.**	97.4
***ω*, deg.**	0

Altitude ≈ 500 km

Sun-synchronous orbit

Baseline variation

Force model

- EGM96 (20 x 20), lunar and solar gravity,
- solar radiation pressure (C_r = 1.0, A = 0.00875 m^2, m = 4 kg)
- atmospheric drag (exp. density model, C_d = 2.38)

Baseline can increase quickly

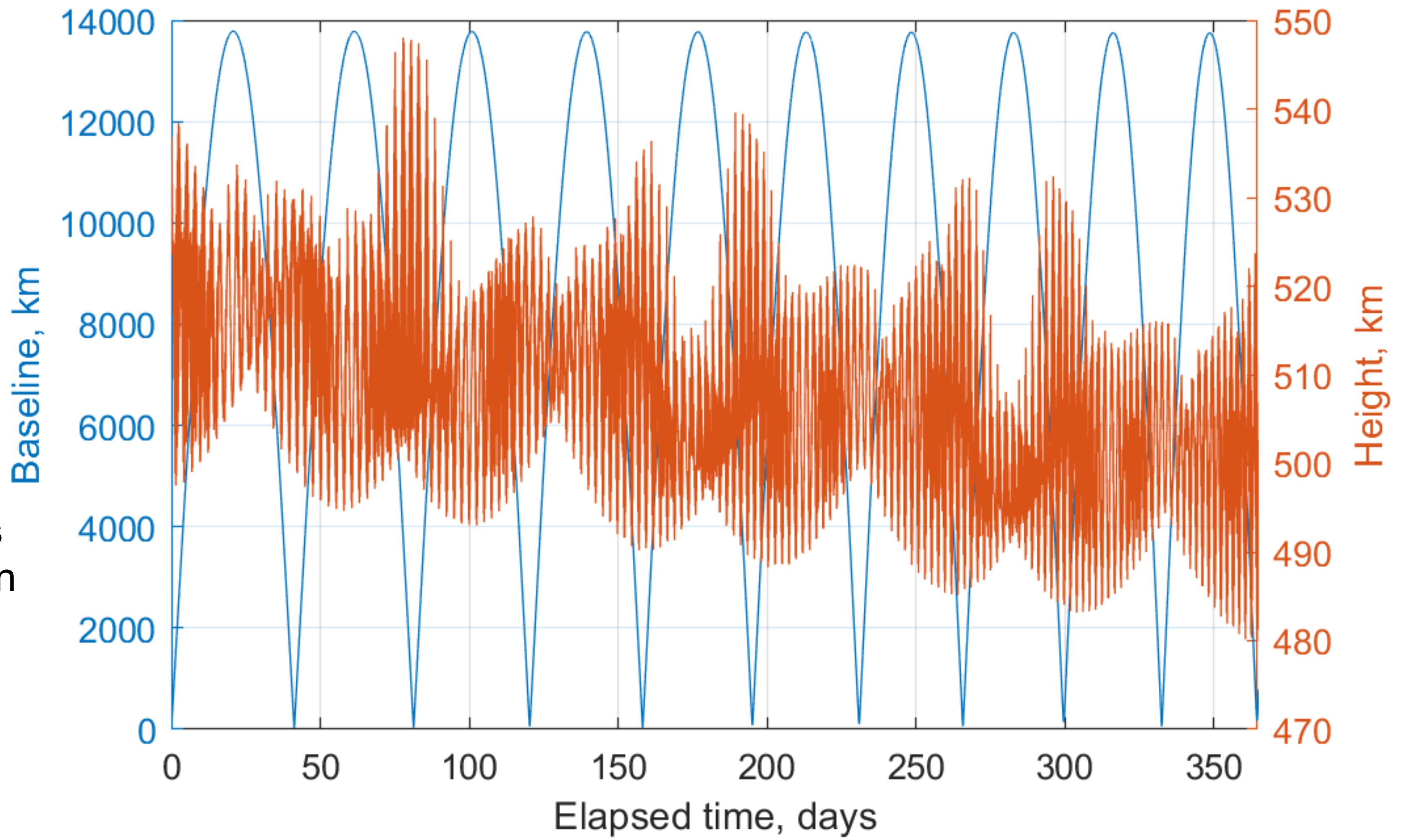
If deployment directions not carefully chosen.

E.g. 2 m/s opposite directions along the velocity : 1000 km in 1 day

E.g. 0.2 m/s opposite directions along the velocity : 100 km in 1 day

No intersection of FoV !

Quick variation and large baselines



To minimize relative drift

Orbit drift due to J2

$$\dot{\Omega} = -\frac{3nR_{\oplus}^{2}J_{2}}{2p^{2}}\cos(i)$$

$$\dot{\omega} = \frac{3nR_{\oplus}^{2}J_{2}}{4p^{2}}\left\{4 - 5\sin^{2}(i)\right\}$$

→

To have J2-invariant relative motion

$$\Delta a_1 = \Delta a_2$$

$$\Delta i_1 = \Delta i_2$$

$$\Delta e_1 = \Delta e_2$$

To minimize relative drift

Variational equations

$$\Delta a = \frac{2}{n}\sqrt{\frac{2\left[1+e\cos(\nu)\right]}{1-e^2}-1}\Delta V$$

$$\frac{di}{dt} = \frac{r\cos(\omega+\nu)}{h}F_W$$

$$\frac{de}{dt} = \frac{\sqrt{1-e^2}}{na}\left\{\sin(\nu)F_R + \left(\cos(\nu)+\frac{e+\cos(\nu)}{1+e\cos(\nu)}\right)F_S\right\}$$

$$\frac{d\Omega}{dt} = \frac{r\sin(\omega+\nu)}{h\sin(i)}F_W$$

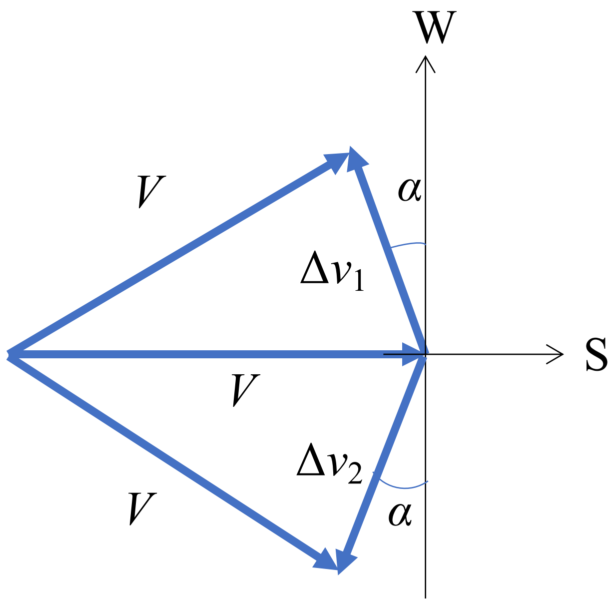
To minimize relative drift

An option :

$$\Delta a_1 = \Delta a_2 = 0$$
$$\Delta i_1 = \Delta i_2 = 0$$
$$\Delta e_1 = \Delta e_2 = 0$$

$$\Rightarrow$$

$$\Delta V = 0$$
$$\nu = 0.5\pi$$
$$\Delta v_{W1} = -\Delta v_{W2}$$
$$\Delta v_{R1} = \Delta v_{R2} = 0$$



$$\alpha = 0.5\pi - \arccos(\Delta v/2/V)$$

Sun-synchronous, but different local solar time

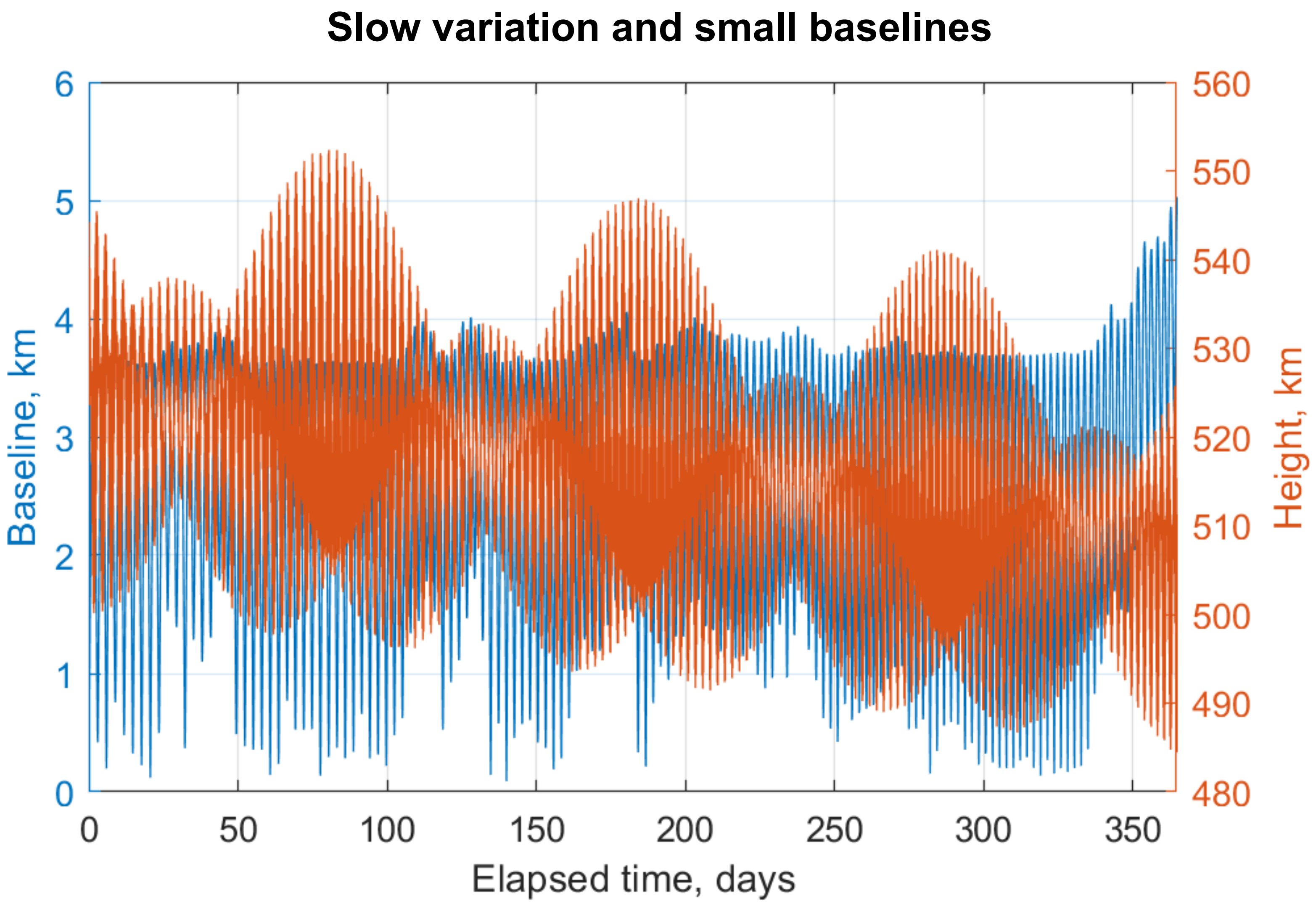
$$-\Delta\Omega_2 = \Delta\Omega_1 = \frac{r}{h\sin(i)}\Delta v_W$$

Slow baseline variation

Baseline < 5 km within 1 year, while the corresponding measurement error > 35 km

No valid stereoscopic measurement in 1 year !

Orbit drift should neither be too quick nor too slow



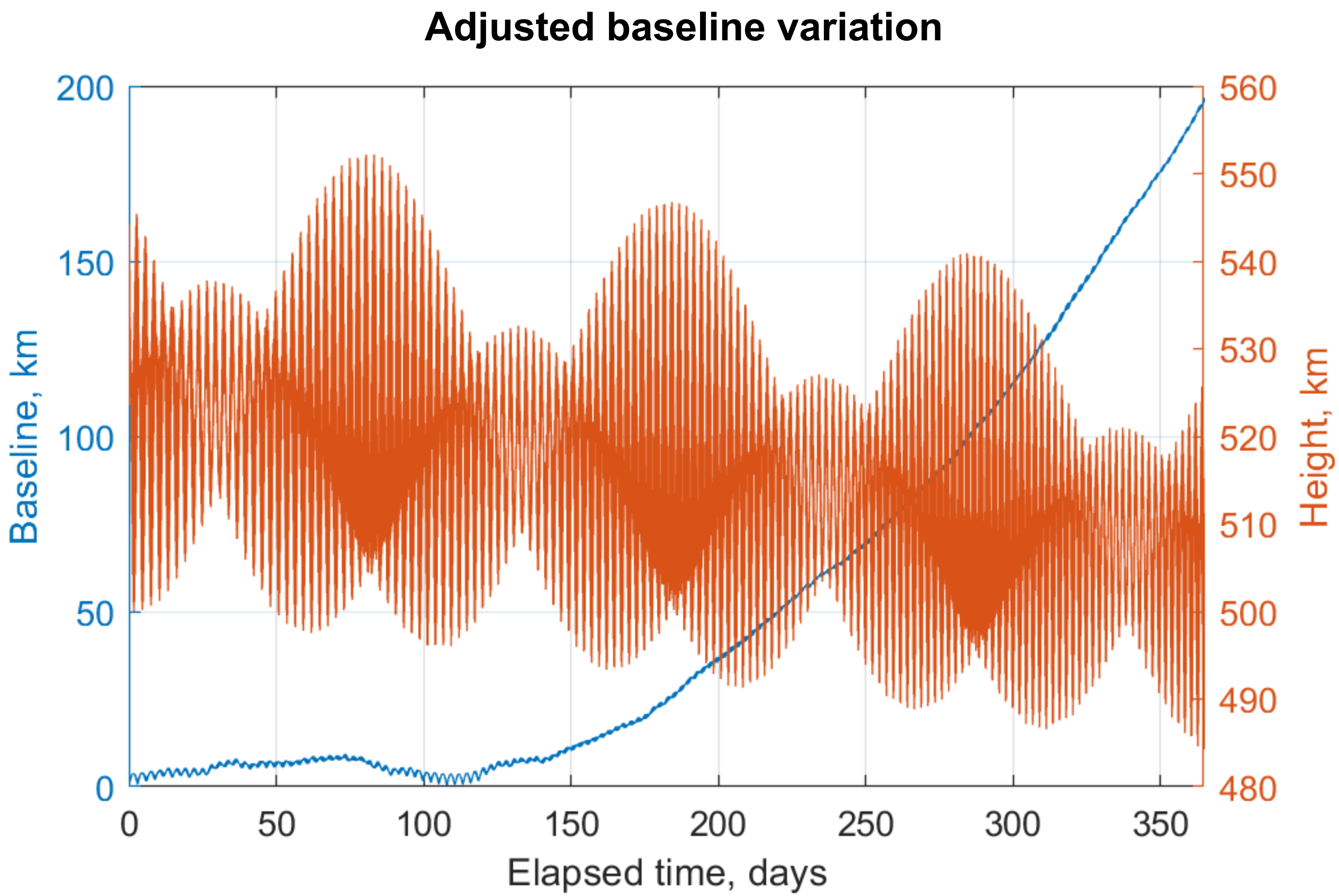
Adjusted baseline variation

- The deployment directions slightly tuned around the Drift suppressing directions

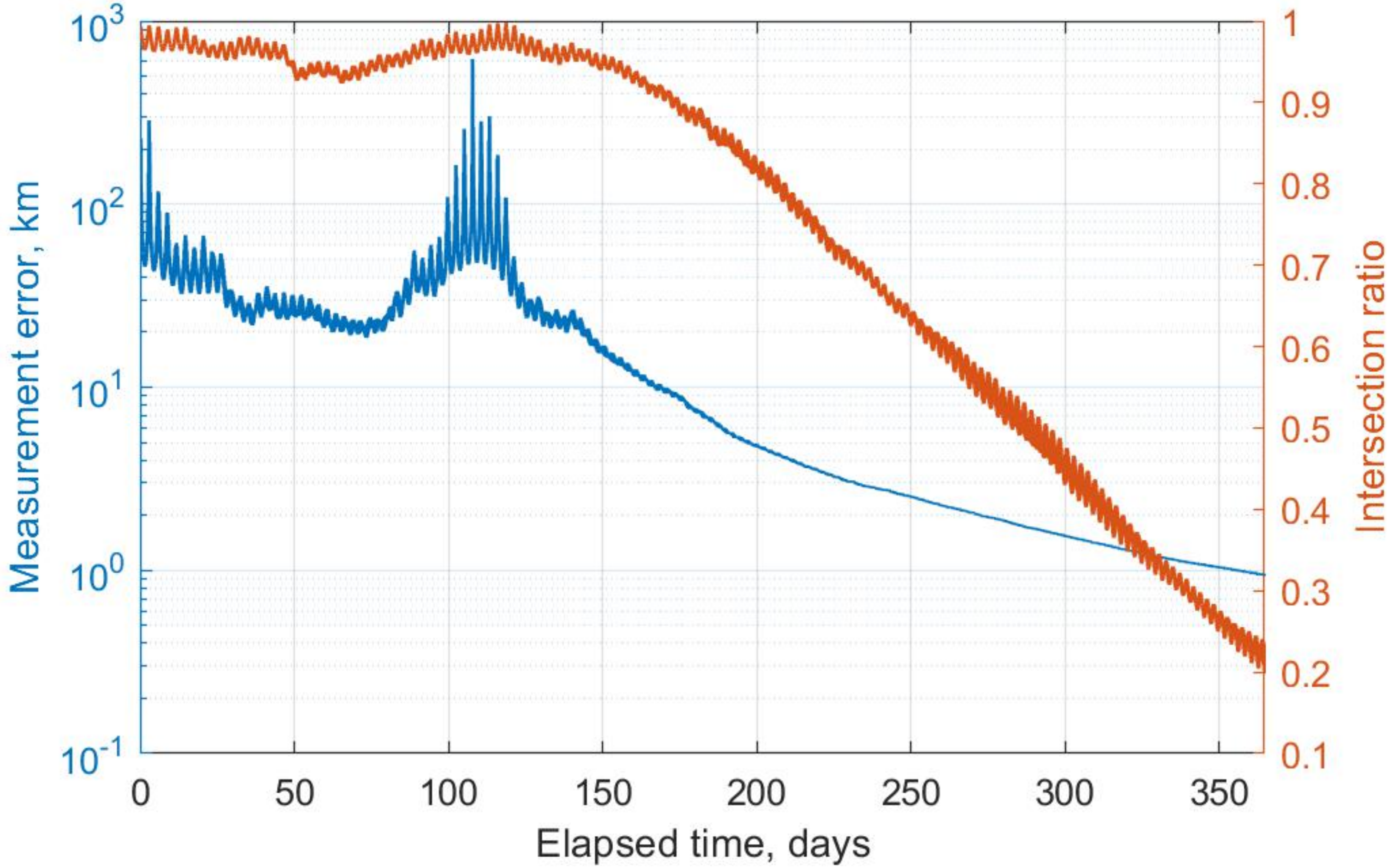
$$\Delta a_1 = \Delta a_2 = 0$$
$$\Delta i_1 = \Delta i_2 = 0$$
$$\Delta e_1 - \Delta e_2 \approx 0$$

$$\Delta V = 0$$
$$\nu = 0.5\pi$$
$$\Delta v_{W1} = -\Delta v_{W2}$$
$$\Delta v_{R1} = -\Delta v_{R2}$$

- Such that the baseline can reach 35 km, and not exceed 85 km soon

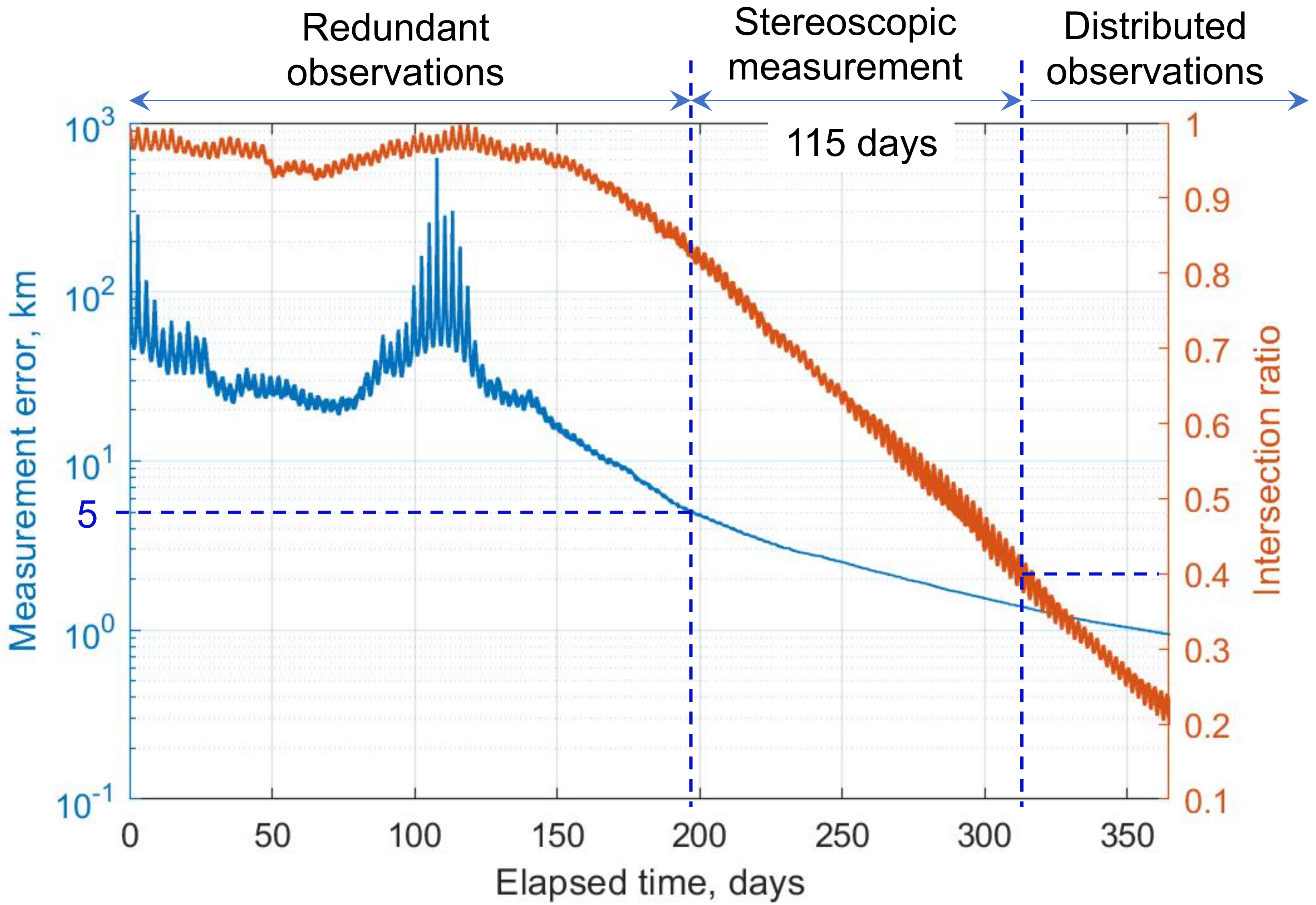


Result



Measurement error, km
Intersection ratio
Elapsed time, days
10^3
10^2
10^1
10^0
10^{-1}
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
50
100
150
200
250
300
350

Result



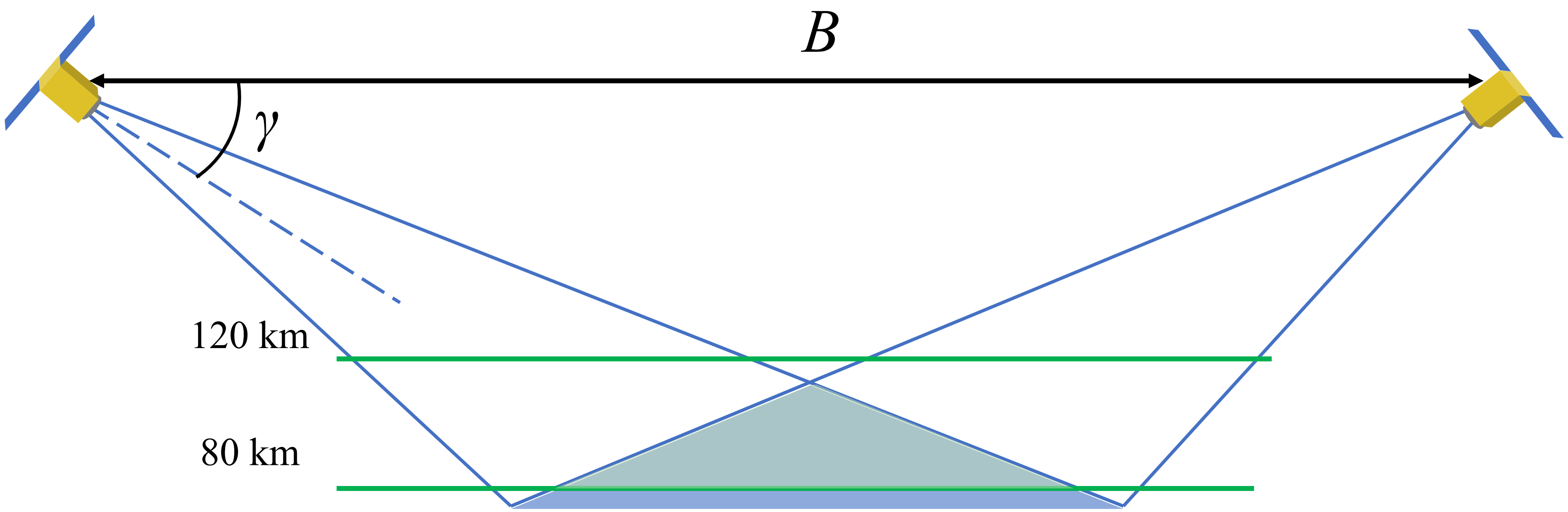
Redundant observations
Stereoscopic measurement
Distributed observations
115 days
Measurement error, km
Intersection ratio
Elapsed time, days
5
10^3
10^2
10^1
10^0
10^-1
0
50
100
150
200
250
300
350
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1

Summary

- Stereoscopic measurement of meteors and debris enabled by a dual-CubeSat cluster flight
  - field intersection
  - measurement error
  - Orbit dynamics
- The trade-off btw measurement error and observable volume determines a desirable baseline btw 35 and 85 km
- By carefully choosing deployment directions, effective stereoscopic measurement made available after 195 days, for 115 days

Future work

1. Loose baseline keeping using 1 or 2 impulses
   - Control of mean elements



2. To find optimal baseline (*B*) and pointing direction (*γ*) to maximize observation performance (error, intersection, **luminosity**), and find the optimal deployment conditions and baseline keeping strategy.

Appendix: Processing chain for detection

(Subject video from ISS, ChiTech, Courtesy, T. Arai)