Monitoring Earth's global energy balance from space

– requirements –

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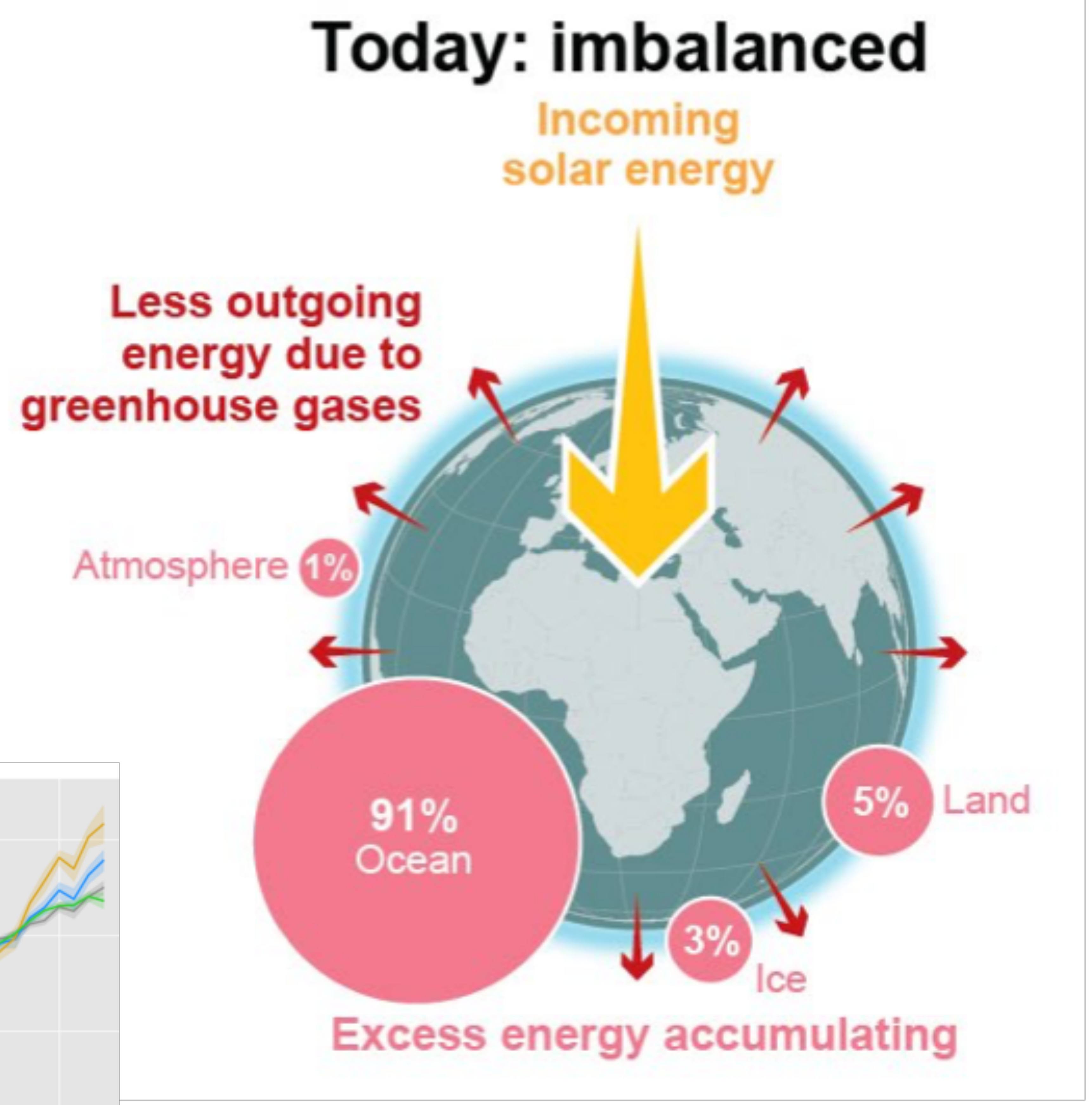
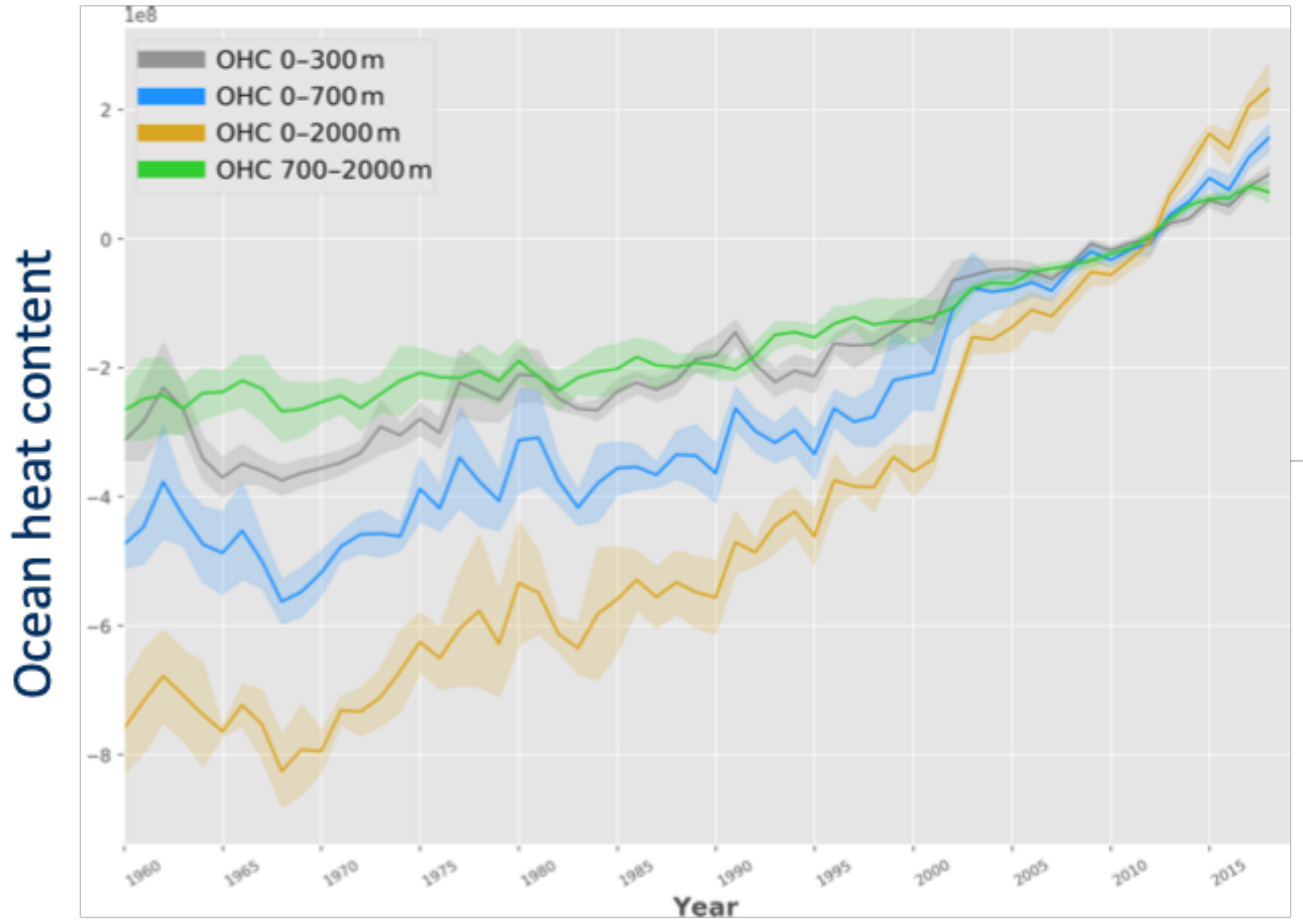
Climate out of balance

- Energy is accumulating because of increasing greenhouse gases
- This causes:
  - Rising temperatures
  - Shifting climate zones
  - Droughts and heat waves
  - Flooding
  - Increasing sea levels
- Yet, imbalance is only 1 out of 340 Wm^{-2}, or **0.3 percent**





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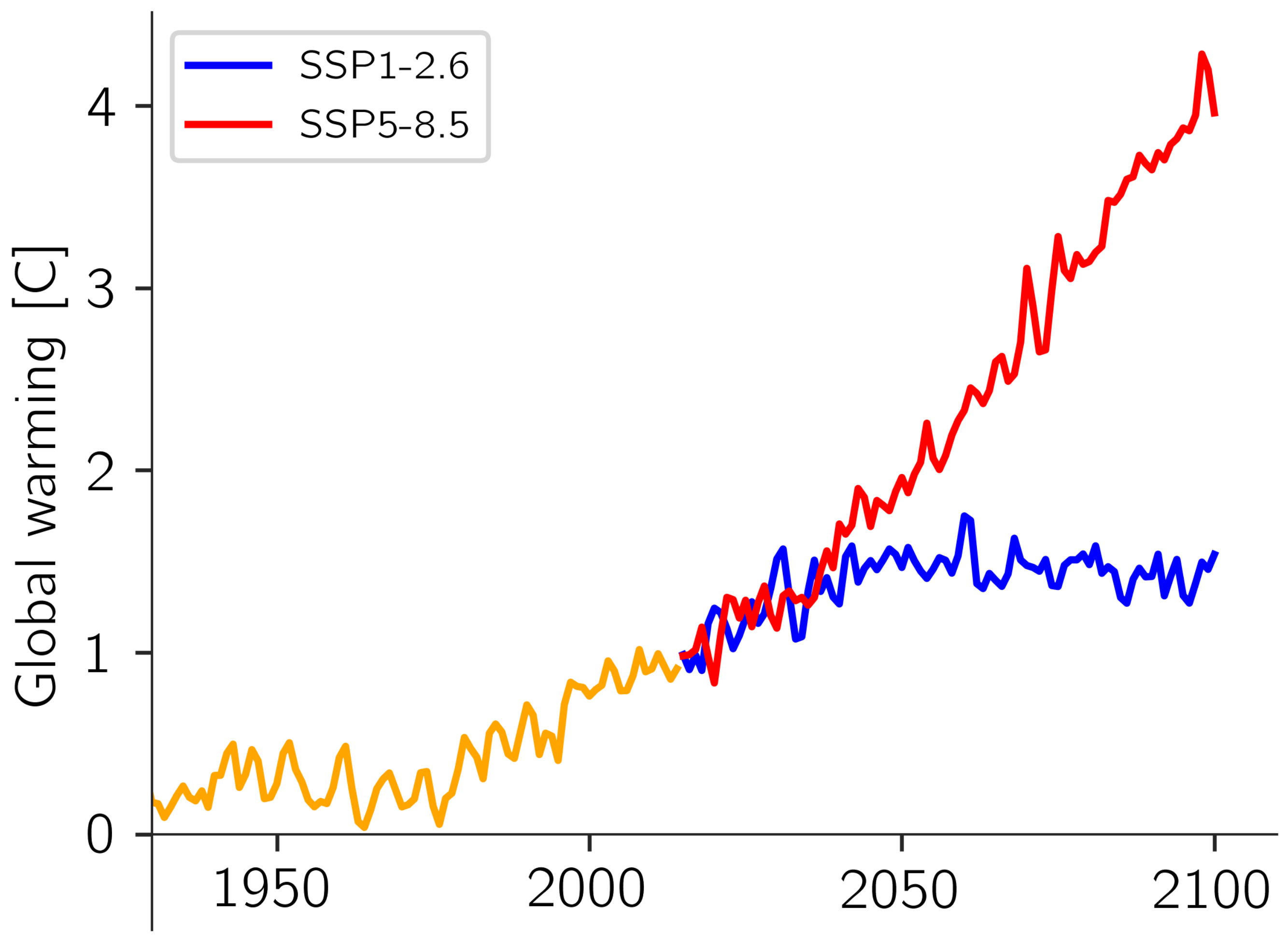
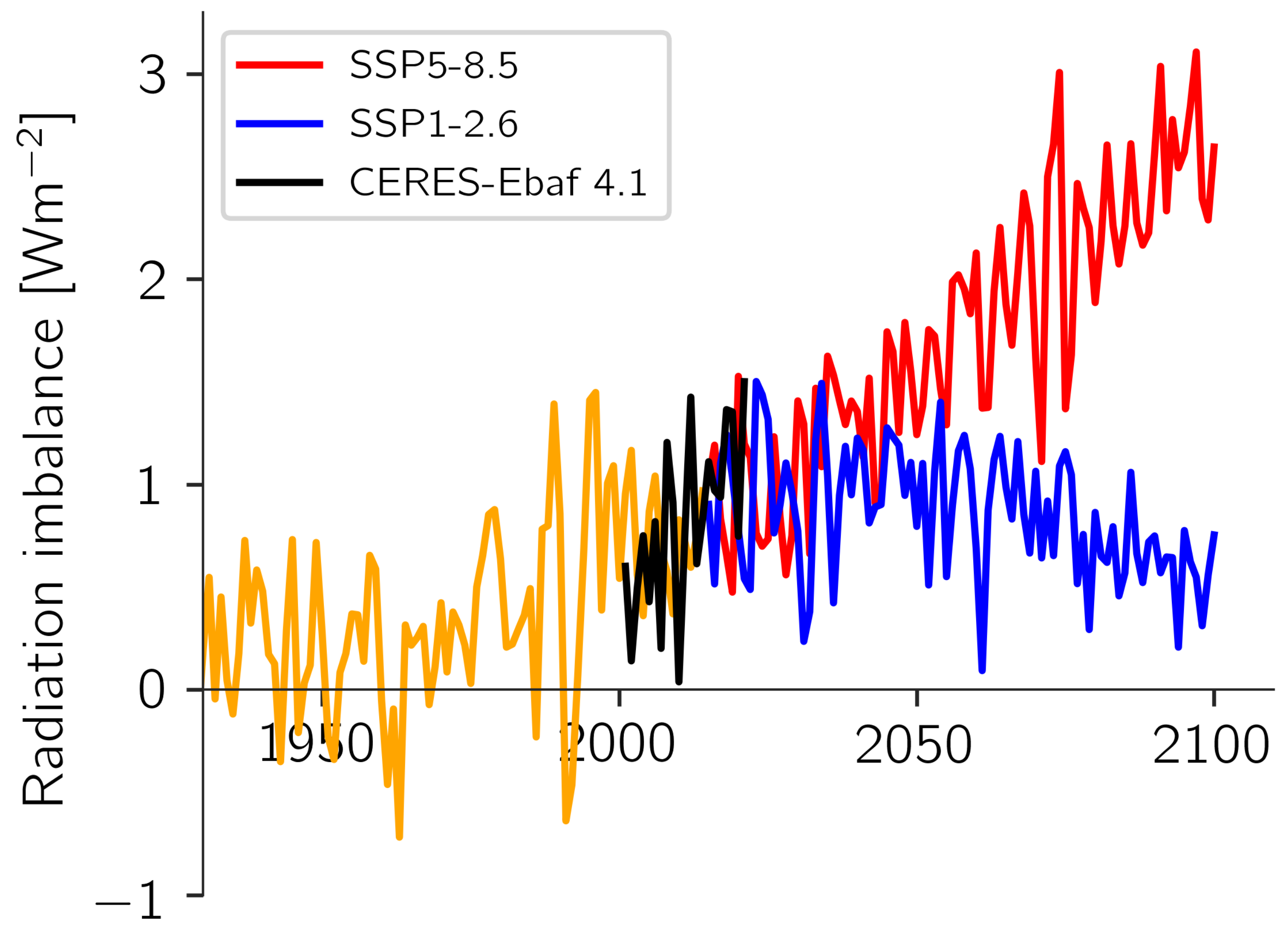
Societal benefits from long term monitoring

Governments of the world have agreed to limit global warming below 2 degrees

- Requires declining imbalance:
  - follow up on international agreement
- Prepare for worst-case scenarios:
  - aerosol forcing larger than expected: rapid warming ahead!
  - global tipping-point, extremely unlikely but catastrophic impact
  - geo-engineering may be needed in future

Simulations of past and future scenarios:





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Requirements

To be useful, a system must have drifts and errors that are smaller than the signal we want to measure, preferably much smaller

Drift	≪ 0.2 Wm^{-2} /decade
Systematic error	< 1.0 Wm^{-2}
Random error	< 1.0 Wm^{-2}

Making the problem simpler

- Sacrifice resolution for accuracy
- Focus on global annual mean imbalance
- Maintainable and stable over decades

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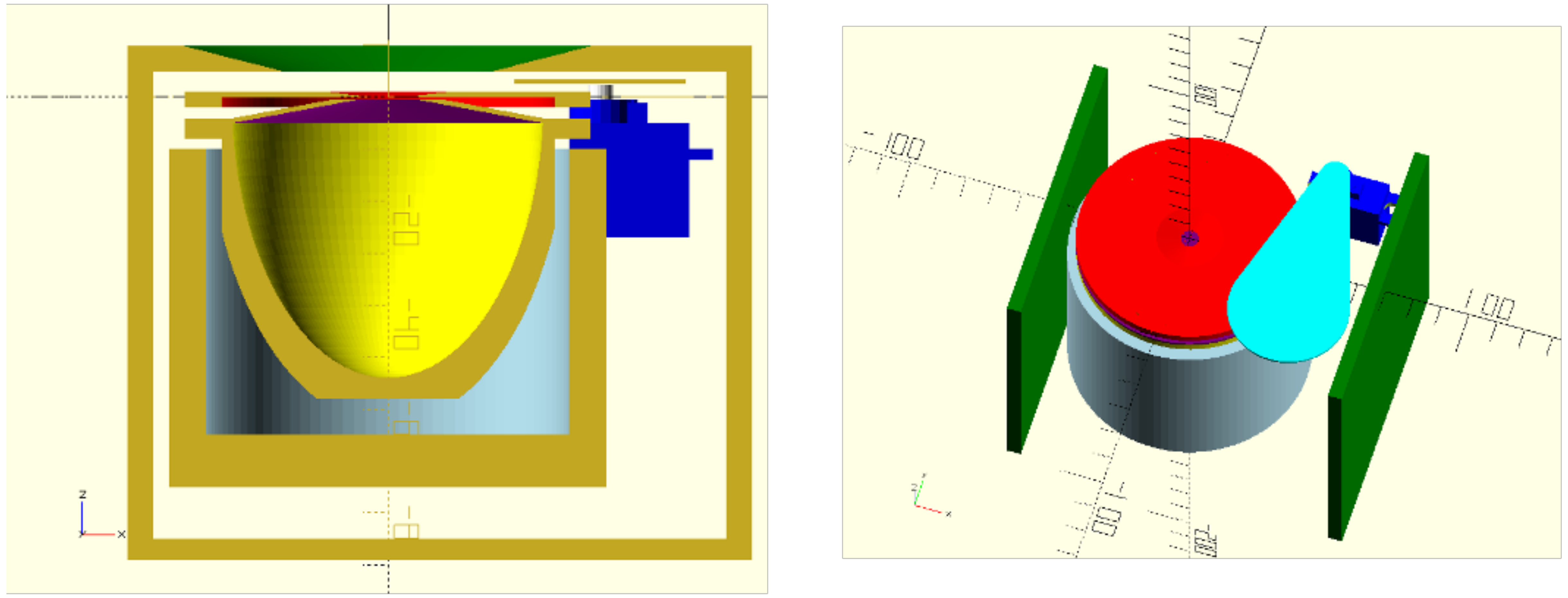
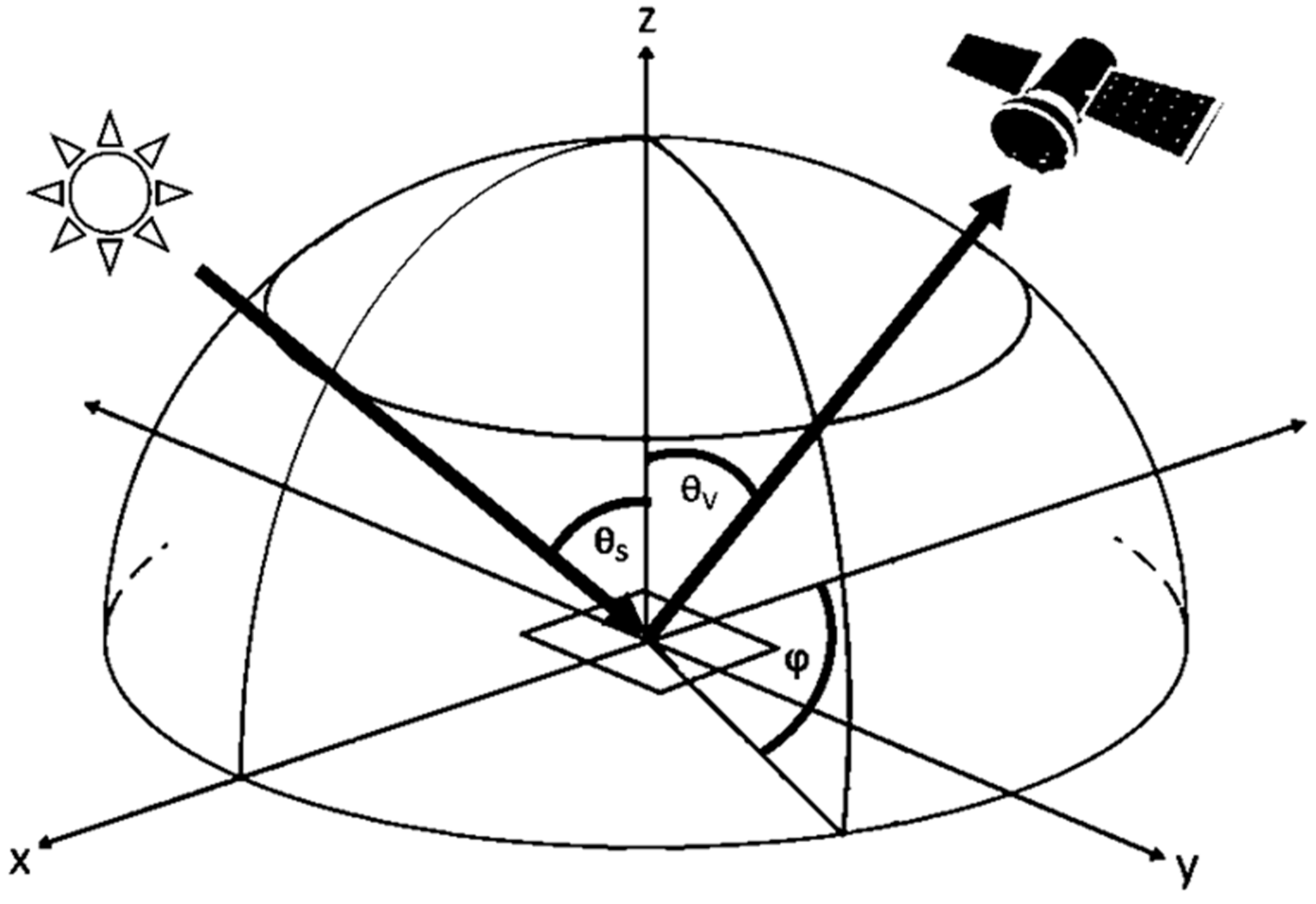


Schifano et al. (2020)

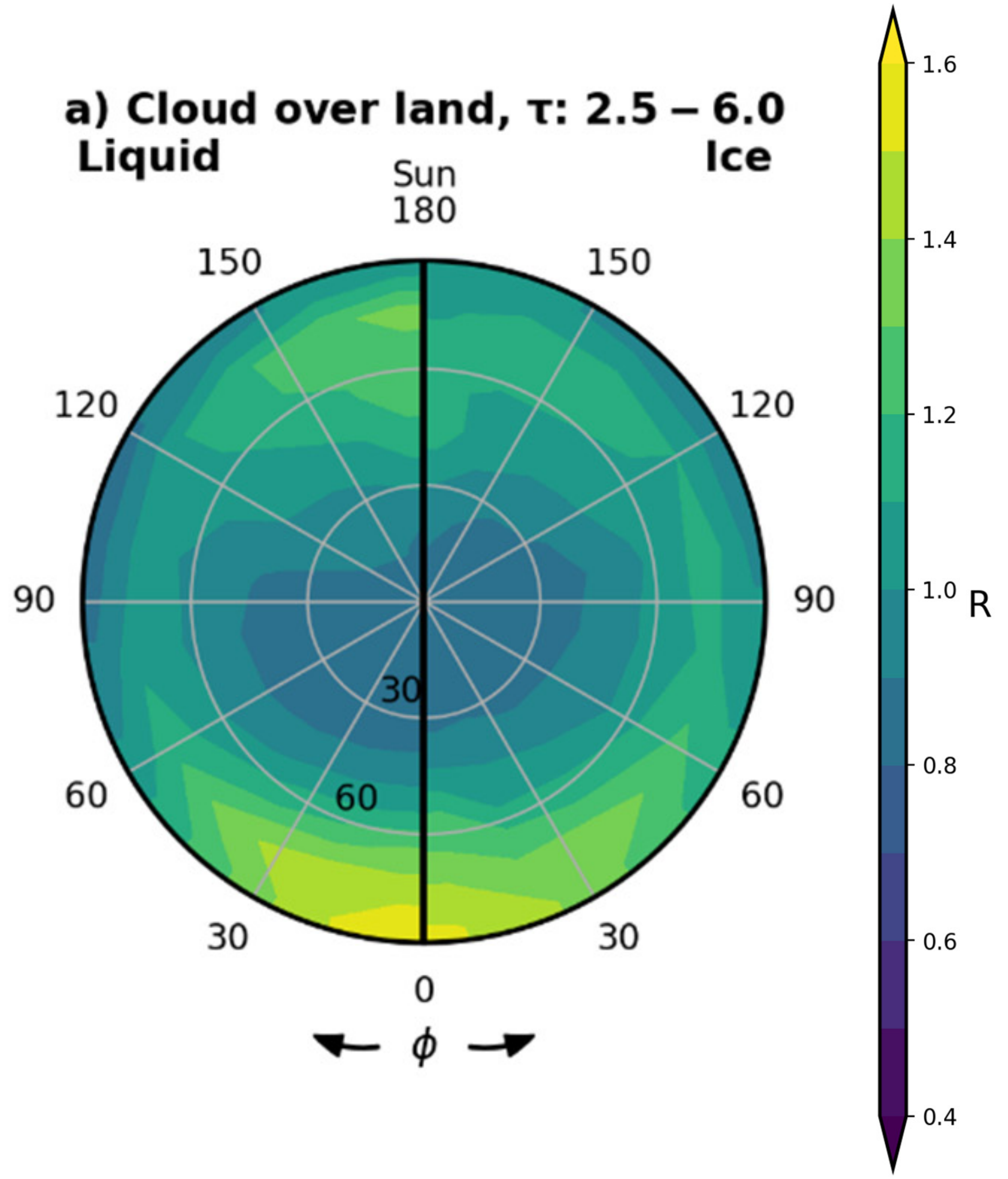
Past, current and planned missions use scanners

All scanning radiometers depend on angular dependency models (ADMs) to correct for narrow field of view

- ERBE
- CERES
- Libera
- CLARREO-Pathfinder
- ESAs TRUTHS, FORUM, IASI-NG



$$F(\theta_S) = \frac{\pi I(\theta_S,\, \theta_V,\, \varphi)}{R(\theta_S,\, \theta_V,\, \varphi)}$$



From Gristey et al. (2021)

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Anisotropic effects

Wide field of view radiometer measures actual flux at satellite position

However, systematic biases in viewing- and solar zenith angles may introduce biases:

- Gristey et al. (2017) explored effects of anisotropic using TRMM angular dependence model (ADM)
- Found difference when introducing ADM of 1.6 Wm^{-2} compared with isotropic case
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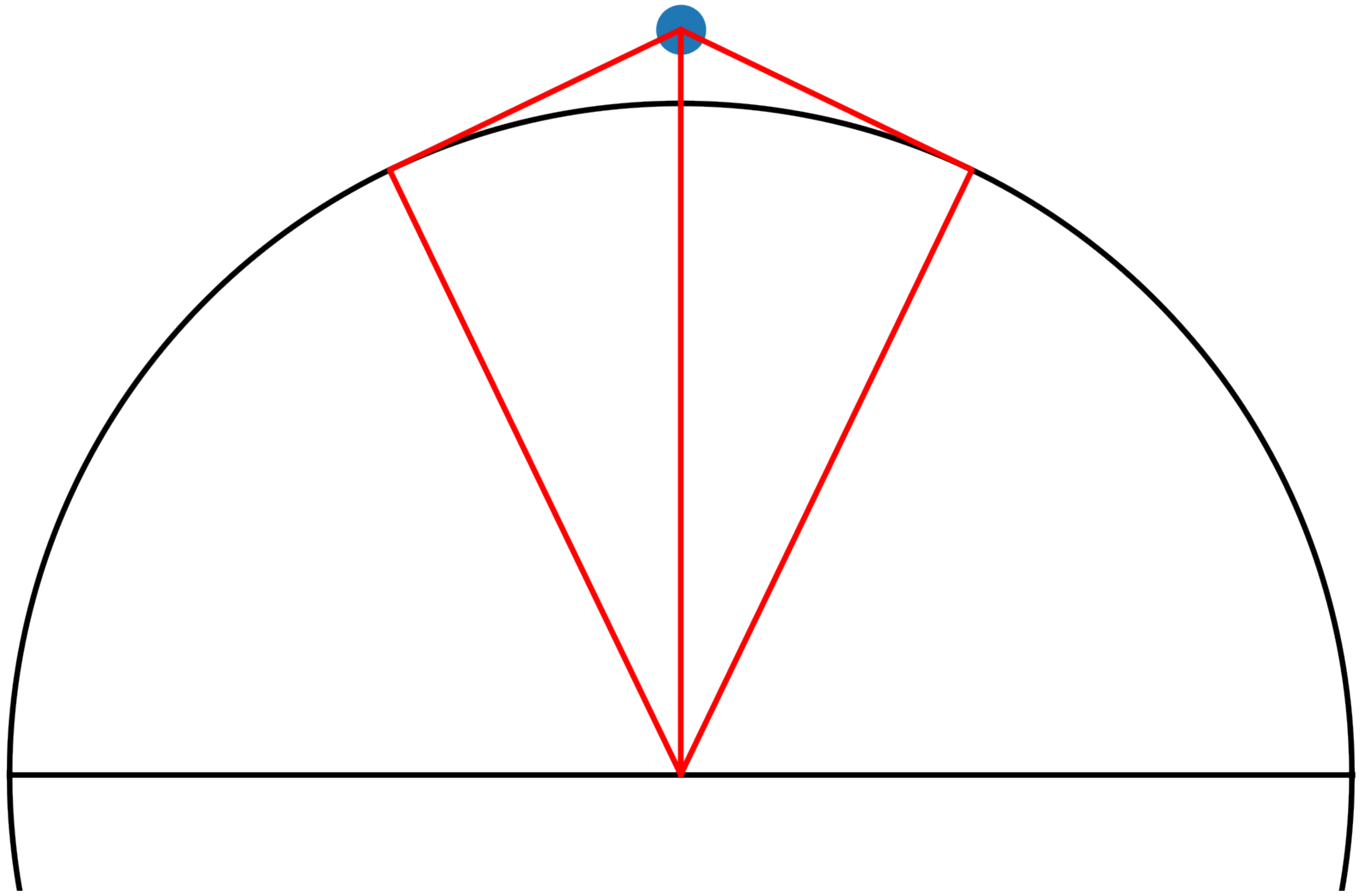

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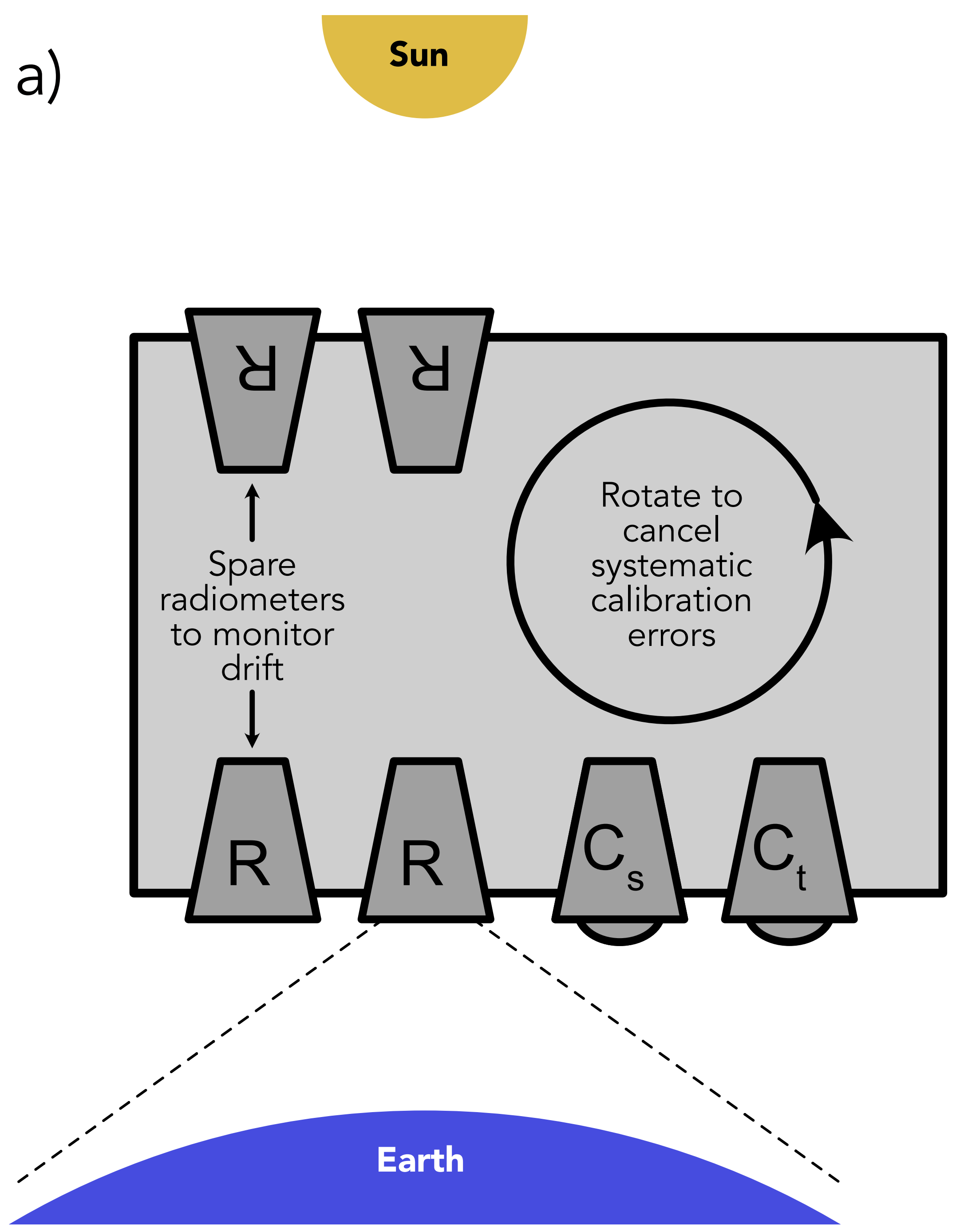
The Earth Climate Observatory (ECO) mission

- Consist of polar orbiting satellites
- Observe incoming and outgoing radiation with identical instruments
- Rotate to cancel systematic calibration errors
- Spare instruments to monitor slow drift
- Wide angle cameras (solar/terrestrial) for separation, scene identification, ADM development, mapping
- Constellation to improve sampling, possibly combining precessing and sun-synchronous orbits

a)



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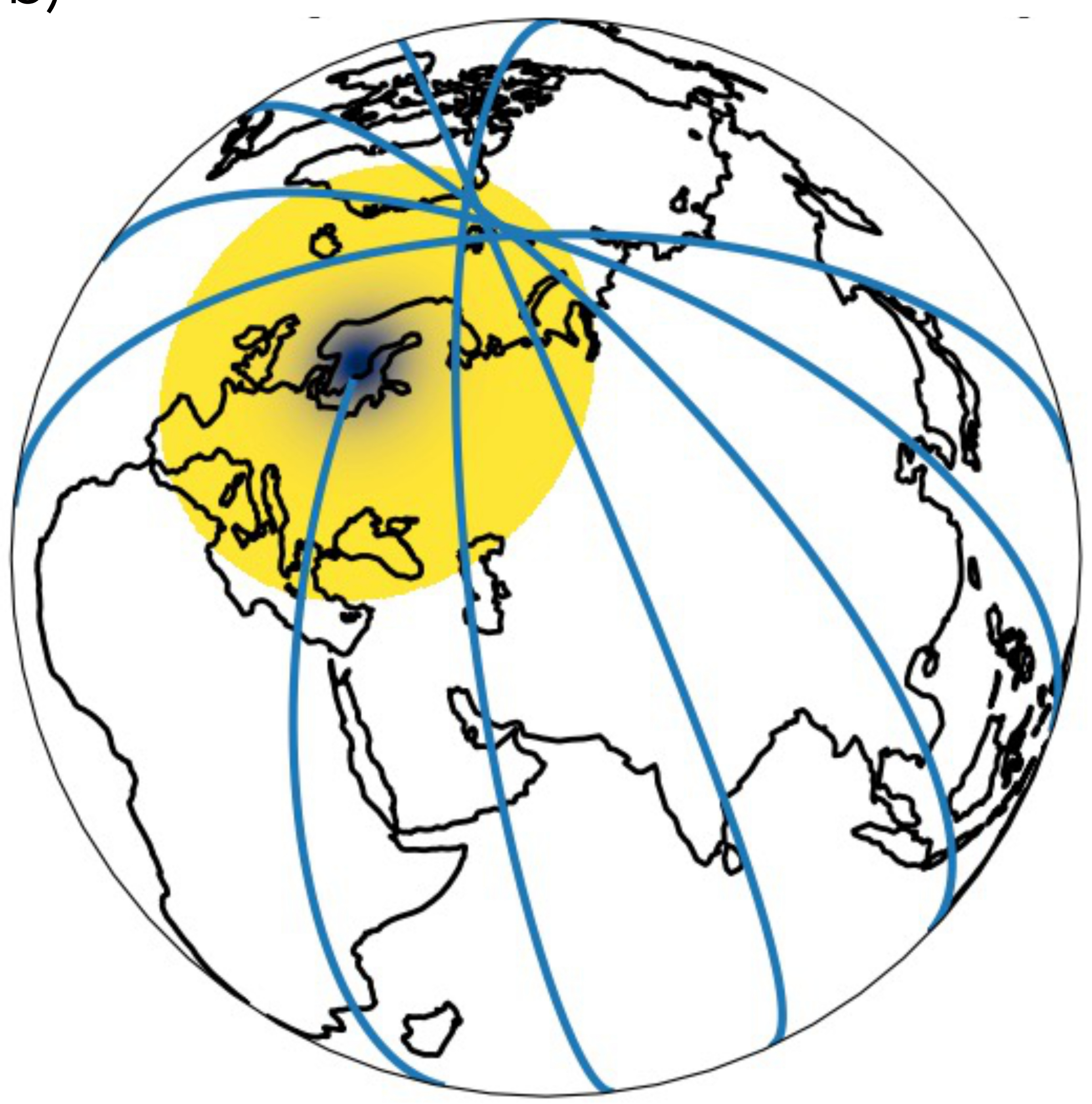

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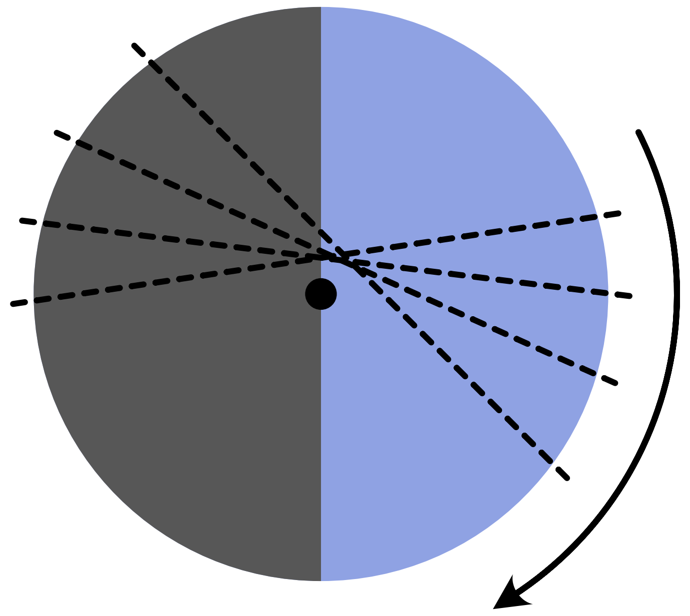
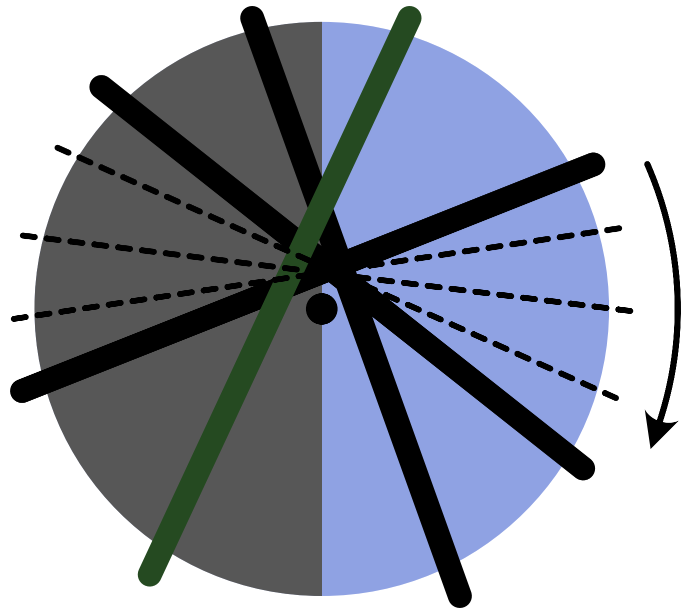


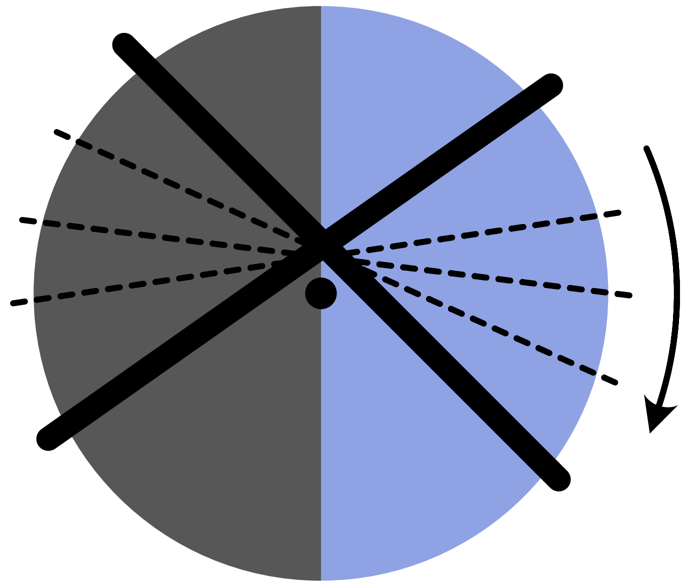
1- 2 satellites in precessing orbits:

- Good sampling of diurnal cycle on annual time scale
- Only annual means
- Single point of failure
- Mapping difficult



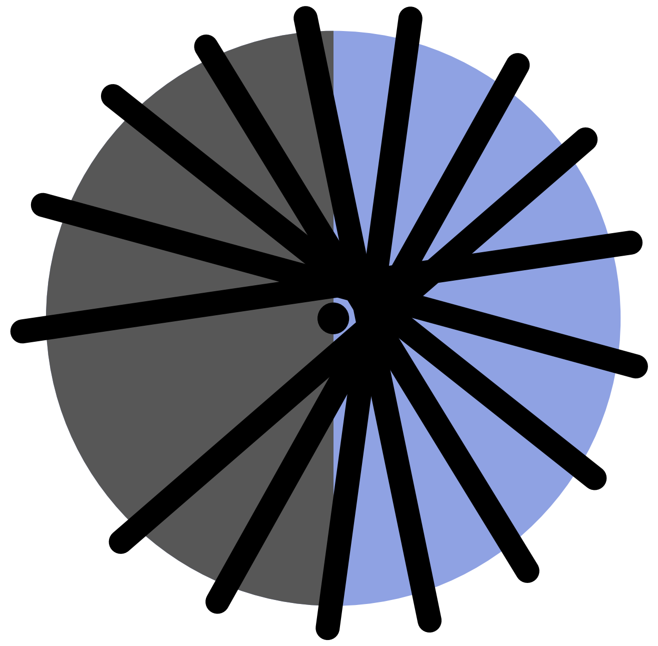
3-4 sun-synchronous + 1-2 precessing:

- Excellent sampling of diurnal cycle on annual time scale
- Cloud feedback monitoring
- Insensitive to failure



2 sun-synchronous + 1-2 precessing:

- Good sampling of diurnal cycle on annual time scale
- Monthly means + mapping possible
- Intercalibration
- Sensitive to failure



8, or more, sun-synchronous:

- Excellent sampling of diurnal cycle on daily time scale
- Footprints overlap, also in tropics
- Excellent mapping
- Robust to failure

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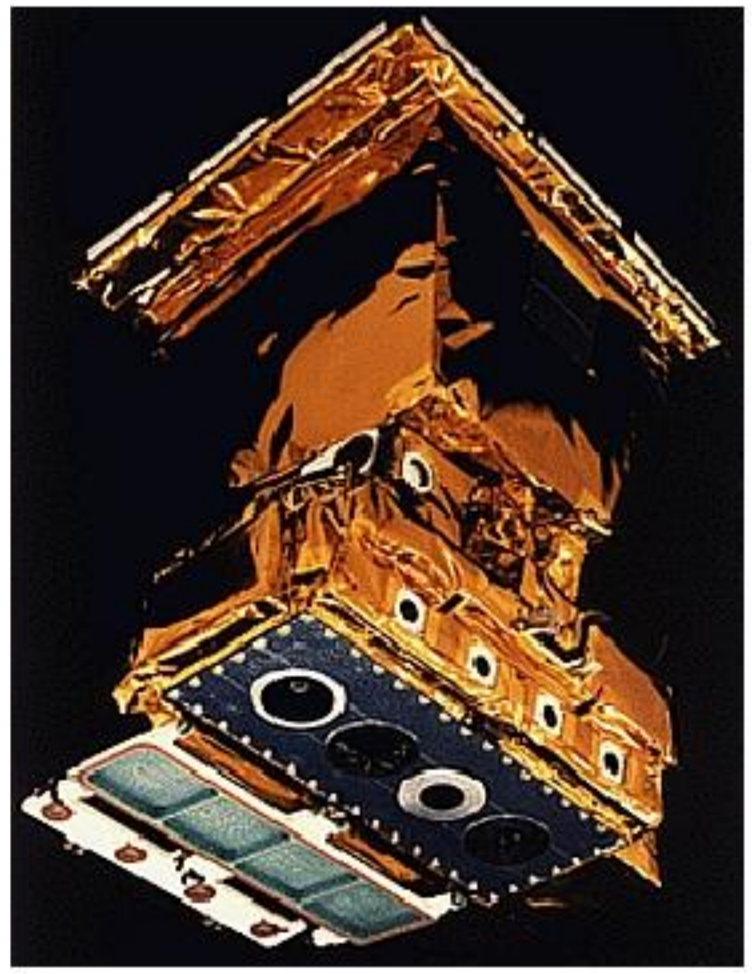
Summary of errors

ERBE non-scanner (from Wong et al. 2018):

Sources of uncertainty	Longwave	Shortwave
Instrument stability (drift)	± 0.5	± 0.1
Instrument absolute accuracy	± 2.5	± 2.5
Intercalibration (footprint mismatch)	± 1.2	± 1.0
Non-scanner inversion (mapping to TOA level)	$< \pm 1.0$	$< \pm 1.0$
Satellite altitude correction	0.0	0.0
Twilight data	n/a	$> \pm 0.2$



~ 3.0 Wm^{-2} per channel

From SRL-2 draft report

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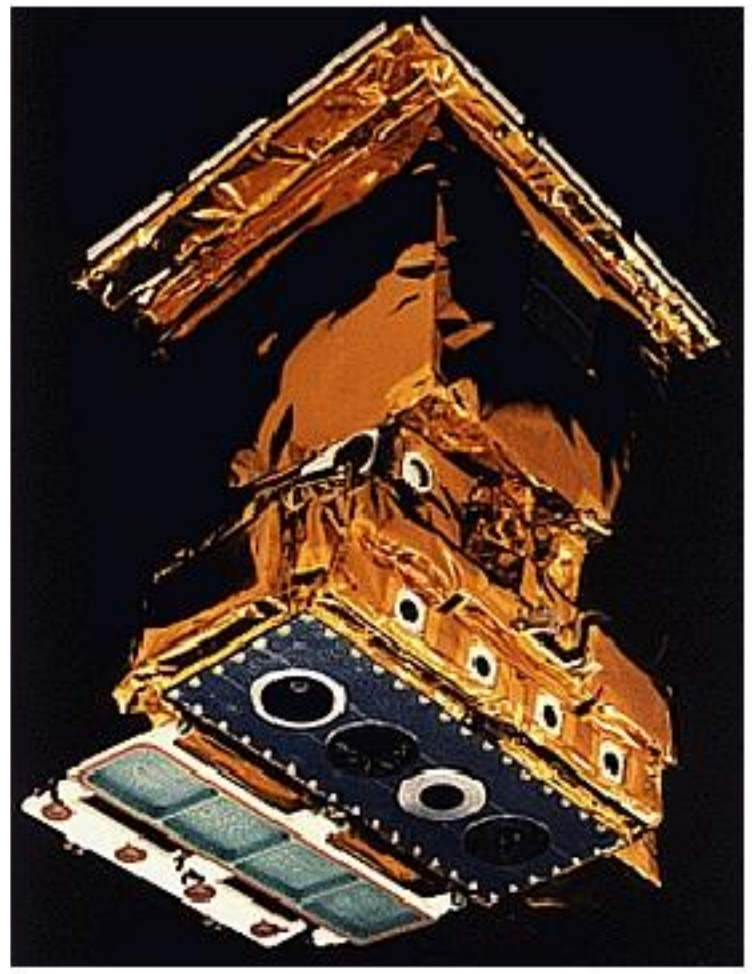
Preliminary ECO mission estimates:

Sources of uncertainty	EEI
Instrument stability (drift per decade)	$\ll \pm 0.1$
Instrument absolute accuracy on difference (preliminary)	$< \pm 0.5$
Intercalibration (footprint mismatch)	n/a
Non-scanner inversion (mapping and reference level)	n/a
Satellite altitude correction	0.0
Twilight data	n/a
Polar regions	?
Diurnal cycle sampling (preliminary estimate)	$\ll \pm 0.3$
Anisotropic correction (literature estimate)	$< \pm 0.1$



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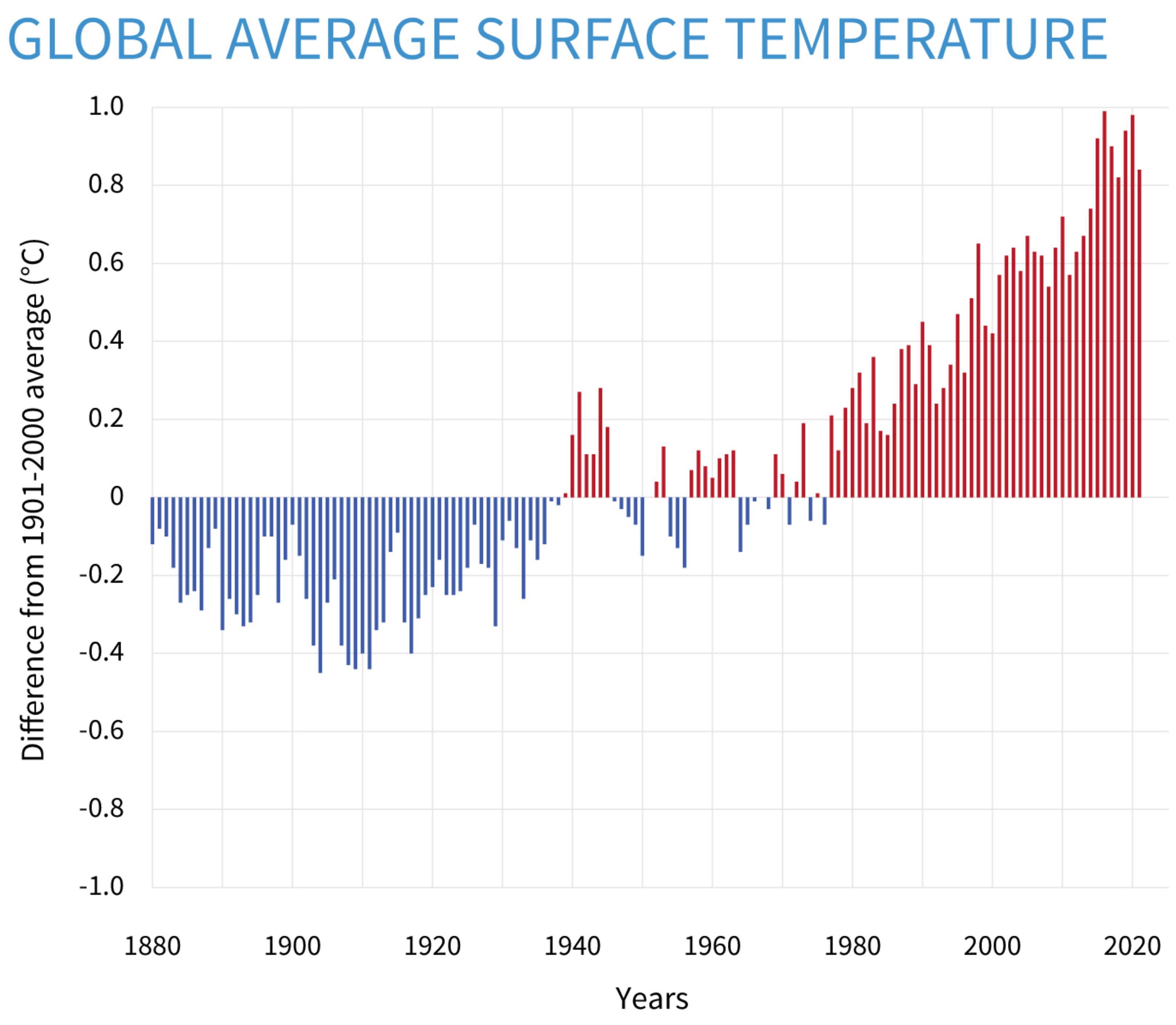
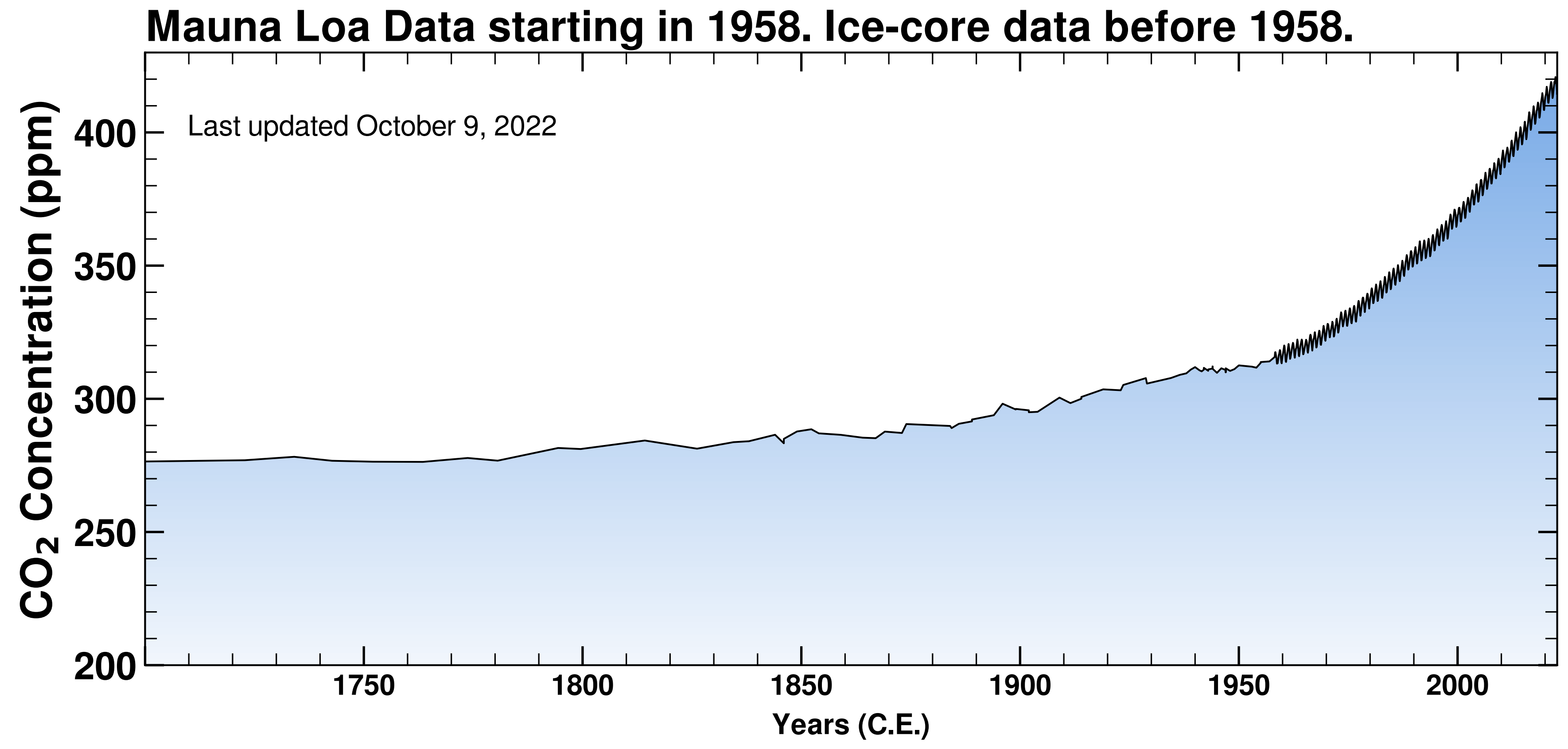
Long term monitoring strategy

ECO mission nominal life time is relatively short (5-10 years), but the idea is that it can develop into a long term monitoring mission:

- Instruments are fairly simple, and most of the cost is in development
- Spare instruments can serve to:
  - Evaluate issues on ground
  - Quickly launch satellites in case of failure
  - Piggyback on other missions, synergies
  - Help improve future missions
  - Be shared with other space agencies
- Challenge: long term monitoring is not so cool





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Project status

We are working towards answering an ESA Earth Explorer call next year

Phase F	9	Science Impact Quantified
Phase E2	8	Science Validated and Matured
Phase E1	7	Science Demonstrated
Phase B, C, D	6	Mission Concept Validated
Phase A/B	5	Mission Performance Assessed
Phase 0	4	Feasibility Shown
Development Phase	3	Requirements Drafted
Development Phase	2	Scientific Idea Consolidated
Development Phase	1	Initial Scientific Idea Formulated

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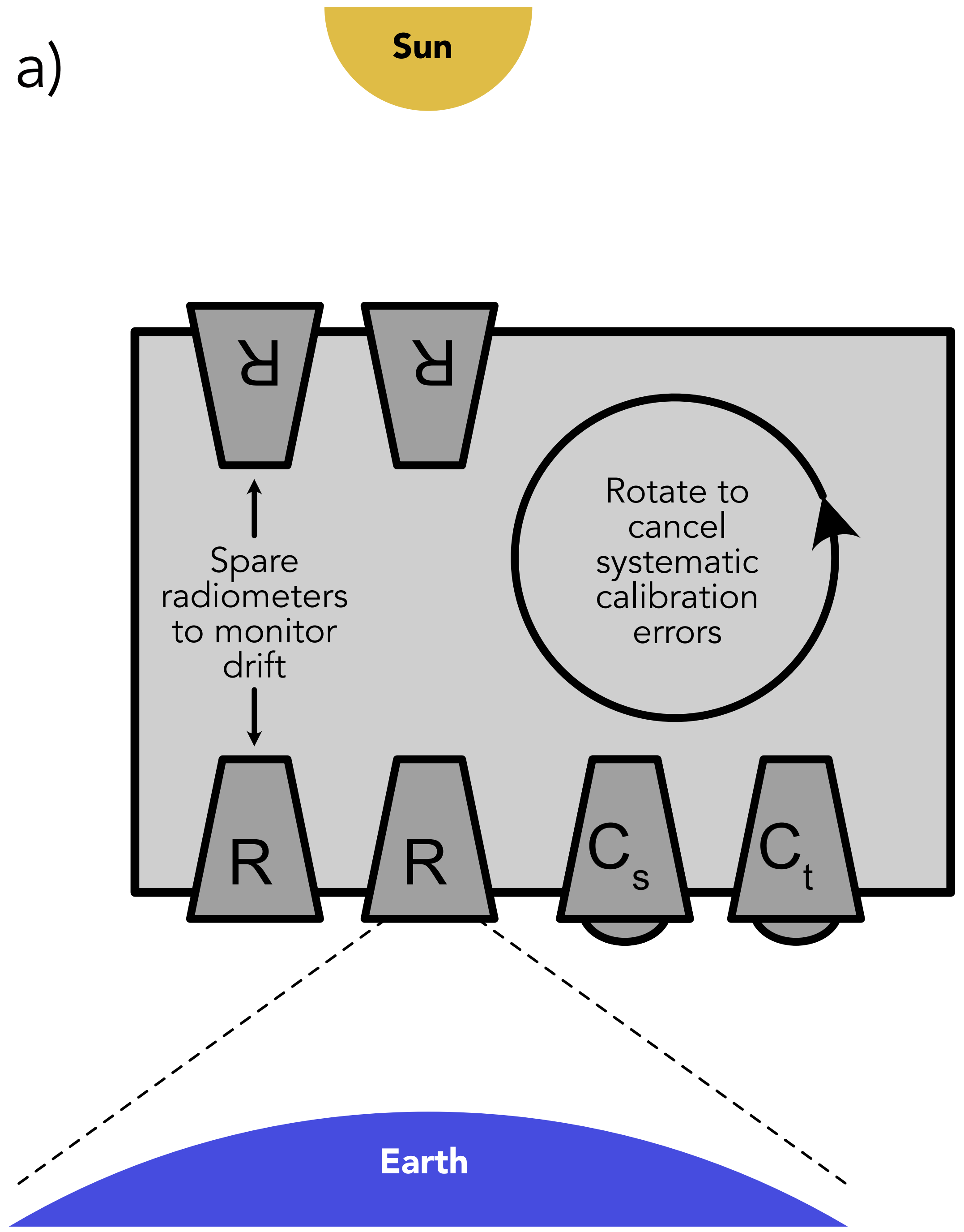
Summary ECO mission

- We aim to provide accurate and robust long term monitoring of Earth's **global mean radiation imbalance**
- Concept based on wide field of view radiometers using differential technique plus two cameras (Steven's talk)
- Use of multiple identical instruments to reduce errors from calibration and drift
- Complementary, to more resolution-focussed "big" missions (spatial, temporal, spectral)
- [long list of things it cannot do]
- A 'gap' filler?

a)



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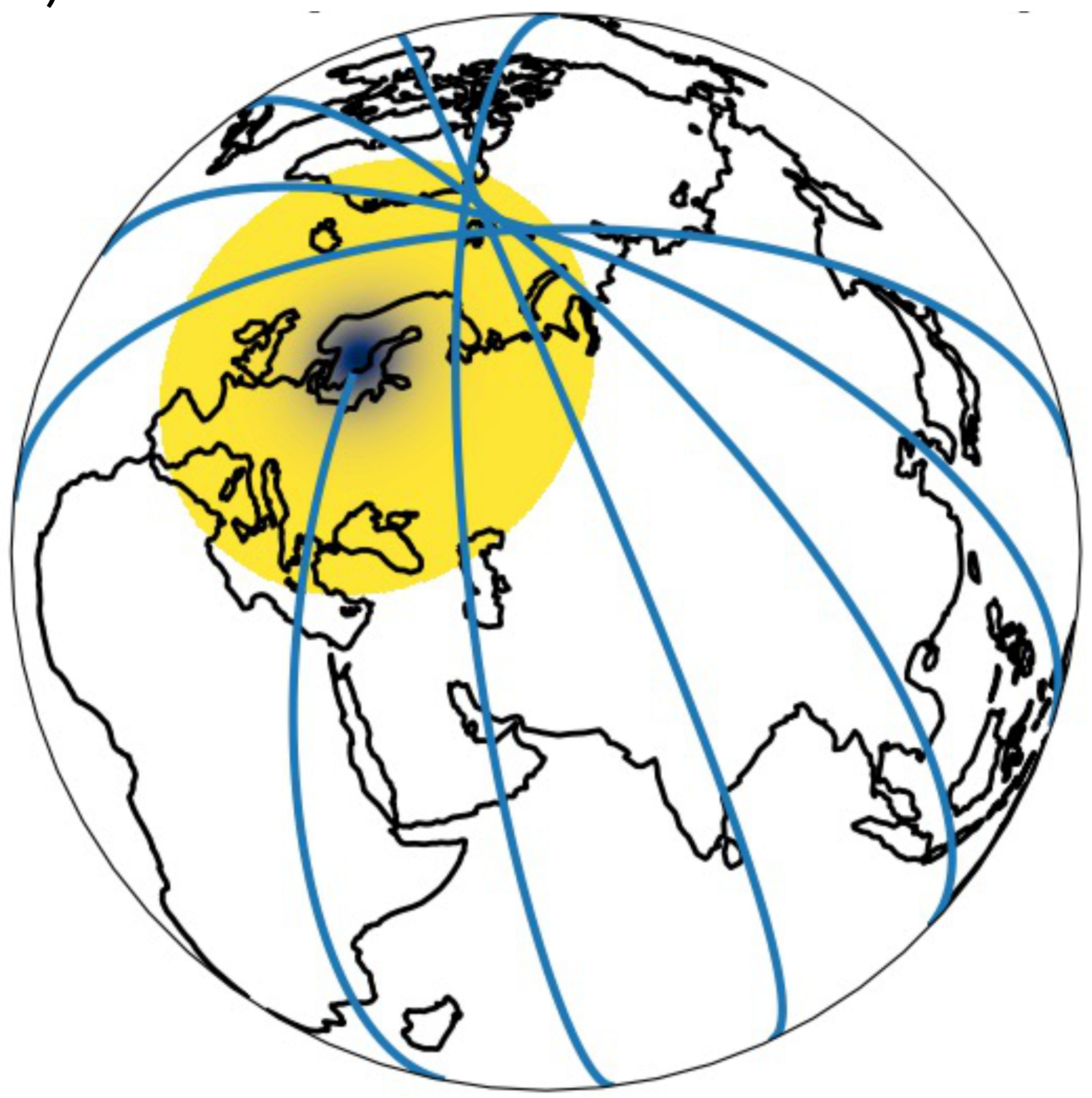

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Extra slides

Anisotropic effects

Wide field of view radiometer measures actual flux at satellite position

However, systematic biases in viewing- and solar zenith angles may introduce biases:

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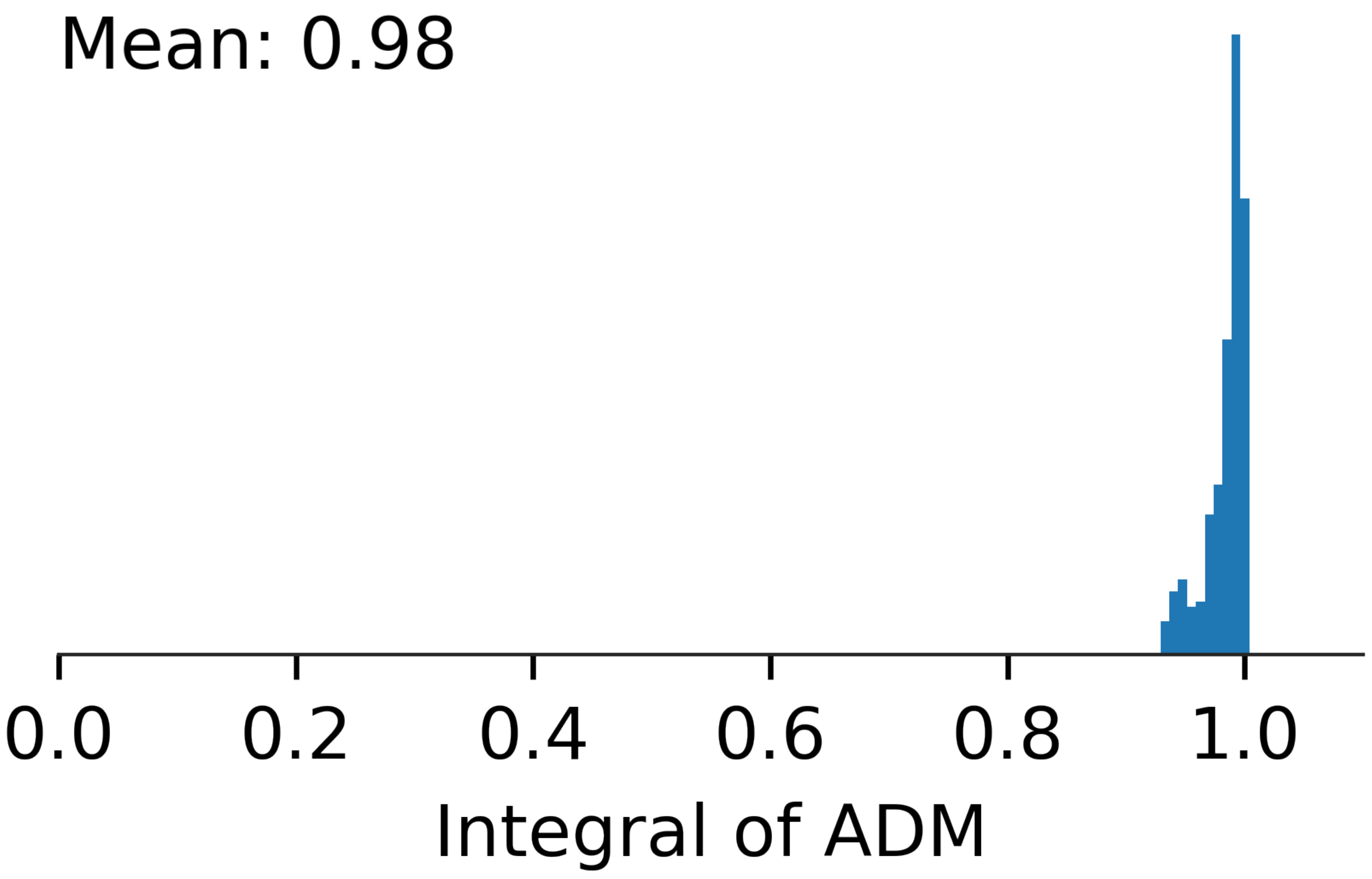
- Explored effects of anisotropic using TRMM angular dependence model (ADM)
- Found difference when introducing ADM of 1.6 Wm^{-2} compared with isotropic case
- But only 0.1 Wm^{-2} between true and randomised ADMs

$$\pi^{-1} \int_0^{2\pi} d\phi \int_0^{\pi/2} d\theta R(\theta_0, \theta, \phi) \cos\theta \sin\theta = 1$$



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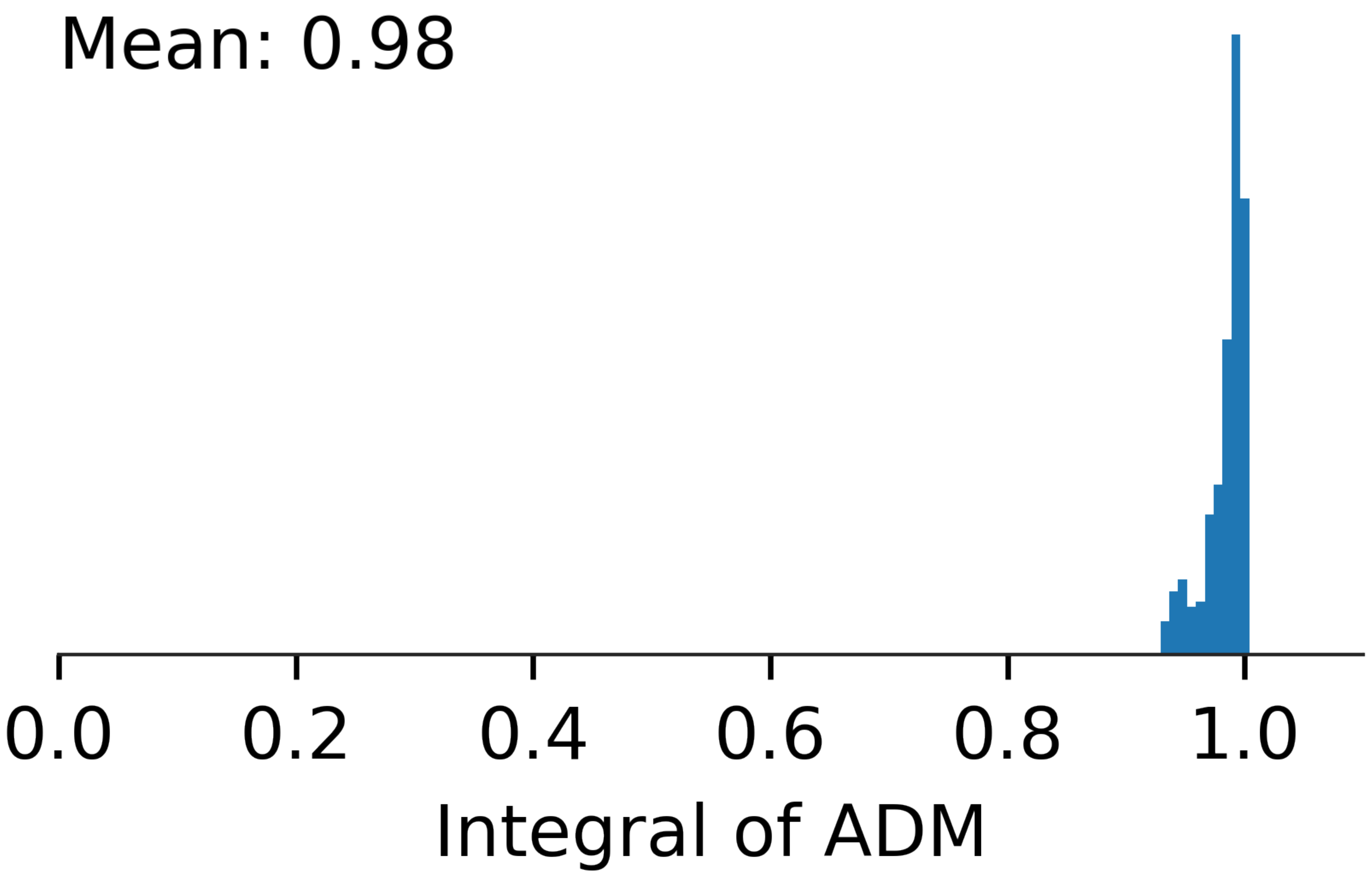
Anisotropic effects

$$\pi^{-1}\int_0^{2\pi} d\phi \int_0^{\pi/2} d\theta R(\theta_0, \theta, \phi) \cos\theta \sin\theta = 1$$

- We currently think the effect is small (~0.1 Wm^{-2})
- In this case we can apply a climatological ADM derived from cameras to correct for this small error
- In the unlikely event the effect is large, a correction using scene dependent ADMs may be needed



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