FIDUCEO has received funding from the European Union's Horizon 2020 Programme for Research and Innovation, under Grant Agreement no. 638822

Evolving the GSICS Approach to Inter-Satellite Calibration

Tim Trent

**Ross Bannister, Tom Block,
Chris Merchant, David Moore,
John Remedios**

Outline

- Brief introduction to FIDUCEO and the aims of WP6.
- Describe the evolution of inter-satellite calibration in relation to GSICS approach and current progress.
- Outline future work.

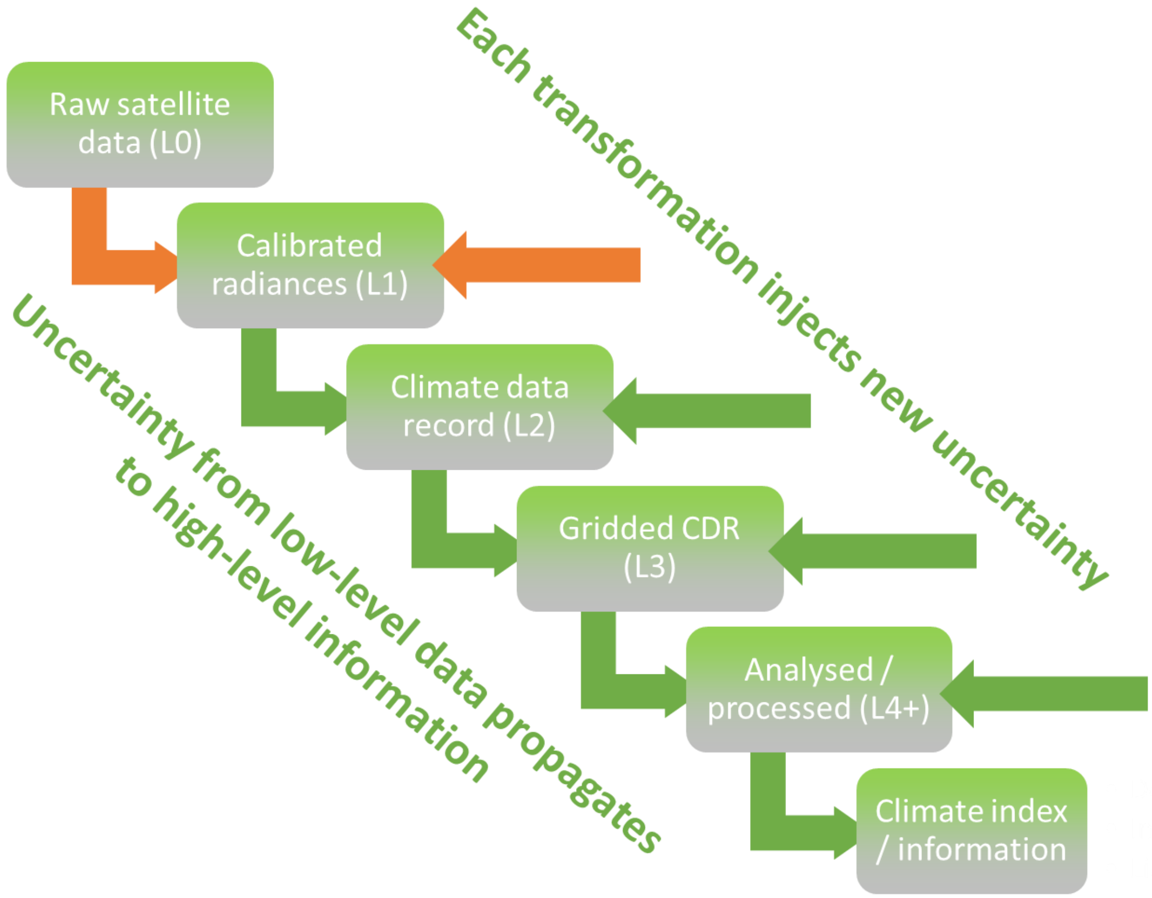
FIDUCEO

- **F**idelity and **U**ncertainty in **C**limate data records from **E**arth **O**bservation.
- **Ambition**: develop a widely applicable metrology framework for Earth observation (EO).
- **Motivation:** establish **defensible**, **uncertainty-quantified** climate data records (CDRs) for climate and environmental change from the satellite record.
- **Limitation of the status quo:** if uncertainty in fundamental climate data records (FCDR) is not characterised it cannot be propagated to the CDR level.

UNIVERSITY OF LEICESTER

Fiduceo

FIDUCEO



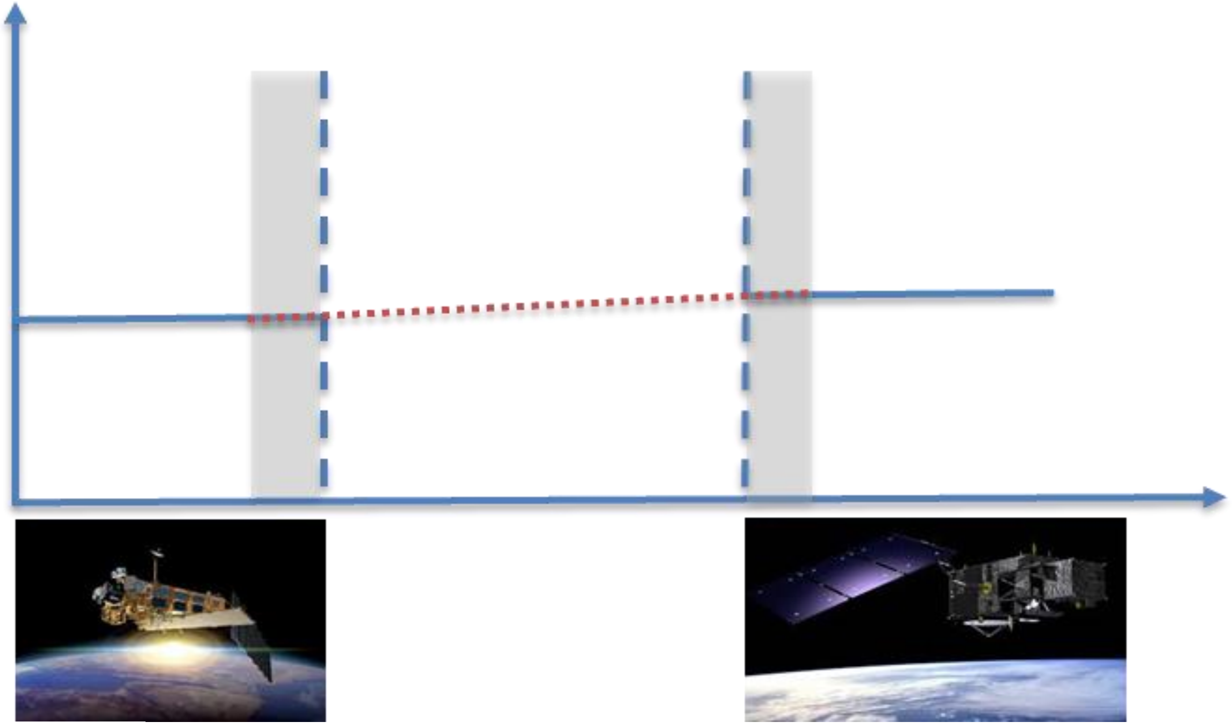
- Further information cn be found at http://www.fiduceo.eu/blogs

UNIVERSITY OF LEICESTER

Fiduceo

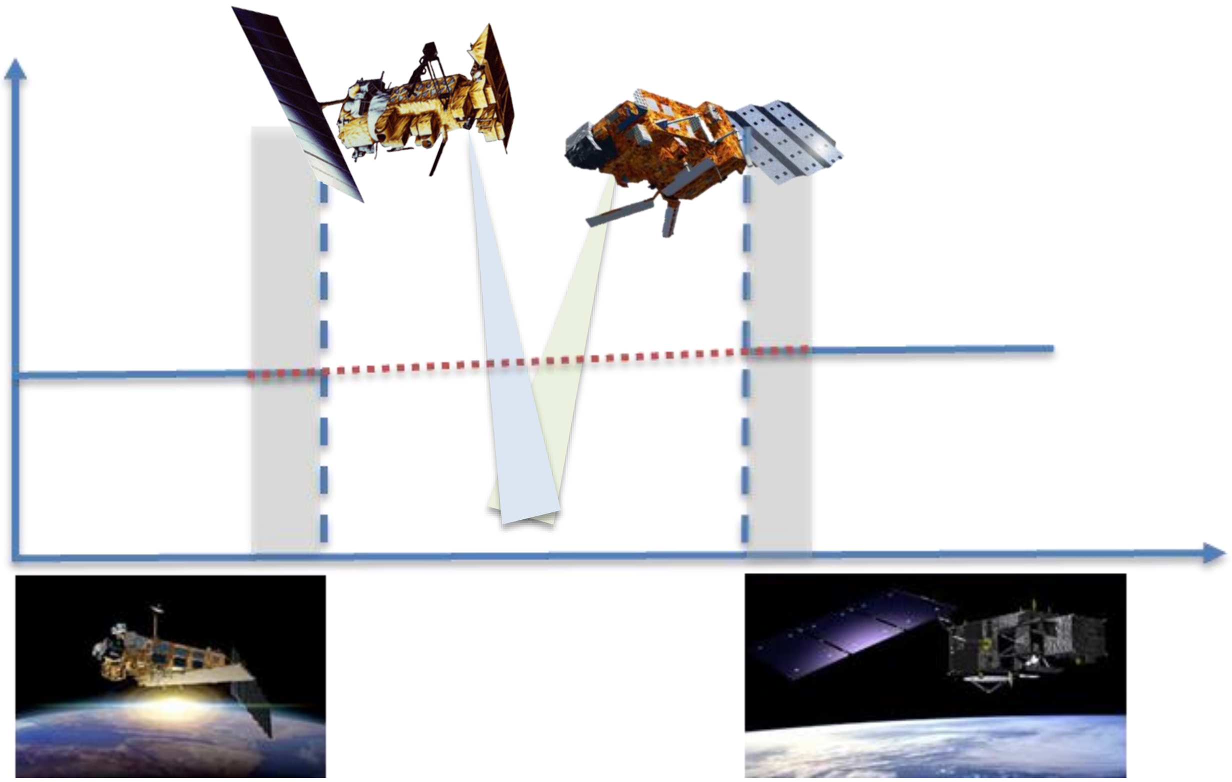
Aims of WP6

- Evaluation of FIDUCEO FCDRs during (A)ATSR-SLSTR gap.
- Goal is to build a generic framework that can handle different intercomparison types: (i) satellite-to-satellite and (ii) satellite-to-in situ



Aims of WP6

- Evaluation of FIDUCEO FCDRs during (A)ATSR-SLSTR gap.
- Goal is to build a generic framework that can handle different intercomparison types: (i) satellite-to-satellite and (ii) satellite-to-in situ

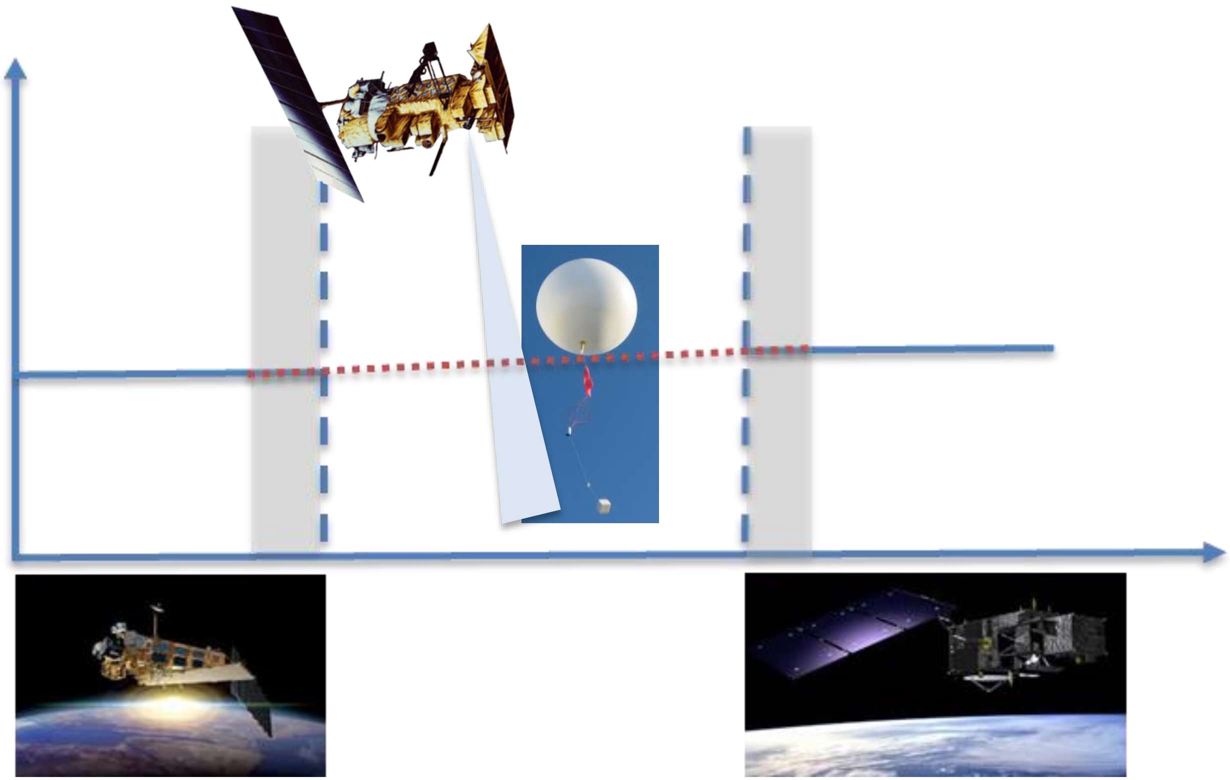


UNIVERSITY OF LEICESTER

FIduceo

Aims of WP6

- Evaluation of FIDUCEO FCDRs during (A)ATSR-SLSTR gap.
- Goal is to build a generic framework that can handle different intercomparison types: (i) satellite-to-satellite and (ii) satellite-to-in situ

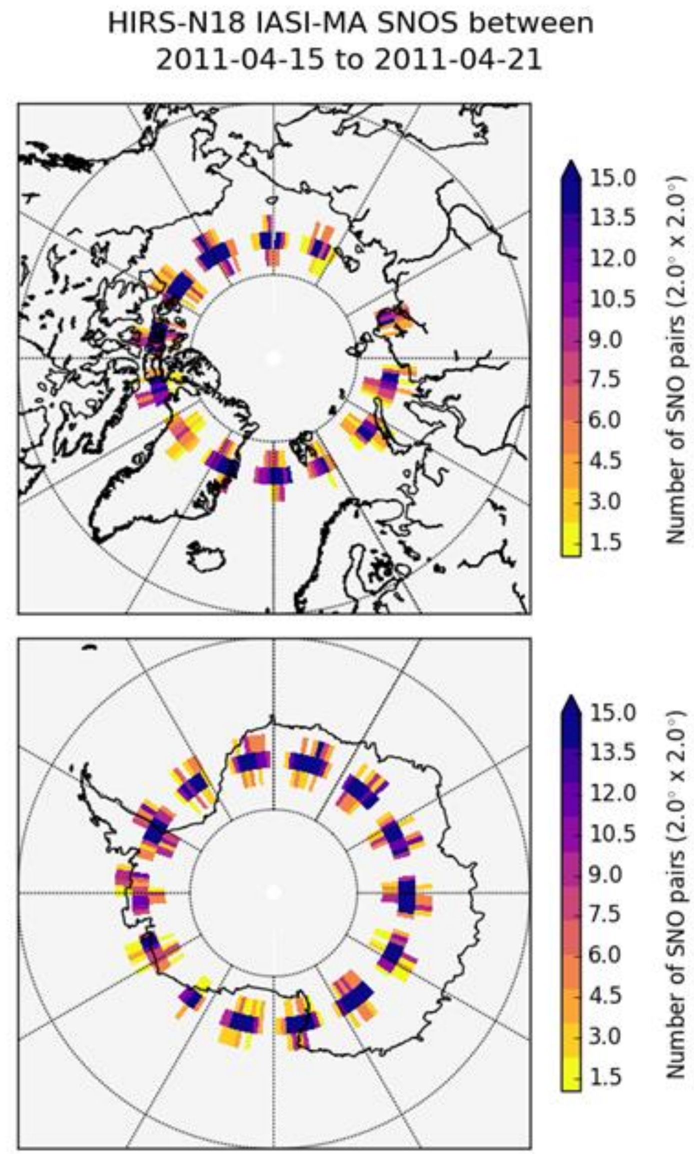


UNIVERSITY OF LEICESTER

Fiduceo

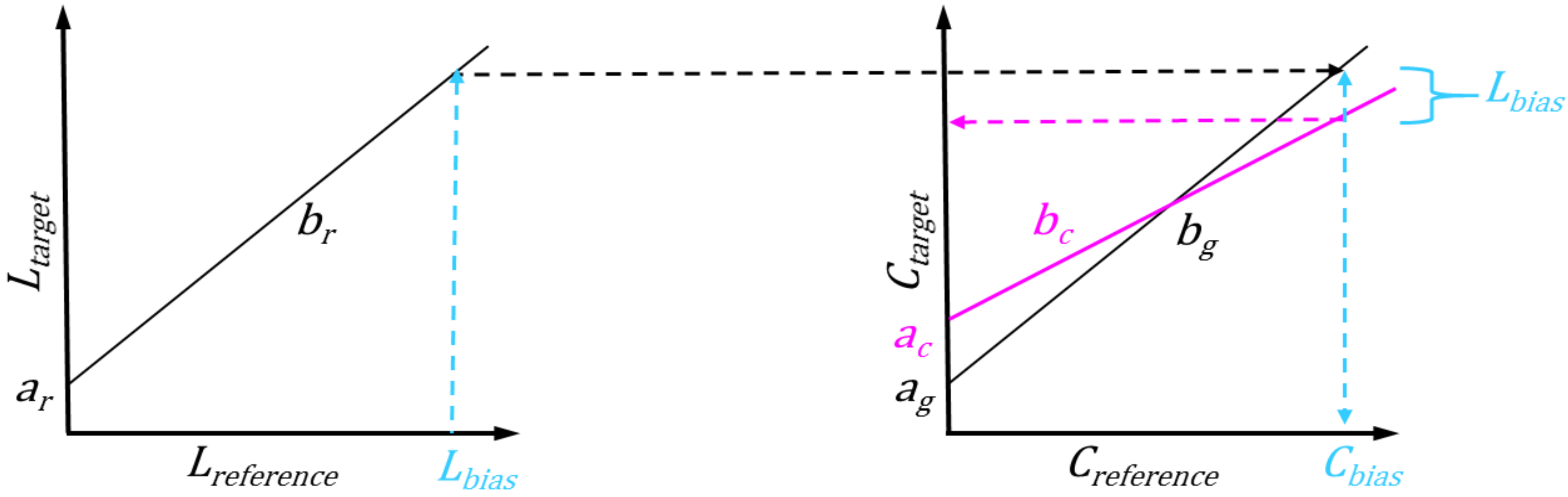
Simultaneous Nadir Overpasses

- Collocation in space and time between to satellite instruments using a tight set of criteria
- Due to time criteria most SNOs occur at the poles.
- SNOs collect in clusters (x,y,t)
  - basis for processing multiple years/platforms
  - can use same definition for radiosonde comparisons.
- The idea is to use a reference standard satellite observation (e.g. IASI) to calibrate a target instrument (e.g. HIRS).



UNIVERSITY OF LEICESTER

GSICS Inter-Calibration Method



- Adaptation of figure 17 from ATBD showing the relationship between radiances observed by the target instrument (L_{target}) and those observed by reference instrument ($L_{reference}$). The left hand plot shows how the difference between the operation target radiance and corrected radiance (L_{bias}) is related to the newly calculated calibration coefficients (a_g, b_g) that are applied to the target instrument digital counts (C_{target}).

UNIVERSITY OF LEICESTER

Fiduceo

GSICS Inter-Calibration Method

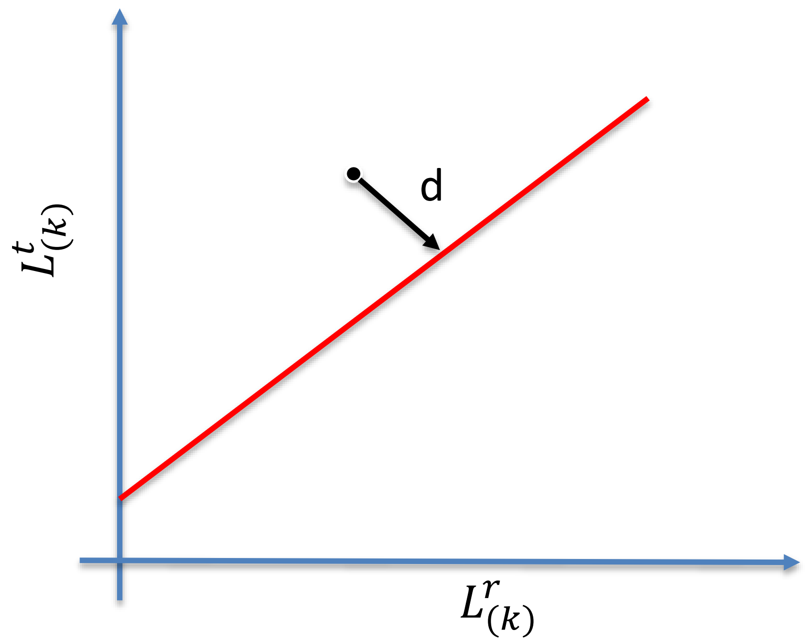
- The GSICS inter-calibration process (Hewison et al, 2013a) uses thousands of SNO pairs from a 14 day window in order to allow comparison of the target and reference instruments via ordinary linear regression (OLS):
  - $L_{target} = a_r + b_r L_{reference}$
- Where a_r and b_r are the correction coefficients and L_{target} is the target instrument radiance. The target radiance is then converted to a consistent reference radiance ($\hat{L}_{target}$) by inverting the linear relationship in equation 1
  - $\hat{L}_{target} = \left(\frac{1}{b_r}\right) L_{target} - \left(\frac{a_r}{b_r}\right)$

GSICS Inter-Calibration Method

- The operational radiance of the target instrument is calculated from the digital counts (C_{target}):
  - $L_{target} = a_c + b_c C_{target}$
- Where a_c and b_c are the operational offset and slope calibration coefficients respectively (EUMETSAT, 2016). The corrected GSICS radiance can then be calculated directly from the raw counts through the substitution of equation 3 into 2:
  - $\hat{L}_{target} = \left(\frac{a_c - a_r}{b_r}\right) + \left(\frac{b_c}{b_r}\right) C_{target}$
- The terms $\left(\frac{a_c - a_r}{b_r}\right)$ and $\left(\frac{b_c}{b_r}\right)$ are also referred to as a_g and b_g respectively.

Evolution of the Inter-Calibration Method

- Current approach assumes no uncertainty in either measurement **or** account of the uncertainty in the collocation.
- Need a system that can account for heterogeneity and measurement uncertainties and their correlations.
- 1st we need to repose the problem so we consider uncertainties in both observations.
  - *"What is the distance between a measurement pair* $\left(L^r_{i(k)}, L^t_{i(k)}\right)$ *and the straight line* $L^t_{(k)} = a^r_{(k)} + b^r_{(k)} L^r_{(k)}$ *where the distance is specified in multiples of the error standard deviations of each measurement?"*



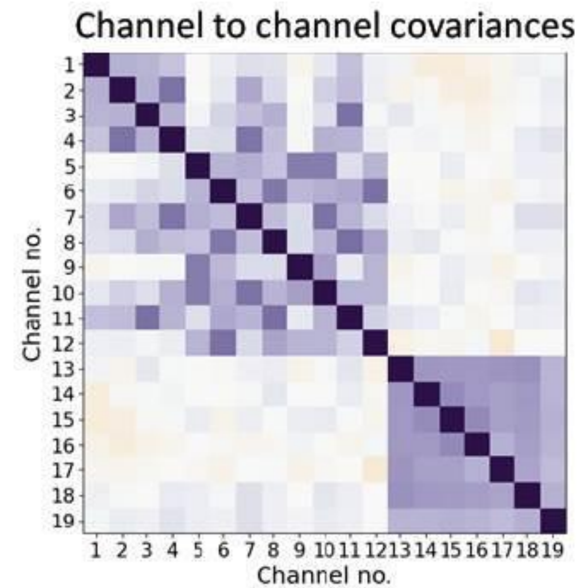
UNIVERSITY OF LEICESTER

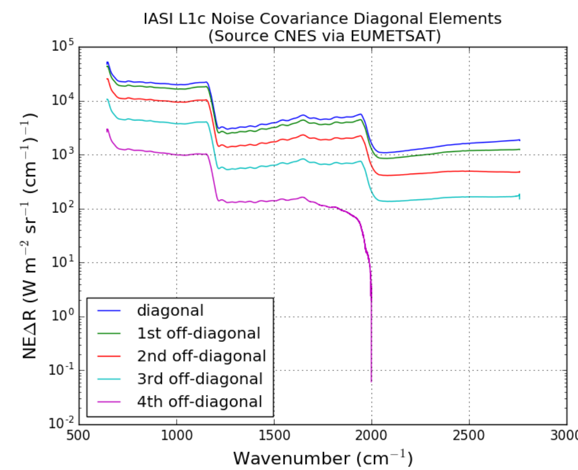
FIduceo

Evolution of the Inter-Calibration Method

- As FCDR products provide detailed covariance’s which account for correlations between channels
  - we need to solve for all channels (k) at once (observational packet = 1 spectra).

- For each MMS file there will be m observational packets (i = obs. packet index).





UNIVERSITY OF LEICESTER

FIDUCEO

Evolution of the Inter-Calibration Method

- Therefore we can define the following objects:

  (i) l^r - observation packet for the reference instrument.

  (ii) l^t - observation packet for the target instrument

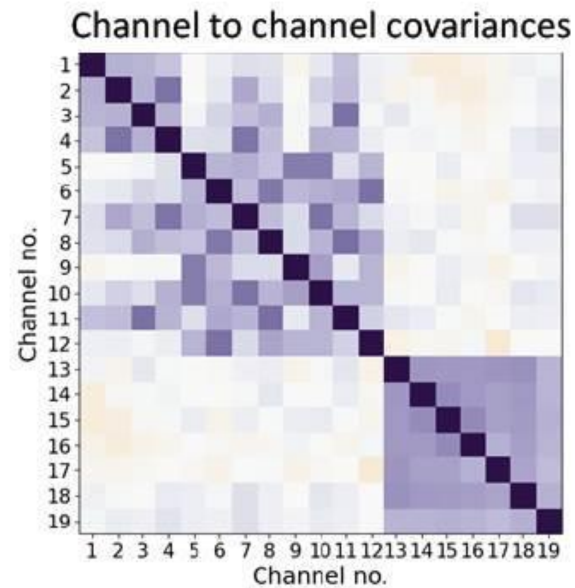
  (iii) a - a k element vector of $a^r_{(k)}$ values.

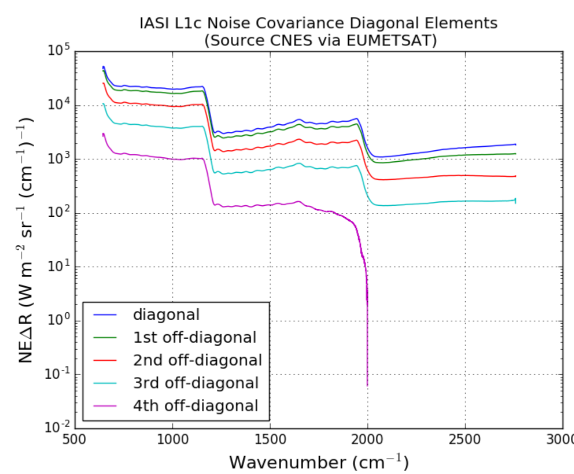
  (iv) $\boldsymbol{B}$ – a k x k matrix whose diagonal values are a vector (b) made up of $b^r_{(k)}$ values.

  (v) $\boldsymbol{R}^r, \boldsymbol{R}^t$ - k x k observation error covarinces

- The regression model relating the 2 obs. packets:

  $$- \; l^t = a + \boldsymbol{B} l^r$$



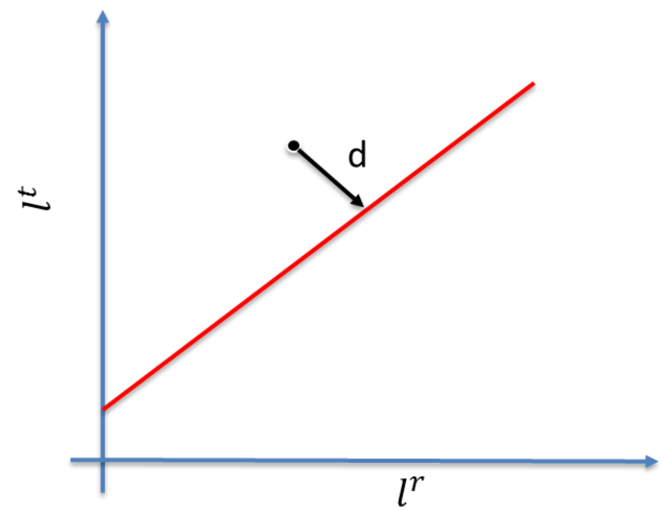


UNIVERSITY OF LEICESTER

FIduceo

Evolution of the Inter-Calibration Method

- Scaled distance:
  - $d_{i(k)}^2 = (l^r - l_i^r)^T \boldsymbol{R}^{r^{-1}} (l^r - l_i^r) + \frac{1}{2}\left(l^t - l_i^t\right)^T \boldsymbol{R}^{t^{-1}} \left(l^t - l_i^t\right)$
- Substituting in for l^t (eq. 8):
  - $d_{i(k)}^2 = (l^r - l_i^r)^T \boldsymbol{R}^{r^{-1}} (l^r - l_i^r) + \frac{1}{2}\left(a + \boldsymbol{B} l^r - l_i^t\right)^T \boldsymbol{R}^{t^{-1}} \left(a + \boldsymbol{B} l^r - l_i^t\right)$
- By making this stationary we can then find the value of l^r that minimises the distance:
  - $\nabla_{l^r} d_i^2 = \boldsymbol{R}^{r^{-1}} (l^r - l_i^r) + \boldsymbol{B}\boldsymbol{R}^{t^{-1}} \left(a + \boldsymbol{B} l^r - l_i^t\right) = 0$
- This happens when:
  - $l^r = \left(\boldsymbol{R}^{r^{-1}} + \boldsymbol{B}\boldsymbol{R}^{t^{-1}}\boldsymbol{B}\right)^{-1} \left[\boldsymbol{R}^{r^{-1}} l_i^r + \boldsymbol{B}\boldsymbol{R}^{t^{-1}} \left(a - l_i^t\right)\right]$



Evolution of the Inter-Calibration Method

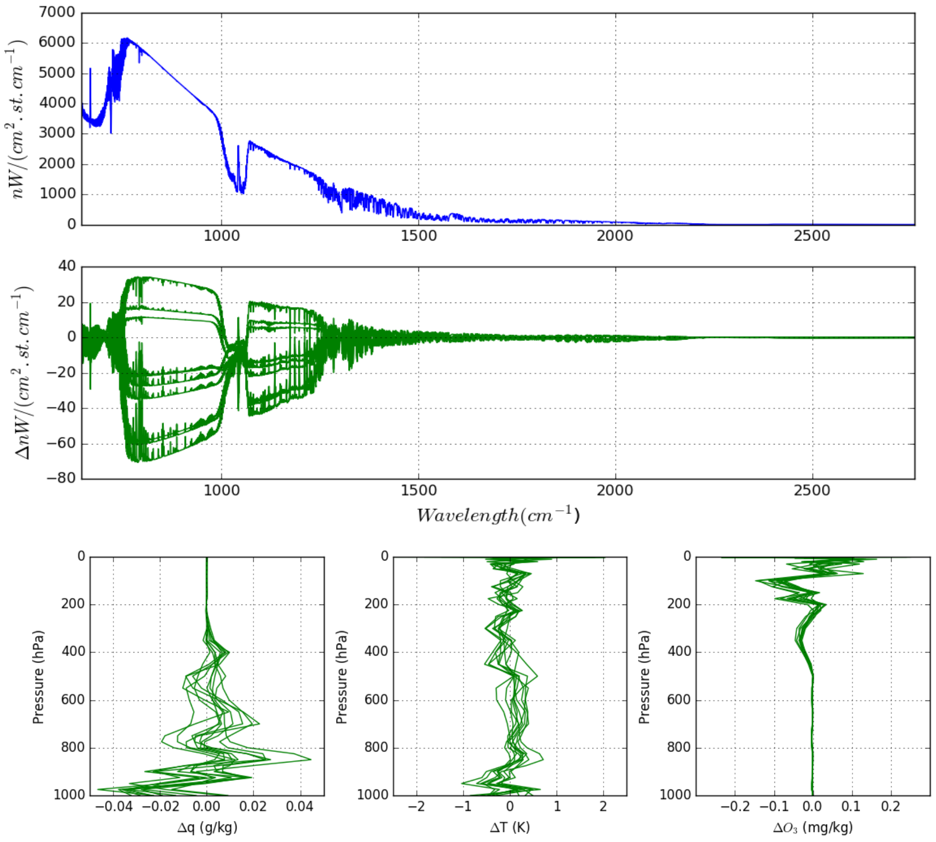
- After substitution and factorisation the cost function which a and b minimises is expressed as:
  - $J[a,b] = \frac{1}{2}\sum_i d_i^2 = \frac{1}{2}\sum_{i=0}^{m}\left[l_i^t - a - \boldsymbol{B} l_i^r\right]^T (\boldsymbol{R}^t + \boldsymbol{B}\boldsymbol{R}^r\boldsymbol{B})^{-1}\left[l_i^t - a - \boldsymbol{B} l_i^r\right]$
- Still some issues to consider …

UNIVERSITY OF LEICESTER

FIduceo

Evolution of the Inter-Calibration Method

- Approach still needs allow for non-coincidental scenes.
- Therefore we apply the following assumptions:
  1. Clear skies (for now)
  2. Access to additional information about the scene from (a) accurate model geophysical variables, and (b) a RTM capable of simulating both instruments.
  3. Both instruments share the same RTM

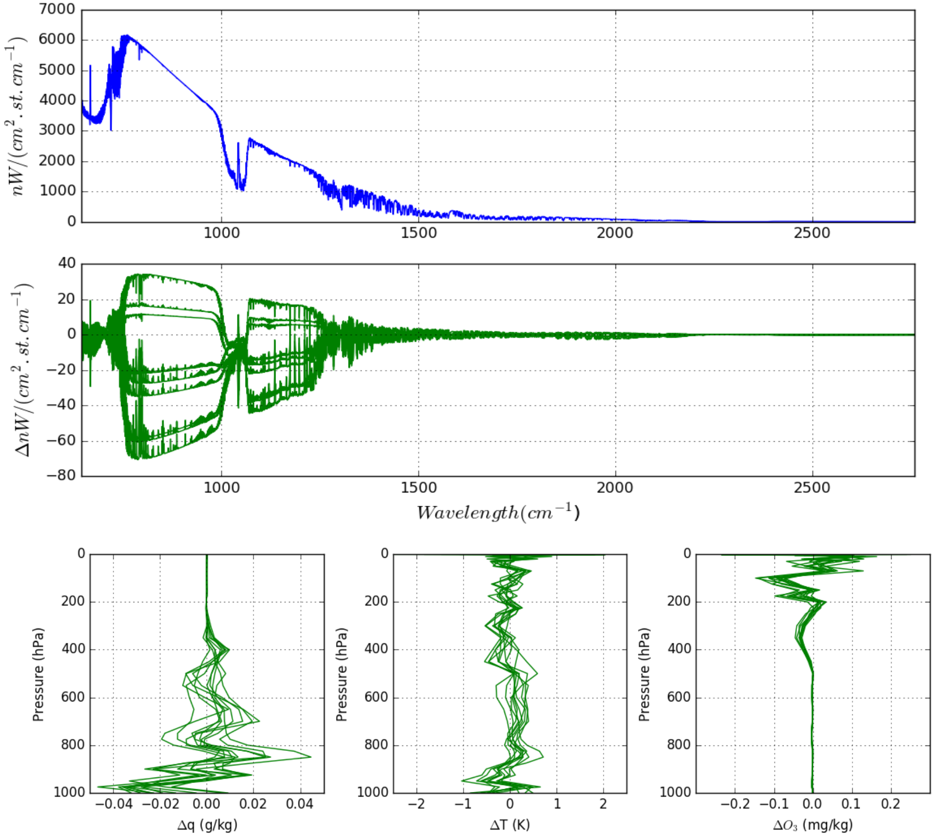


UNIVERSITY OF LEICESTER

FIduceo

Evolution of the Inter-Calibration Method

- **Assumption 1**: Employ the IASI L1c cloud flag
- **Assumption 2**: ERA 5 analysis + 10 member ensemble fields
- **Assumption 3**: Reference Forward Model (RFM), line-by-line RTM, can vary all inputs including spectroscopy, emissivity, atmospheric state vector and cloud properties



UNIVERSITY OF LEICESTER

FIduceo

Evolution of the Inter-Calibration Method

- Using these assumptions we can continue to adapt the method to account for non-coincidence.
- Expand the list of defined variables to include terms base don new assumptions.
- Define a set of relationships that link them.

Variable	Description	Variable	Description
x^r	Atmospheric state vector for the reference instrument	x^t	Atmospheric state vector for the target instrument
δx^r	Uncertainty on the reference instrument state vector	δx^t	Uncertainty on the target instrument state vector
θ^r	Viewing angle of the reference instrument	θ^t	Viewing angle of the target instrument
x^r_{true}	True version of x^r	x^t_{true}	True version of x^t
l^r	Observation packet from the reference instrument	l^t	Observation packet from the target instrument
δl^r	Uncertainty on reference observational packet	δl^t	Uncertainty on target observational packet
l^r_{true}	Noise-free observation packet that a perfect reference instrument would observe	l^t_{true}	Noise-free observation packet that a perfect target instrument would observe
$h(x,\theta)$	The RTM output	ϵ^h	Uncertainty of RTM output
δx^{rt}	Difference in reference and target state vectors	$\delta\theta^{rt}$	Difference in viewing angles of reference and target instruments.

UNIVERSITY OF LEICESTER

FIduceo

Evolution of the Inter-Calibration Method

- We want to regress l^t to something close to l_{true}^t
- Using the defined relationships we can develop an expression for l_{true}^t
  - $l_{true}^t = h(x_{true}^t, \theta^t) - \epsilon_2^h$
  - $l_{true}^t = l^r - \delta l^r + \epsilon_1^h + \boldsymbol{H}_{x^r,\theta^r}\delta x^r + \boldsymbol{H}_{x^r,\theta^r}\delta x^{rt} + \boldsymbol{H}_{\theta^r,x^r}\delta\theta^{rt} - \boldsymbol{H}_{x^t,\theta^t}\delta x^t - \epsilon_2^h$
- This allows us to relate the l^r to the l_{true}^t, rearranging allows us to collect the terms:

$$\mathrm{l}_{\mathrm{true}}^{\mathrm{t}} = \underbrace{\mathrm{l}^{\mathrm{r}} + \mathbf{H}_{\mathbf{x}^{\mathrm{r}},\theta^{\mathrm{r}}}\delta\mathbf{x}^{\mathrm{rt}} + \mathbf{H}_{\theta^{\mathrm{r}},\mathbf{x}^{\mathrm{r}}}\delta\theta^{\mathrm{rt}}}_{\boxed{\text{known/calculable}}} + \underbrace{-\delta\mathrm{l}^{\mathrm{r}} + \mathbf{H}_{\mathbf{x}^{\mathrm{r}},\theta^{\mathrm{r}}}\delta\mathbf{x}^{\mathrm{r}} - \mathbf{H}_{\mathbf{x}^{\mathrm{t}},\theta^{\mathrm{t}}}\delta\mathbf{x}^{\mathrm{t}}}_{\boxed{\text{statistics known}}} + \underbrace{\epsilon_1^{\mathrm{h}} - \epsilon_2^{\mathrm{h}}}_{?}$$

Reference measurement (l_i^r)

Reference Error covariance ($\boldsymbol{R}^r$)

UNIVERSITY OF LEICESTER

FIduceo

Evolution of the Inter-Calibration Method

$$\left\langle \delta \mathbf{l}^{\mathrm{r}} \delta \mathbf{l}^{\mathrm{r}\,\mathrm{T}} \right\rangle$$

$$J[\mathbf{a},\mathbf{b}] = \frac{1}{2}\sum_i d_i^2 = \frac{1}{2}\sum_{i=1}^{m}\left[\mathbf{l}_i^{\mathrm{t}} - \mathbf{a} - \mathbf{B}\mathbf{l}_i^{\mathrm{r}}\right]^{\mathrm{T}}\left(\mathbf{R}^{\mathrm{t}} + \mathbf{B}\mathbf{R}^{\mathrm{r}}\mathbf{B}\right)^{-1}\left[\mathbf{l}_i^{\mathrm{t}} - \mathbf{a} - \mathbf{B}\mathbf{l}_i^{\mathrm{r}}\right]$$

$$\mathbf{l}^{\mathrm{t}}_{\mathrm{true}} = \underbrace{\mathbf{l}^{\mathrm{r}} + \mathbf{H}_{\mathbf{x}^{\mathrm{r}},\theta^{\mathrm{r}}}\delta\mathbf{x}^{\mathrm{rt}} + \mathbf{H}_{\theta^{\mathrm{r}},\mathbf{x}^{\mathrm{r}}}\delta\theta^{\mathrm{rt}}}_{\text{known/calculable}} + \underbrace{-\delta\mathbf{l}^{\mathrm{r}} + \mathbf{H}_{\mathbf{x}^{\mathrm{r}},\theta^{\mathrm{r}}}\delta\mathbf{x}^{\mathrm{r}} - \mathbf{H}_{\mathbf{x}^{\mathrm{t}},\theta^{\mathrm{t}}}\delta\mathbf{x}^{\mathrm{t}}}_{\text{statistics known}} + \underbrace{\epsilon_1^{\mathrm{h}} - \epsilon_2^{\mathrm{h}}}_{?}$$

Reference measurement (l_i^r)

Reference Error covariance ($\boldsymbol{R}^r$)

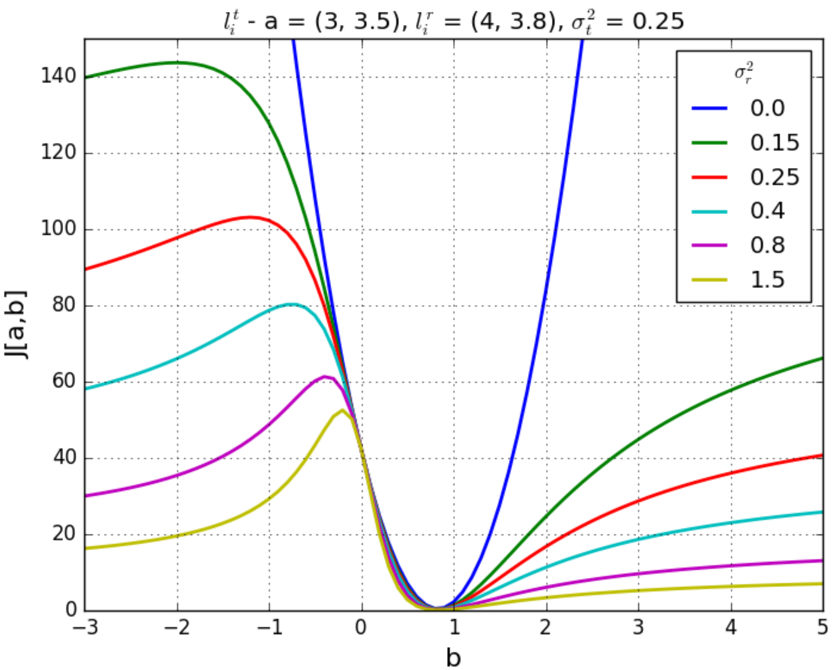
$$\begin{aligned}\mathbf{R}^{\mathrm{r}} &= \left\langle \delta\mathbf{l}^{\mathrm{r}}\delta\mathbf{l}^{\mathrm{r}\,\mathrm{T}}\right\rangle + \left\langle\left(\mathbf{H}_{\mathbf{x}^{\mathrm{r}},\theta^{\mathrm{r}}}\delta\mathbf{x}^{\mathrm{r}}\right)\left(\mathbf{H}_{\mathbf{x}^{\mathrm{r}},\theta^{\mathrm{r}}}\delta\mathbf{x}^{\mathrm{r}}\right)^{\mathrm{T}}\right\rangle + \left\langle\left(\mathbf{H}_{\mathbf{x}^{\mathrm{t}},\theta^{\mathrm{t}}}\delta\mathbf{x}^{\mathrm{t}}\right)\left(\mathbf{H}_{\mathbf{x}^{\mathrm{t}},\theta^{\mathrm{t}}}\delta\mathbf{x}^{\mathrm{t}}\right)^{\mathrm{T}}\right\rangle \\ &+ \left\langle\left(\mathbf{H}_{\mathbf{x}^{\mathrm{r}},\theta^{\mathrm{r}}}\delta\mathbf{x}^{\mathrm{r}}\right)\left(\mathbf{H}_{\mathbf{x}^{\mathrm{t}},\theta^{\mathrm{t}}}\delta\mathbf{x}^{\mathrm{t}}\right)^{\mathrm{T}}\right\rangle + \left\langle\left(\mathbf{H}_{\mathbf{x}^{\mathrm{t}},\theta^{\mathrm{t}}}\delta\mathbf{x}^{\mathrm{t}}\right)\left(\mathbf{H}_{\mathbf{x}^{\mathrm{r}},\theta^{\mathrm{r}}}\delta\mathbf{x}^{\mathrm{r}}\right)^{\mathrm{T}}\right\rangle\end{aligned}$$

Evolution of the Inter-Calibration Method

- Final thing to consider is how to minimise the cost function.

$$\boxed{J[\mathbf{a},\mathbf{b}] = \frac{1}{2}\sum_i d_i^2 = \frac{1}{2}\sum_{i=1}^{m}\left[\mathbf{l}_i^{\mathrm{t}} - \mathbf{a} - \mathbf{B}\mathbf{l}_i^{\mathrm{r}}\right]^{\mathrm{T}}\left(\mathbf{R}^{\mathrm{t}} + \mathbf{B}\mathbf{R}^{\mathrm{r}}\mathbf{B}\right)^{-1}\left[\mathbf{l}_i^{\mathrm{t}} - \mathbf{a} - \mathbf{B}\mathbf{l}_i^{\mathrm{r}}\right]}$$

- The problem is not quadratic. Example: for a case of 2 pairs, single channel and Rr diagonal elements of possible values range from 0-1.5. This results in non-quadratic cost function with a less well-defined minimum, an asymmetric profile around the minimum, and a nearby maximum.
- Currently looking at methods to solve this, potential to use block gradient descent approach.



UNIVERSITY OF LEICESTER

FIDUCEO

Outlook

- Functional pre-processing stage, which includes:
  - Scripts for downloading ERA5 data based on cluster information
  - User defined RTM functionality regarding Emissivity (λ), trace gases and clouds
- Creation of regression tool box
- Initial setup for RFM complete and tested for optimisation. Each SNO case requires 24 RFM runs jobs are submitted as an array of all cases in a cluster x 24.
- Currently working with 1 test cluster – can run others when happy with RFM setup (no FCDR data needed at this stage).
- Create cluster meta data
- Build in ability to process collocations with GRUAN
  - additional complexity
  - GRUAN Processor (GAIA-CLIM)
- Inter-comparison between FIDUCEO methodologies
  - (see http://www.fiduceo.eu/content/gracious-wobbling-new-dancing)

Thank you for listening