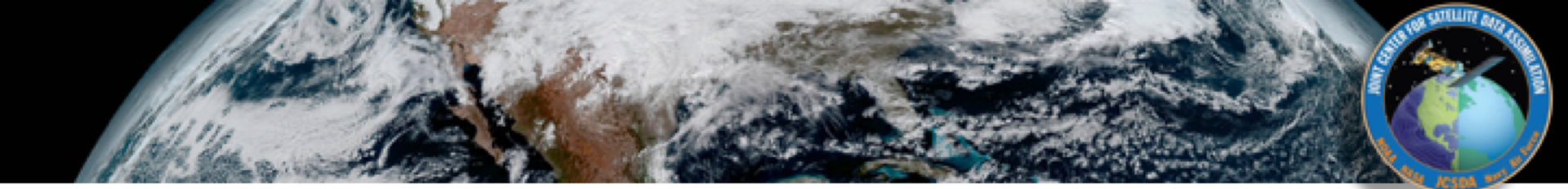

Implementation of GNSS RO operators in JEDI/UFO

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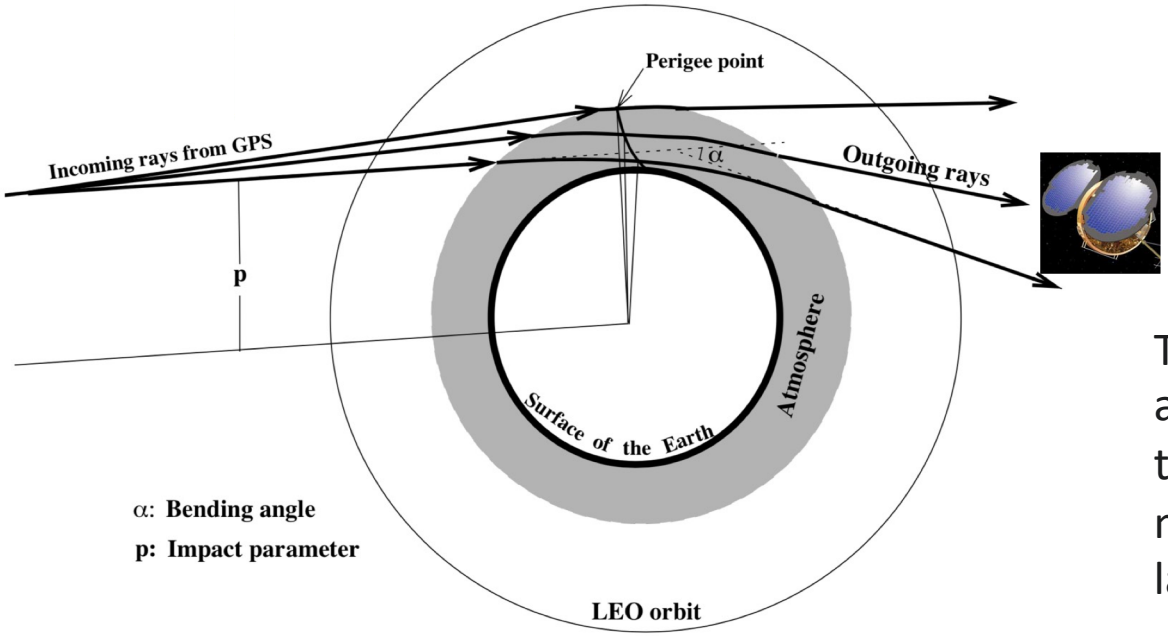
Acknowledgement: JEDI core team: *Yannick Tremolet, Anna Shlyaeva, Dan Holdaway, Mark Miesch, Maryam Abdioskouei, Stephen Herbener, Xin Zhang*
GNSSRO team: *Surya Dutta*

Outline

* Global Navigation Satellite System Radio occultation

- GNSSRO operators Overview
- JEDI GNSSRO operators status
- Preliminary tests
- Generic QC

GNSSRO operators Overview: Geometry



A **setting**/**rising** radio occultation (RO) occurs when a low-Earth orbit (LEO) **sets**/**rises** behind the Earth.

The ray connecting the GNSS and LEO is refracted/bent due to the different temperature and moisture of the atmospheric layers.

The total amount of bending accumulated during the ray path trajectory, i.e., the **bending angle**, can be retrieved.

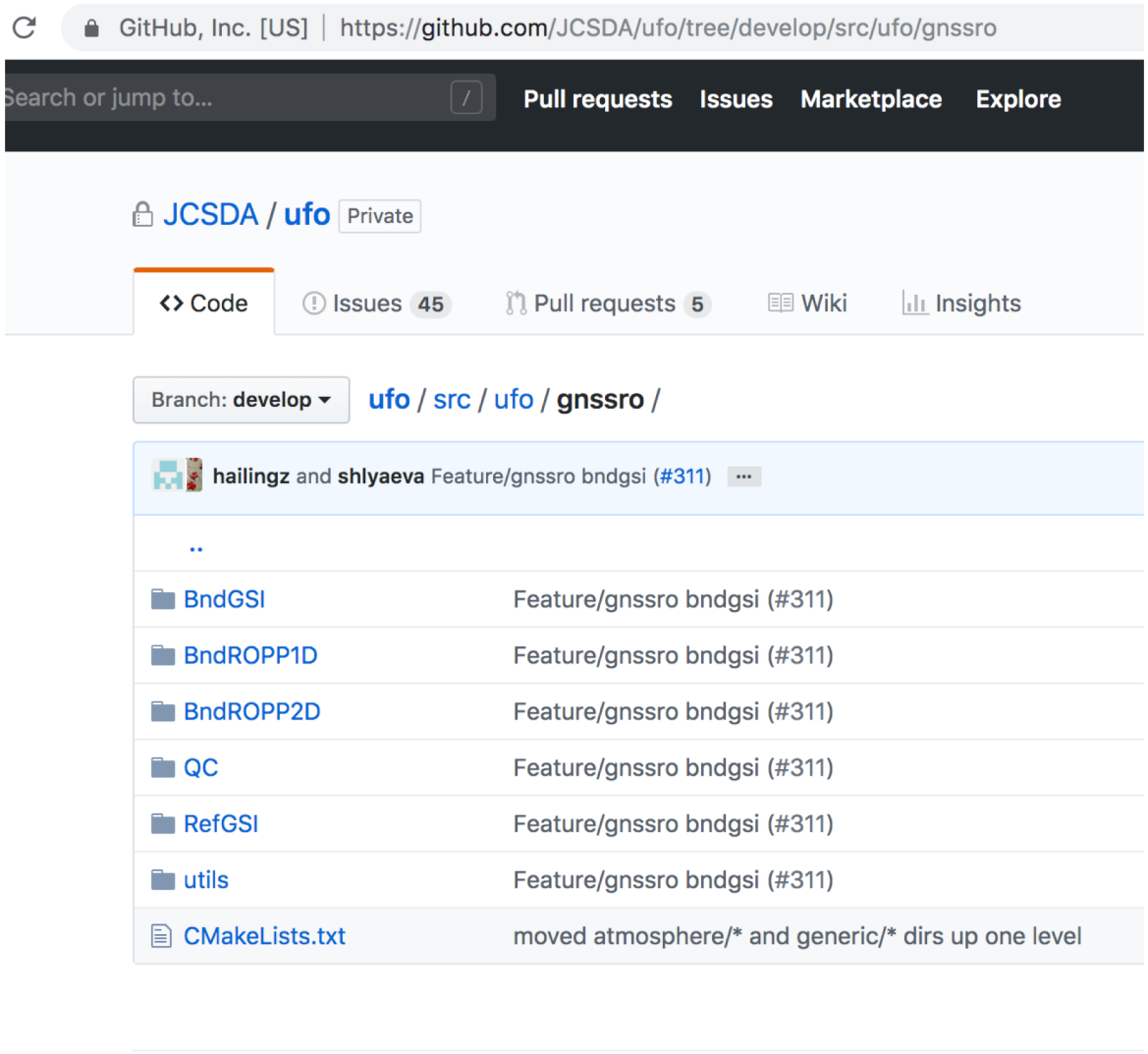
Zou et al. 1999

GNSSRO operators Overview

	BndGSI	BndROPP1D	BndROPP2D	RefGSI
Operation	NCEP	NRL	ECMWF	NCEP
Assimilated Observable	Bending angle	Bending angle	Bending angle	refractivity
	Vertical integral		take account of the real limb nature of the measurement; solve a set of ray path equations	Local refractivity operator
Equation	$\alpha(a) = -2a\int_a^\infty \frac{d\ln n/dx}{\sqrt{x^2-a^2}}dx$		$\frac{dr}{ds} = \cos\phi$ $\frac{d\theta}{ds} = \frac{\sin\phi}{r}$ $\frac{d\phi}{ds} \approx -\sin\phi\left[\frac{1}{r} + \left(\frac{\partial n}{\partial r}\right)_\theta\right]$	$N = 77.6\left(\frac{P}{T}\right) + 3.73\times 10^5\left(\frac{P_v}{T^2}\right)$
Reference	Cucurull et al. 2013	Healy and Thepaut 2006	Healy et al. 2007	Cucurull et al. 2007

* **ROPP** – Radio Occultation Processing Package by EUMETSAT

JEDI GNSSRO operators status



JEDI GNSSRO operators status

ROPP1D/2D bending angle operators

- Originally contributed by Ben Ruston (NRL) and Sean Healy (ECMWF) in the GNSSRO code sprint in August 2018

- Radio Occultation Processing Package (**ROPP**) is expected to be obtained from EUMETSAT, and Interface/cmake files are provided at https://github.com/JCSDA/ropp-ufo

- Operators, model-obs-ufo interface, at https://github.com/JCSDA/ufo/tree/develop/src/ufo/gnssro/BndROPP2D

```
ObsTypes:
- ObsSpace:
    name: GnssroBndROPP2D
    ObsDataIn:
     obsfile: ROData/gnssro_obs_2018041500_f.nc4
    ObsDataOut:
     obsfile: ROData/gnssro_3dvar_gfs_ropp2d_2018041500_m.nc4
  ObsOperator:
    name: GnssroBndROPP2D
    ObsOptions:
      res: 40
      n_horiz: 31
  Covariance:
    covariance: diagonal
  - Filter: Domain Check
    where:
    - variable: impact_height
      minvalue: 0
      maxvalue: 50000
  - Filter: RObserror
    variable: bending_angle
    errmodel: ROPP
```

Healy 2014, ROM SAF Report 19

JEDI GNSSRO operators status

GSI bending angle operator

- Follow GSI operation (Cucurull et al. 2007; 2013)
- Originally contributed by Hui Shao (JCSDA) in the GNSSRO code sprint in August 2018
- Profile check not applied yet:
  - Observation error inflation
  - Observation-side super refraction check
- Flexibilities through yaml configuration
  - Generic QC (more later)
  - Observation error model

```
ObsTypes:
- ObsSpace:
    name: GnssroBndGSI
    ObsDataIn:
     obsfile: ROData/gnssro_obs_2018041500_f.nc4
    ObsDataOut:
     obsfile: ROData/gnssro_3dvar_gfs_gsi_f.nc4
  ObsOperator:
    name: GnssroBndGSI
    ObsOptions:
      use_compress: 1
  Covariance:
    covariance: diagonal
  ObsFilters:
  - Filter: Domain Check
    where:
    - variable: impact_height
      minvalue: 0
      maxvalue: 50000
  - Filter: Background Check
    variables:
    - bending_angle
    threshold: 3.0
  - Filter: RObserror
    variable: bending_angle
    errmodel: ROPP
```

JEDI GNSSRO operators status

- There are two RO observation error models for bending angle and one for refractivity
- Currently applied through ObsFilter factory
- Easy to add new error models

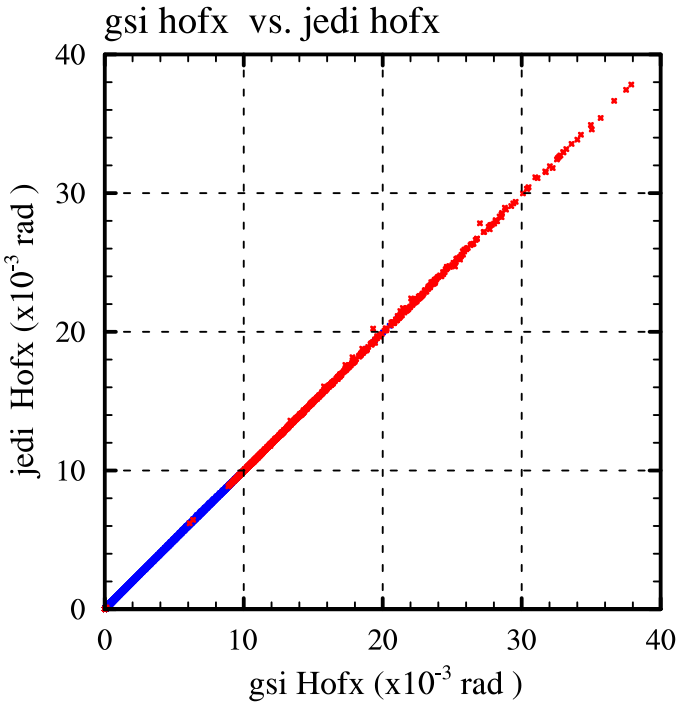
```
  - Filter: ROobserror
    variable: bending_angle
    errmodel: ROPP
```

```
  - Filter: ROobserror
    variable: bending_angle
    errmodel: GSI
```

Preliminary tests

Unit test – BndGSI

- 2018041500 NCEP GPSRO.bufr
- Processing
  - Run modified GSI to generate model background profiles at each observation location
  - Output GSI HofX values and QC flags
- Unit test
  - use the exactly same background "diagnosed" in GSI
  - Run JEDI BndGSI to generate JEDI HofX

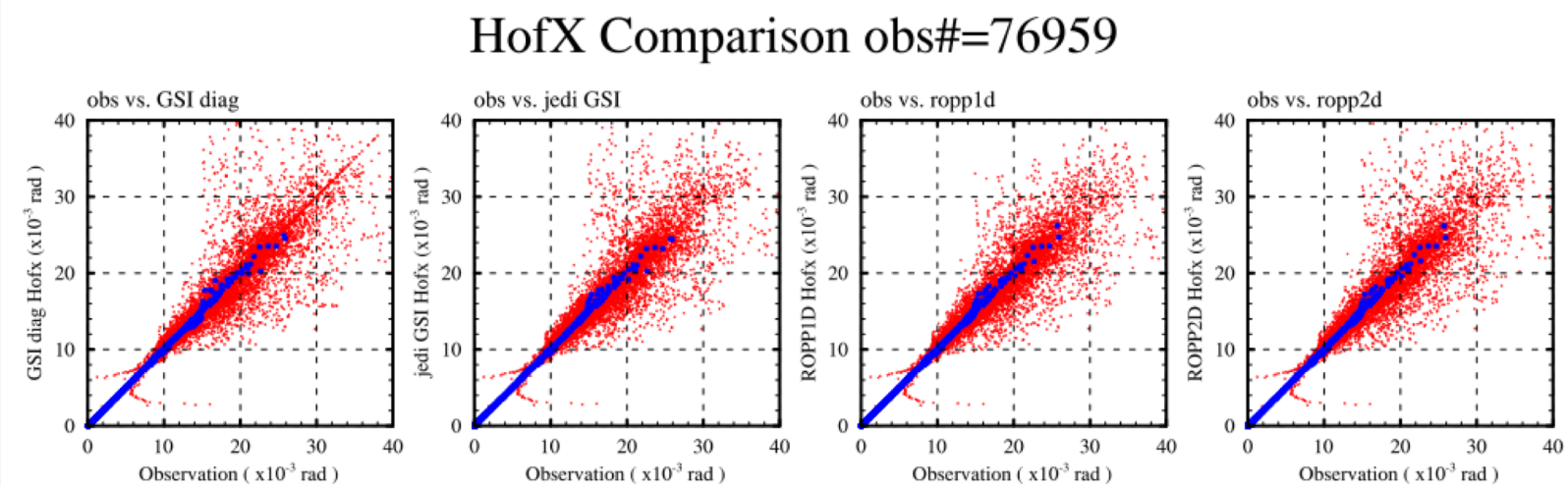


Preliminary tests

FV3JEDI HofX

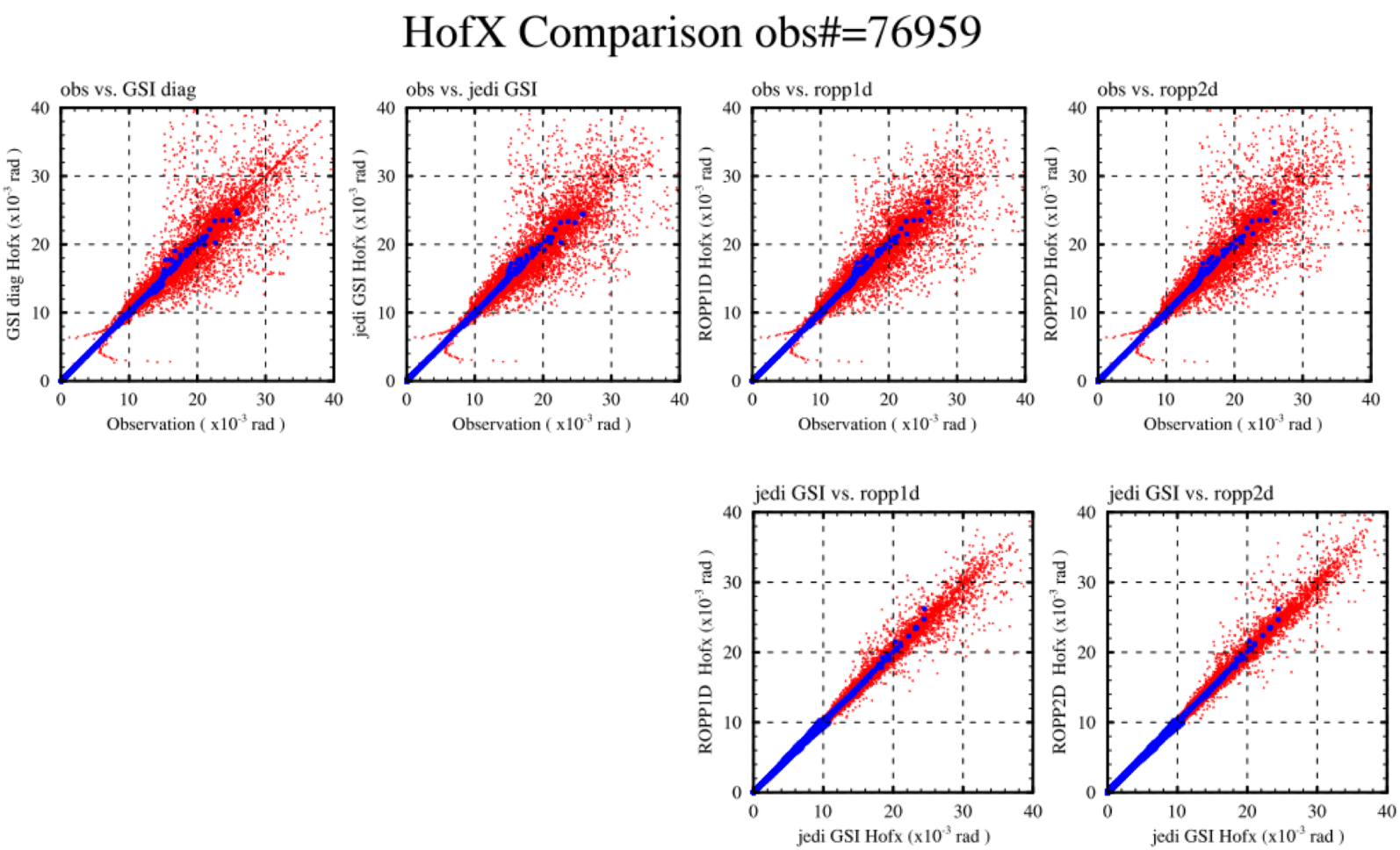
GSI Diag HofX:
obtained by running GSI;
background is GFS 6h forecast @T1534 L64
GSI Horizontal interpolation

JEDI HofX:
obtained by running fv3jedi_hofx;
background is fv3 6h forecast @c48 64L
JEDI BUMP Horizontal interpolation

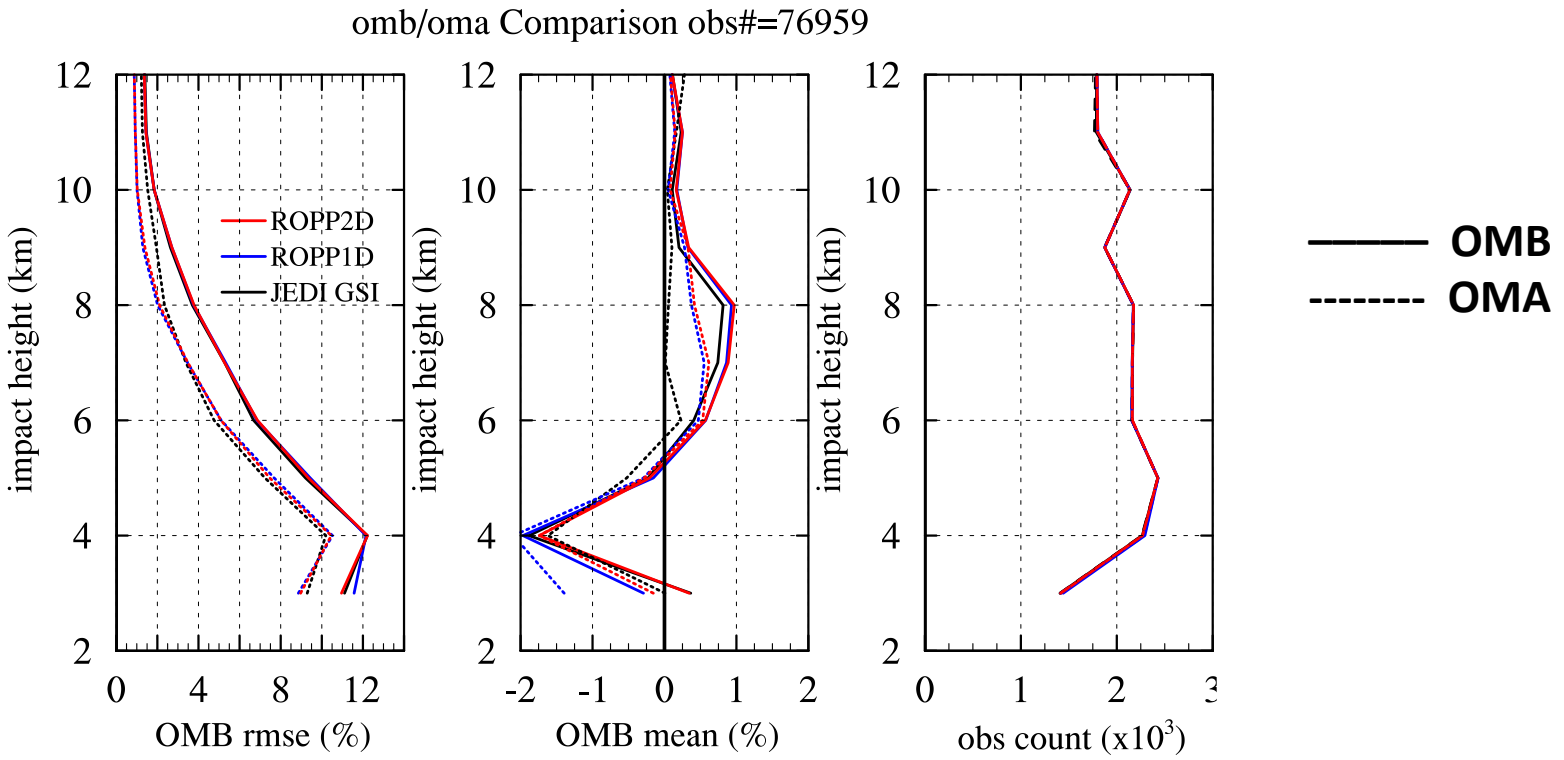


Time: 2018041500 **Blue: GSI QC flag= 0** **Red: GSI QC flag > 0**

Preliminary tests



Preliminary tests



Generic QC

- Apply generic QC in configuration files than in codes.
  - No need of recompiling
  - Reduces R2O time

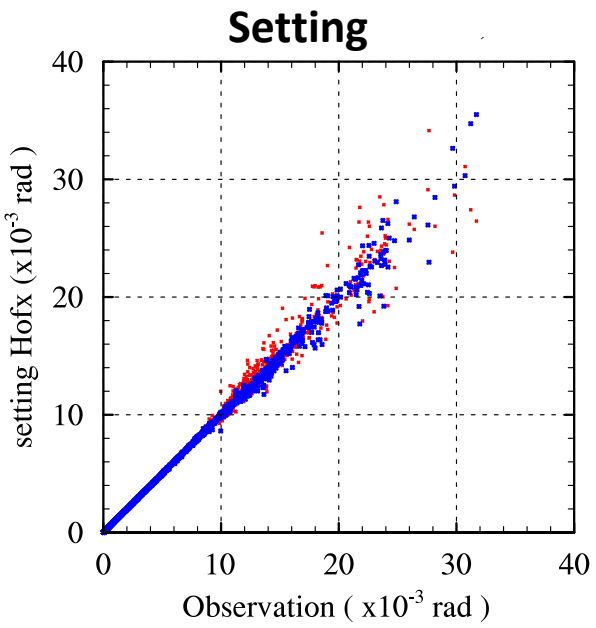
- Easy to handle complex satellite configuration
  - Allows flexible rejection combination of a particular LEO, a particular GNSS constellation, or rising/setting profiles
  - Useful to assess new missions, e.g., Metop-C, KOMPSAT5, commercial missions, etc

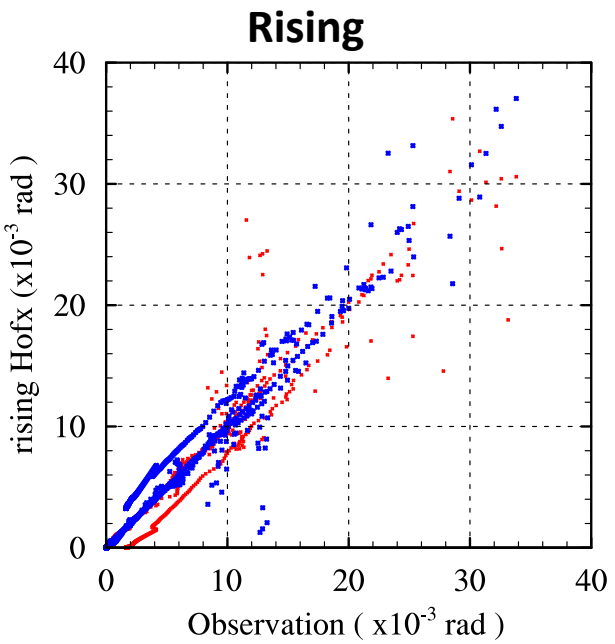
Generic QC : example 1

Rejecting KOMPSAT5 rising profiles

Data:
- KOMPSAT5 bending angles at 2018041500
- Approved for NCEP operation
- Setting only

```
ObsFilters:
- Filter: Domain Check
  variable: occulting_sat_id
  is_in: 825
  where:
  - variable:  ascending_flag
    is_in: 0
```





Generic QC: example 2

Rejecting MetOP-A&B below 8 km impact height

```
!       Remove MetOP/GRAS data below 8 km
        if((alt <= eight) .and. ((data(isatid,i)==4) .or. (data(isatid,i)==3))) then
          qcfail(i)=.true.
          data(ier,i) = zero
          ratio_errors(i) = zero
          muse(i)=.false.
        endif
```

```
  ObsFilters:
  - Filter: Domain Check
    variable: occulting_sat_id
    is_in: 3-4
    where:
    - variable: impact_height
      minvalue: 8000
```

- MetOp A&B
- will become **3-5** when **MetOp-C** becomes operational

- <=8km

Summary and Future work

- Four GNSSRO operators are implemented and preliminarily tested in JEDI (with fv3 and MPAS)
- Working on more real case study with higher-resolution fv3 model background