COMBINED AND CONSISTENT ANALYSIS OF CLIMATE-RELATED SPACE GEODETIC OBSERVATION TYPES WITH THE GEOSAT SOFTWARE

By

Per Helge Andersen

Per-helge.andersen@ffi.no

Forsvarets forskningsinstitutt, FFI

CLIMATE CHANGE OBSERVED FROM SPACE

There is a need for a system to monitor the climate status and nature's response to changes in human climate-drivers.

In order to monitor, model and predict Earth's climate, we need to measure mass transport within and between the elements of the Earth system with respect to a long-term stable reference.

A multitude of observation types give complementary information. The "climate signal" is partly "hidden" in measurement noise and a mixture of technique-dependent systematic errors.

NMA will contribute to the Earth monitoring system in two ways:

- With new instrumentation, f ex a new space observatory in Ny Ålesund with VLBI+SLR+GNSS+DORIS++
- With adequate analysis software (GEOSAT) and analyses with this software.

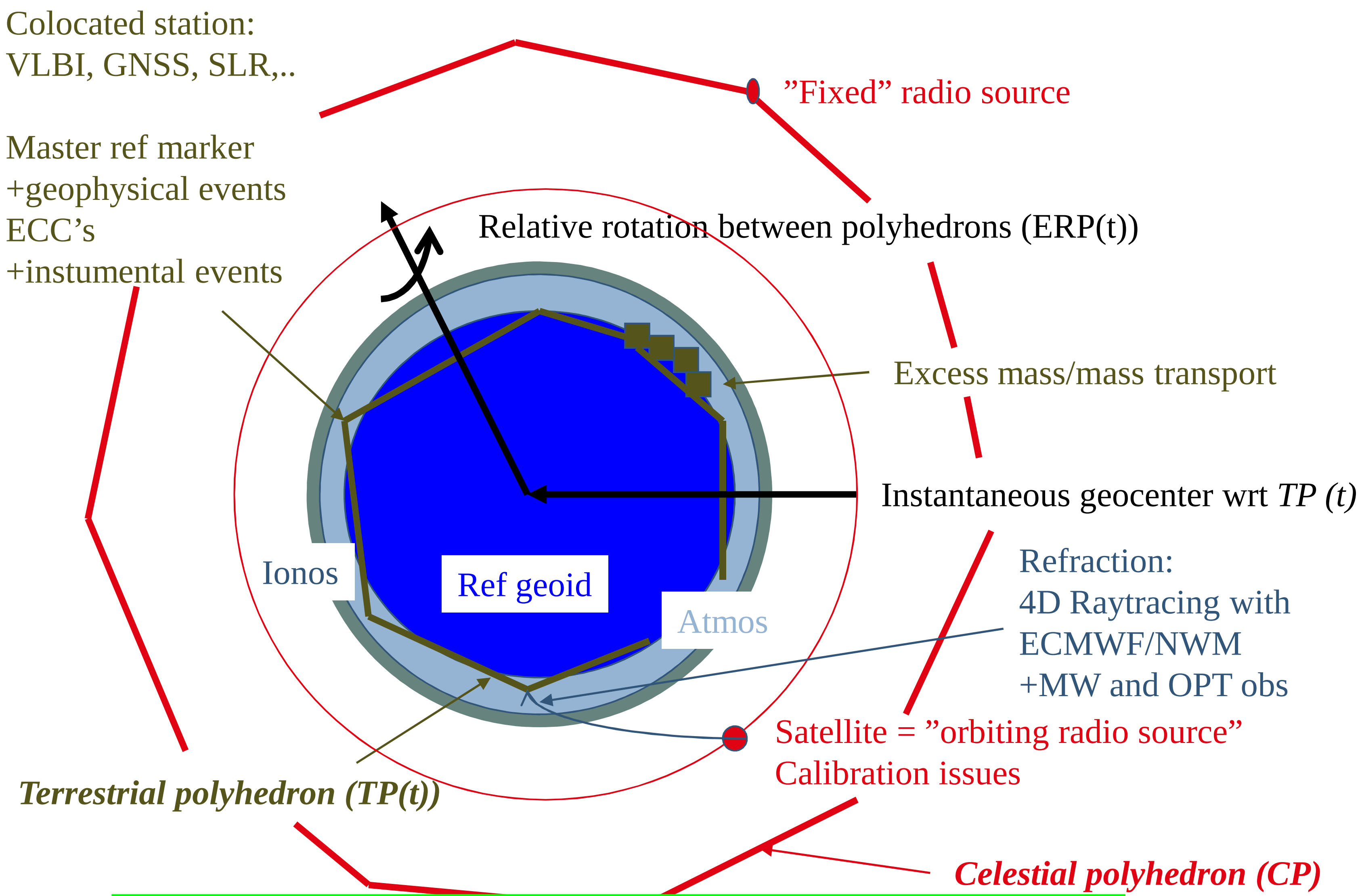
COLLABORATION BETWEEN NMA AND FFI

A long-term collaboration is established between NMA and FFI. The GEOSAT software developed by FFI during the last 30 years, will gradually be taken over by NMA. Three scientists at NMA are involved in this process and in the further development of the software.

Observation types like **accelerometer** (gradiometer) and **altimetry** are being implemented in GEOSAT (the GRAVNOR and ALTNOR projects, Eirik Mysen and Kristian Breili/NMA). FFI (myself) will implement satellite-to-satellite tracking (GRACE KBR and LEO/GNSS).

NMA is in the process of being accepted as an IVS Analysis Center with analysis of VLBI observations using GEOSAT

PHILOSOPHY OF THE GEOSAT SOFTWARE:
CONSISTENT DETERMINATION OF GEOM – ERP – GRAV
INCLUDING TEMPORAL CHANGES



GEOSAT philosophy realized with GEOM – ERP – Simple GRAV

“STANDARD ANALYSIS STRATEGY”

Step 1:

For each observation type/technique: Generate multi-year sol for TRF/ERP assuming linear station motion.

Software, model parameterization, and analysis strategy dependent on technique.

Step 2:

Use linear station motion from Step 1 to determine satellite orbit => technique-dep orbits.

Step 3:

Based on orbits from Step 2 generate OMC_G for ACC, OMC_K for KBR, and OMC_A for ALT.

Step 4A:

Estimate techniue-dep gravity (geoid) from OMC

Step 4B:

Generate technique-dep and satellite-dep instantaneous *sea surface level*.

SOME SOURCES OF SYSTEMATIC ERRORS WITH ”STANDARD ANALYSIS STRATEGY”

Observation errors:

Gravity sensor calibration, SLR/GNSS/ALT/KBR range biases, DORIS freq offsets, GNSS cycle-slips, multipath, clock drifts .. multi-generations of satellite-station/instruments, network temporal changes…

Model errors:

Use of technique-dep TRF, ERP and CRF, linear deformation of polyhedrons, errors in refraction models, errors in technique-dep corrections, errors in instrumental ECC’s, misinterpretations of IERS conventions, program code errors, numerical computer errors, the use of simplified polynomials for the representation of complicated time evolution of physical parameters…

Software errors:

Individual software for analysis of each technique amplifies the problems with technique-dep systematic model errors

WITH THE GEOSAT STRATEGY MOST SYSTEMATIC ERRORS WILL BE SIGNIFICANTLY REDUCED

REDUCTION OF SYSTEMATIC ERRORS USING GEOSAT

Reduction of systematic observation errors (examples):

Introduce empirical parameters at the single observation level to absorb techn-dep syst errors

=> RELATIVE CALIBRATION OF THE TECHNIQUES!

Only possible with multi-technique combination of observations at the observation level.

De-correlation of estimated model parameters with multi-technique combination

Extensive use of stochastic parameterization

Reduction of systematic model errors (examples):

Consistent techn-indep model:

Ex ZD: Epoch-by-epoch same atmosph for MW and consistent with OPT(SLR) signal delay

Ex ERP: Epoch-by-epoch the same Earth orientation/rotation

Ex Geocenter: Epoch-by-epoch the same geocenter

Ex Station motion: Epoch-by-epoch one set of coords of station ref marker. Estimate ECC's.

Ex Earth quakes: Epoch–by-epoch the same changes in pos- No apriori assumptions on motion.

4D raytracing without use of mapping function. Consistent MW and OPT.=> Improved scale consistency between all geometric techniques. ECMWF/NWM provides time-dep statistics to be used as constraints in the estim of atmosph params in MUD (Multi-satellite DU-factorized KF).

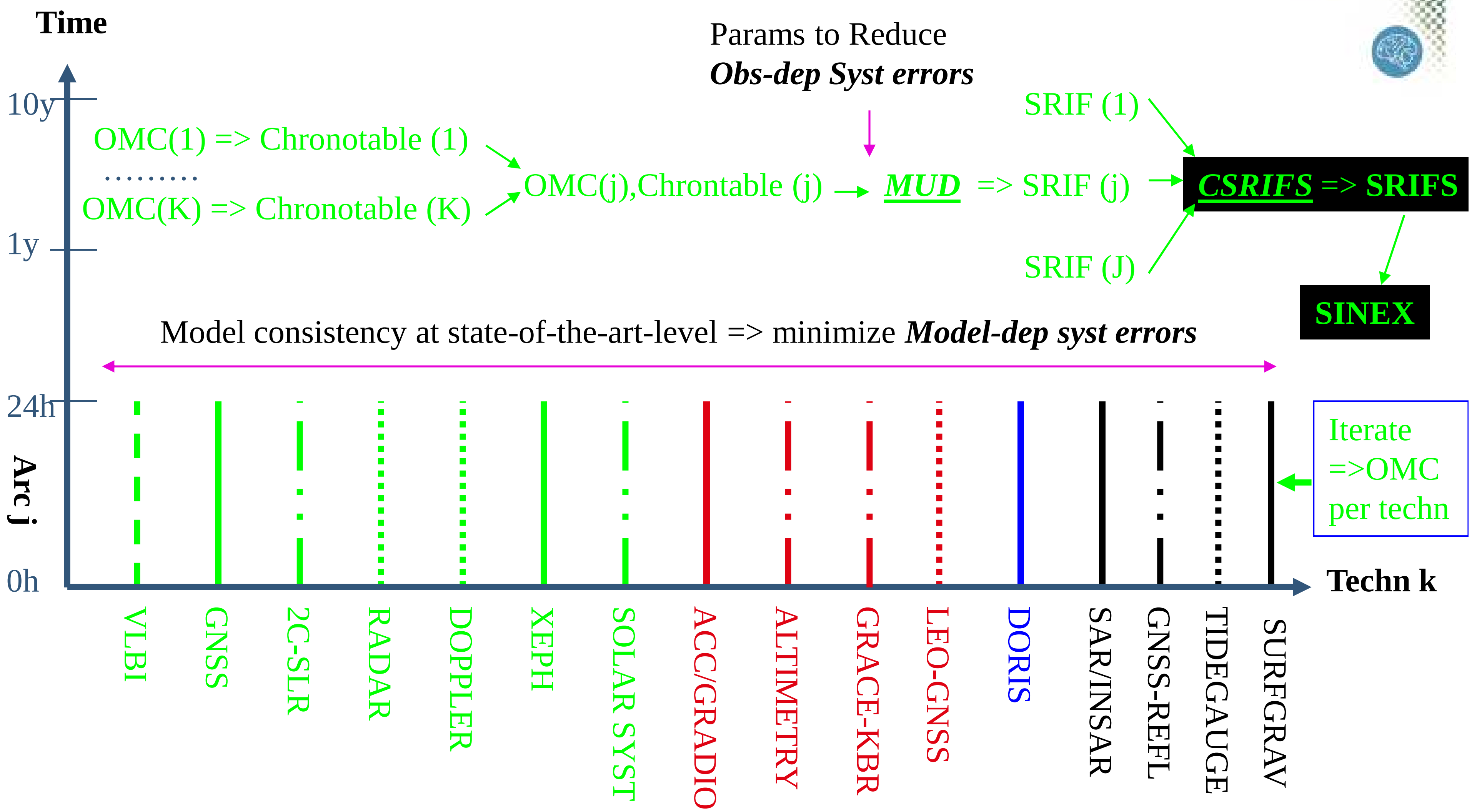
2nd and 3rd order ionospheric correction for GNSS. Not necessary for VLBI since X-band frequencies.

Straight forward weighting of obs at the single observation level instead of at the technique-level.

Tech-dep systematic errors easily observed with this processing strategy

Simplified interpretation of results since only one TP and CP

GEOSAT PROCESSING SCHEME



Operational
State-of-the-art results

Under construction

Some modifications needed

In the future?

MUD: Multi-sat UD-fact KF

CSRIFS:Comb Sq-Root-Inform-Filter-and-Smoother

GEOSAT STRATEGY

Step 1: Single arc

Combination at the observation level of VLBI, GNSS, SLR, (DORIS), KBR and ACC (only to calc non-conserv acc $\Delta\mathbf{D}(t)$ on S/C) including LEO's with UD/KF. Produce time series with inner constraints. 40 VLBI/40 SLR/100 GPS/50 DORIS

=> 2500 params

Step 2: Single arc

Generate OMC_G for ACC and KBR using results from Step 1

Generate OMC_A for ALT with residuals and partials interpolated to nearest fine grid point (Multi-sat/gen relative calibration with cross-correlation). A single arc will produce only a partly filled fine grid.

Step 3: Single arc

Generate NEQS for OMC_G with state vector

$$\Delta\mathbf{x}^t{}_{arc} = \left(Grav, Acc\_calibr, Grace\_orb \quad \boxed{\Delta\mathbf{D}(t)}\right)^t$$

Eliminate last part of state-vector to generate single-arc RNEQS

Step 4A: Multiple arcs/TRF-EOP-CRF

Combine single-arc SRIF's to multi-year sol

Based on time series of TP(t)

Step 4B: Multiple arcs/gravity

Combine single-arc RNEQS with state vector

$$\Delta\mathbf{x}^t{}_{multi-arc} = \left(Grav \quad Acc\_calibr, Grace\_orb\right)^t$$

Eliminate last part of state-vector to generate gravity-alone RNEQS. Estimate gravity.

360 x 360 field=> 1 GB RAM

Step 4C: Multiple arcs/altimetry

Produce fine grid time series simultaneous with multi-sat calibr (in time and range using fine grid cross-correlation)

STATUS

Target	ALTITYDE (km)	VLBI	SLR	GNSS	ACC	ALT	DORIS	KBR
Radio sources		Y						
LAGEOS 1 & 2	5800		Y					
GPS	20000		(Y)	Y				
GOCE	250		Y	Y	Y(6)			
GRACE A & B	500		Y	Y	Y(1)			Y
CHAMP	450		Y	Y	Y(1)			
JASON 1 & 2	1300		Y	Y		Y	(Y)	
TOPEX	1300		Y	Y		Y	(Y)	
CRYOSAT 2	700		Y			(Y)	(Y)	

SLR: Two-color

GNSS: Ambiguity resolution using a priori un-differenced residuals. Success rate: 80-90 %

Operational Under construction Some modifications needed In the future?

Status::

LEO/GNSS: Small modifications/generalizations of some existing subroutines.

ACC: Routines are developed and are presently being de-bugged.

Gravity inversion software: Modify some existing subroutines.

ALT: End-program for correcting altimetry data for improved orbit and performing cross-correlation for relative calibration. Relatively simple task.

KBR: Easy task since well tested routines can be applied.

CONCLUSIONS

With the inclusion of gravity-like techniques in GEOSAT, the software becomes a ”total” software applicable for any kind of high-precision space-geodetic work

GEOSAT realizes GGOS philosophy with unified treatment of geometry, Earth orientation and gravity

Major advantages:
•In-house software
•100 % control of software code and models
•Independent of external software except for a FORTRAN-compiler
•Runs on any LINUX/UNIX platform
•Array of GEOSAT-dedicated computers at FFI (within end of 2010):
Approx 120 CPU’s. 180 GB RAM, 35 TB disk space.
•”Easy” to extend GEOSAT for special applications

Secure future maintainance and development of GEOSAT. Responsability to be taken over by NMA.

NMA service to IVS using GEOSAT
In the future NMA service to ILRS, IERS, GGOS ???

One of many applications of GEOSAT:
To monitor local/regional/global mass transport via influence on geometry and gravity

ACKNOWLEDGEMENT:

Work is funded by NMA.
Greatly appreciated!

EXAMPLE OF SYNERGY EFFECTS:
LEO ORBIT DETERMINATION USING GPS AND ACC OBSERVATIONS

$$\frac{d^2\mathbf{r}}{dt^2} = \mathbf{A}_{conservative} + \Delta\mathbf{D}(\mathbf{a}_{obs}, \mathbf{a}_{\mathrm{mod}}(\mathbf{L}_{cal}))$$

Accelerometer calibration benefits from combined processing with LEO/GPS (and LEO/SLR)