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Satellite geodesy with VLBI in the GGOS era: observation concepts, geodetic products and the technical feasibility

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Space Geodesy

Space-Geodetic Techniques, Reference Frames and Earth Orientation Parameters

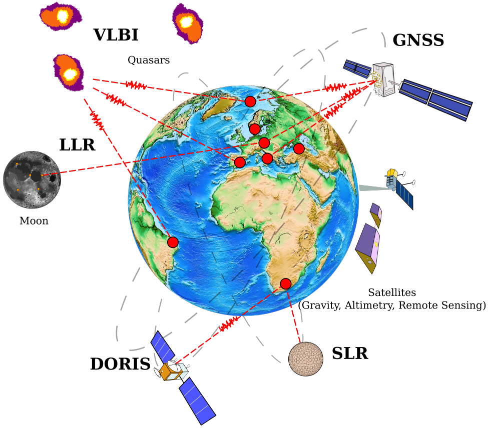

Fig. 2.1 from Klopotek (2020)

Space geodesy:

- facilitates our understanding of Earth dynamics and is fundamental for providing accurate and long-term stable global reference frames (celestial and terrestrial)
- relies (to a large extent) on observations from multiple techniques: VLBI, GNSS, SLR, LLR, GNSS, and DORIS

Each space-geodetic technique:

- sensitive to **different sets** of Earth-based parameters
- conducts observations with **different spatio-temporal resolution**
- provides geodetic products with **different latency and quality**

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Combination of Space-Geodetic Techniques

Local Ties, Space Ties and Global Geodetic Parameters

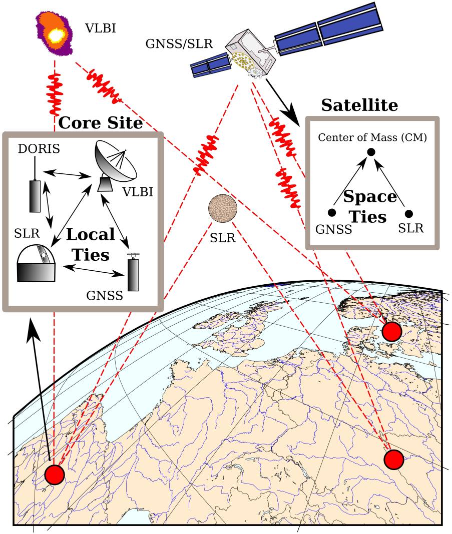

Fig. 2.3 from Klopotek (2020)

Combination of Space-Geodetic Techniques:

- Overcome technique-specific weaknesses and identify biases
- Improved terrestrial reference frame
- Highest possible quality and homogeneity of station-based and global geodetic parameters:
  - Earth Orientation Parameters
  - Geocenter Motion
  - ...

Geodetic and Astrometric VLBI

Legacy VLBI System vs VLBI Global Observing System (VGOS)

Legacy (S/X) VLBI System:

The current network of telescopes employed for routine observations

- **Different telescope types** (telescope size, mounting type, slew speed, obs. sensitivity)
- Dual-band system: S-band (2.2–2.4 GHz) and X-band (8.1–8.9 GHz)
- Long-observation scans
- Delay Uncertainty: **9.3 mm (31 ps)** (on a weak radio source, Niell et al. (2018))
- Operationally stable with global coverage

VLBI Global Observing System (VGOS):

The next-generation (broadband) VLBI System and a milestone step towards GGOS

- **Unified telescope structure** (compact design, 13-m telescope reflectors, fast-slewing, obs. sensitivity)
- Broadband characteristics: 2–14 GHz
- **An improved observation density** and **short-observation** scans
- Delay Uncertainty: **2.4 mm (8 ps)** (on a weak radio source, Niell et al. (2018))
- Reaching an operationally stable global network of telescopes

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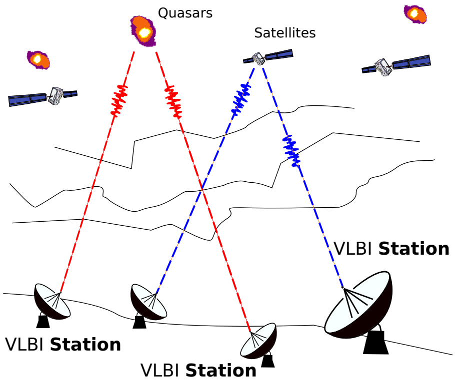
Satellite Geodesy with VGOS in the GGOS era
Geodetic VLBI and Earth Satellites



Combination of quasar and VLBI-based satellite observations:

- Extend the field of VLBI research with new applications
- Potential contribution of VLBI in co-location in space (space ties)
- With the ultimate goal of **routine** quasar + satellite observations (if beneficial) **without degradation** of standard VLBI-derived geodetic products
- Several questions related to satellite observations with (geodetic) VLBI:
  - **theoretical aspects** (sensitivity to conventional/new parameters, delay uncertainty, quality of solve-for parameters)
  - **technical feasibility** (frequency setup, signal characteristics)

Geodetic VLBI Simulations
Simulated VLBI Observables (group delays)

c5++ (Hobiger et al. 2010, Hobiger & Otsubo 2014) and its simulation module (Klopotek et al. 2018) for geodetic VLBI:

$$\tau_{sim} = \tau_g + (ZWD_2 \cdot MF_w(\varepsilon_2) + clk_2) - (ZWD_1 \cdot MF_w(\varepsilon_1) + clk_1) + \tau_{rnd}$$

- Geometric delay τ_g for quasars or artificial radio sources at a finite distance (Duev et al. 2012)
- Zenith wet delay ZWD_i
- Wet mapping function $MF_w(\varepsilon_i)$
- Station clock variation clk_i
- Observation noise τ_{rnd} (white noise)

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- Geometric delay τ_g for quasars or artificial radio sources at a finite distance (Duev et al. 2012)
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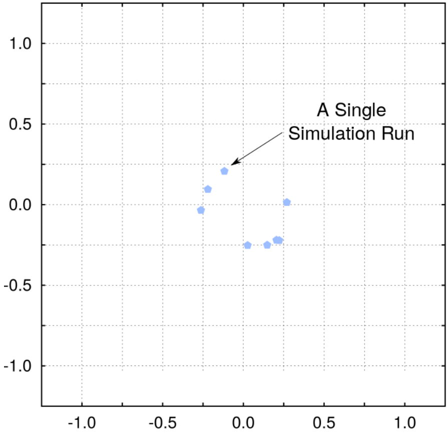
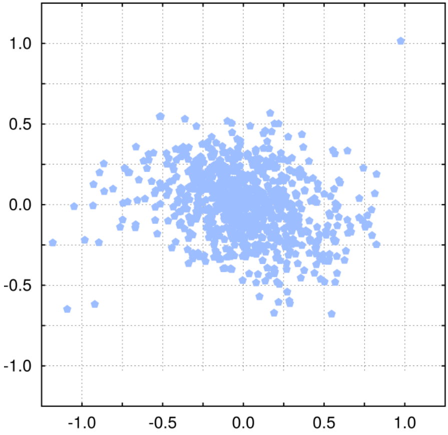
Monte-Carlo Simulations



- A mathematical model + stochastic behaviour of the input parameters
- Target parameter quality derived **empirically** through repeated statistical sampling

Monte-Carlo Simulations



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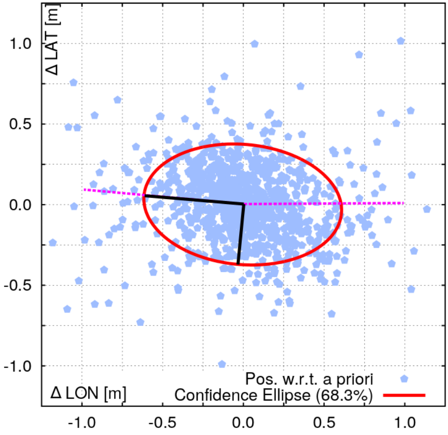
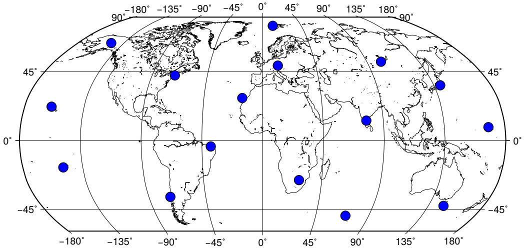


- A mathematical model + stochastic behaviour of the input parameters
- Target parameter quality derived **empirically** through repeated statistical sampling
- Monte-Carlo (MC) simulations **are good tools to validate** the performance of **new concepts**
- MC simulations are only **as realistic as the stochastic (and mathematical) models utilized** to produce the simulated input data

Observation Concepts

Combination of quasar and satellite observations
VGOS network



The basis of this study forms a VGOS-type schedule (with 16 stations), which was used during the conceptual stage of VGOS

Combination of satellite and quasar observations on the **observation level** based on **3-day VGOS-type schedules** to determine:

- Earth Rotation Parameters (ERP): polar motion (x_p, y_p), Earth Rotation $(UT1\text{-}UTC)$
- Positions of VLBI antennas

Thanks to satellite observations one can derive additionally:

- Satellite Orbits
- Geocenter (Offsets)

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Combination of quasar and satellite observations

Incorporation of satellite observations into VGOS schedules

A simple 'scheduling' approach:

Replacing every 8^{th} quasar scan* with a satellite scan, in which one of the Galileo (GAL) satellites is observed (in total 6 GAL satellites in the schedule)

Schedule name	Satellites used	Number of observations (3-day solution)		
		Quasars	Satellites	
			Total	Per Satellite
GAL-S6-R8-VGOS	E01, E02, E04, E07, E12, E26	213 951	9 902	1 342/2 237/ 1 210/1 949/ 2 134/1 030
Reference Schedule	-	213 951	-	-

* (A single scan should be understood as a (natural/artificial) radio source that is observed simultaneously by several VLBI telescopes)

Combination of quasar and satellite observations

Simulation Environment

Simulation Environment:

- Simulate Zenith Wet Delays (ZWDs), station clocks, and baseline-based observation noise $\sigma_{\text{rnd-qsr}} = 0.14$ cm (for quasars) and $\sigma_{\text{rnd-sat}}$ (for satellite observations)
- Three different noise levels for satellite observations (in cm): $\sigma_{\text{rnd-sat}} = [0.14, 1.41, 13.86]$
- **No acceleration noise** is present
- For each simulation run, an input (a priori) satellite position vector perturbed randomly with $\sigma = 30$ m before being used in the estimation process

Based on the MC runs, one can access precision and accuracy metrics*:

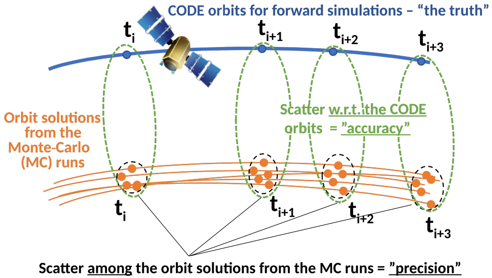

Fig. 2 from Klopotek et al. (2020)

*(In this study, t_{i+1}-t_i= 5 min)

Combination of quasar and satellite observations
Parameterization of the estimated parameters

Common parameters (ZWDs, troposphere gradients, station positions, Earth Rotation Parameters (ERP), station clocks):

- Derived using **both** observation types, proportionally to the applied weighting (based on σ_{rnd} and elevation dependent)

Satellite observations:

- Station-specific **clock biases** (w.r.t. the reference station in the network) estimated once per 3-day arcs as constant parameters

Orbit Determination:

- Conventional **dynamic** POD approach (numerous satellite force models, a numerical integrator) in an iterative least-squares approach
- Hybrid model: box-wing model and the five-parameter Empirical CODE Orbit Model (ECOM-1, Beutler et al. 1994):
  estimating D_0, Y_0, B_0, B_S, B_C (one set per 3-day solution)
- **No pseudo-stochastic pulses** are estimated

Geocenter (offsets):

- One set per 3-day solution

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Geodetic Products

Geo VLBI for POD of GAL satellites: A simulation study

VGOS: Satellite Orbits - Performance I

Sat.	Satellite observation precision [cm] ($\sigma_{\text{rnd-sat}}$)	3-D Orbit Quality (WRMS_{O3D}) [cm] *QS-OS*	*QS-OSG*	*QS-OSE*	*QS-OSEG*
E01;E02; E04;E07; E12;E26	0.14	**1.0**(1.0)	**1.0**(1.0)	**1.0**(1.0)	**1.0**(1.0)
	1.41	**1.6**(1.6)	**1.7**(1.7)	**1.6**(1.6)	**1.7**(1.7)
	13.86	**12.4**(12.5)	**13.3**(13.3)	**12.4**(12.5)	**13.3**(13.4)

- The values in bold represent the mean WRMS_{O3D} calculated based upon the corresponding measures evaluated for each satellite

- The values in parentheses refer to the parameter accuracy

- For all analysis options and the considered satellite measurement noise levels, the quasar observation precision was set to 0.14 cm

* (*QS-OSEG* - read as: using quasar (*Q*) and satellite (*S*) observations,(-) estimate satellite orbits (*O*), station positions (*S*), ERP (*E*) and geocenter offsets (*G*); similar applies to other analysis options; complementary to four analysis options: reference solutions (either *Q-S* or *Q-SE*), i.e., the same geometry, but without satellite observations)

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Geo VLBI for POD of GAL satellites: A simulation study

VGOS: Satellite Orbits - Performance II

Shown for 3 Galileo Satellites (from *GAL-S6-R8-VGOS* and *QS-OS*)

Orbit scatter ($\mathrm{WRMS_{O3D}}$, precision) for $\sigma_{\text{rnd-sat}} = 1.41$ cm:
(yellow dots - VGOS stations, small dots - pos. of satellites at observation epochs)

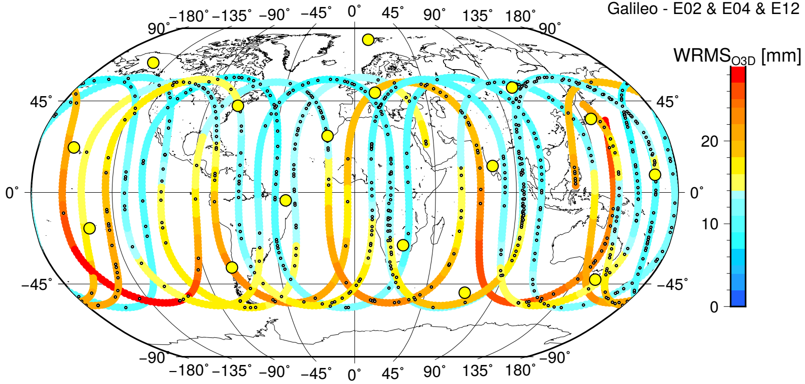

Fig. 9 from Klopotek et al. (2020)

- Average $\mathrm{WRMS_{O3D}}$ for E02, E04 and E12: 1.5 cm

Geo VLBI for POD of GAL satellites: A simulation study

VGOS - Geocenter

- Geocenter Offsets:

WRMS (X/Y/Z) [cm]

(accuracy, $\sigma_{\text{rnd-sat}}$= 0.14 cm):
QS-OSG 0.36/0.45/0.68
QS-OSEG 0.36/0.46/0.68

(accuracy, $\sigma_{\text{rnd-sat}}$= 1.41 cm):
QS-OSG 0.56/0.60/1.01
QS-OSEG 0.56/0.61/1.01

(accuracy, $\sigma_{\text{rnd-sat}}$= 13.86 cm):
QS-OSG 4.38/4.87/8.19
QS-OSEG 4.38/4.87/8.19

- Close to the detection level of geocenter motion for $\sigma_{\text{rnd-sat}}$= 0.14 cm

In reality*:

- Z geocenter component **highly correlated** with ECOM-1's $\mathbf{D}_0$ (empirical) parameter :=(

- One might need to consider 1-day arcs in order to diminish prospective orbit modeling errors or spurious signals

- Improve orbit modelling to account for non-gravitational unmodelled perturbing forces
- Investigate sensitivity aspects more thoroughly

*(Also in connection to orbits)

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Geo VLBI for POD of GAL satellites: A simulation study

VGOS - Station Positions and ERP

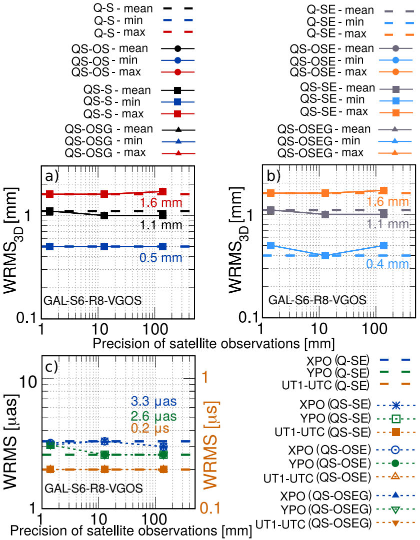


Fig. 10 from Klopotek et al. (2020)

Compared to the quasar-only reference solutions (either *QS-S* or *QS-SE*):

- Derived station positions are **not affected negatively** by satellite observations

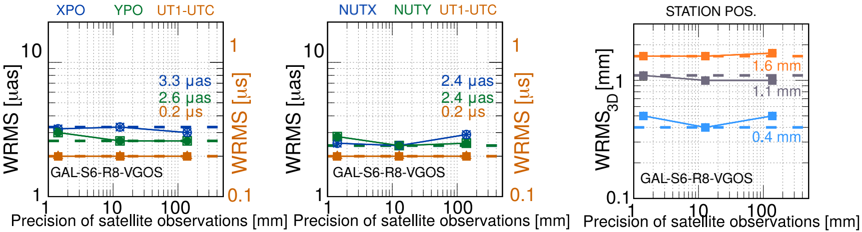
- Additional satellite observations **do not degrade** the estimated Earth rotation parameters

Additional Simulations

VGOS - Extension to EOP (ERP + Celestial Pole Offsets)

The same schedule (*GAL-S6-R8-VGOS*):

- Average $\mathrm{WRMS}_{\mathrm{O3D}}$ [cm] (accuracy, $\sigma_{\text{rnd-sat}}$= 1.41 cm):
QS-OSE 1.6 cm / *QS-OSEG* 1.8 cm
- Geocenter Offsets WRMS (X/Y/Z) [cm] (accuracy, $\sigma_{\text{rnd-sat}}$= 1.41 cm):
QS-OSEG 0.59/0.61/1.01 cm



Similar results when estimating EOP, i.e.,
ERP + Celestial Pole Offsets (NUTX, NUTY) :-)

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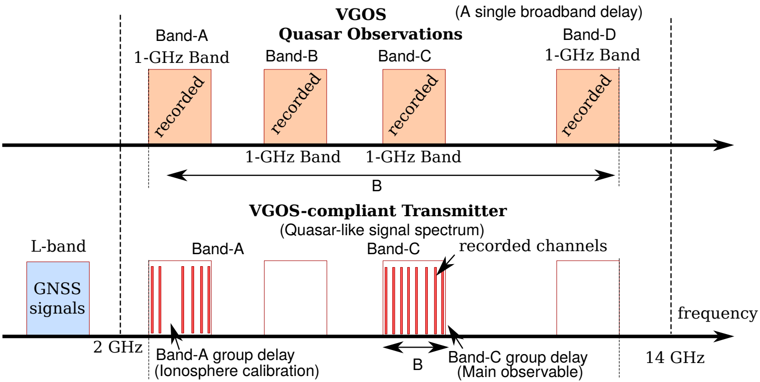
The Technical Feasibility

Prospective VLBI transmitter
Signal Characteristics and Frequency Setup - VGOS-type observations



Delay Uncertainty (group delays) proportional to the spanned bandwidth (B) in Hz:

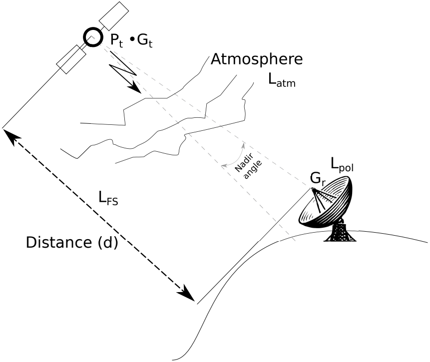
$$\sigma_\tau \sim \frac{1}{2\pi\,\mathrm{SNR}_{\mathrm{baseline}}(0.4 \cdot B)}\,[\mathrm{s}] \tag{1}$$

Specific frequency bands and signal strength for prospective VLBI transmitter(s) in accordance with ITU-R Recommendations

Prospective VLBI transmitter
Signal Strength

Assuming clear-sky conditions*:

$$P_r[dBW] = P_t + G_t - L_{FS} - L_{atm} - L_{other} - L_{pol} + G_r$$



X-band observations (at 10° elevation) and a VLBI transmitter with (for instance) 0.5 W per band to minimize thrust effects (Steigenberger et al. 2018) and G_t= 3 dBi for a satellite @ 20 000 km:

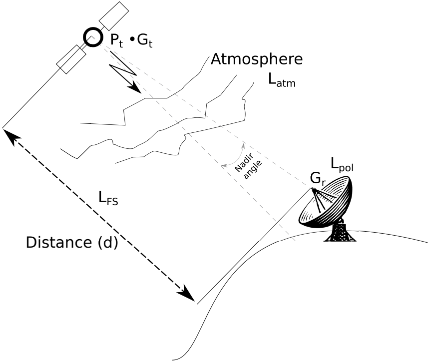
- $L_{FS} = \left(\frac{4 \cdot \pi \cdot d}{\lambda}\right)^2 \approx$ 197 dB @ 8.5 GHz
- L_{pol} assumed 3 dB
- L_{other} (out-of-main-beam obs., other) assumed 5 dB
- L_{atm} up to 0.24 dB @ 8.5 GHz

* (Although possible, link during rain conditions is more comprehensive and sensitive to the chosen location, frequency band or assumed time availability of the signal)

Prospective VLBI transmitter
Signal Strength

Assuming clear-sky conditions*:

$$P_r[dBW] = P_t + G_t - L_{FS} - L_{atm} - L_{other} - L_{pol} + G_r$$



X-band observations (at 10° elevation) and a VLBI transmitter with (for instance) 0.5 W per band to minimize thrust effects (Steigenberger et al. 2018) and G_t= 3 dBi for a satellite @ 20 000 km:

Assuming VGOS-type (13-m) antennas and recording with 8 channels 4 MHz wide:

$P_r = 2.4{\times}10^{-15}\mathrm{W} \rightarrow 9.3\times 10^{-25}\mathrm{Wm^{-2}Hz^{-1}}$ ≈ 93 Jansky (Jy)

Natural radio sources (quasars) for geodetic purposes ≈ 1 Jy

* (Although possible, link during rain conditions is more comprehensive and sensitive to the chosen location, frequency band or assumed time availability of the signal)

Prospective VLBI transmitter

Past, present and future satellite missions

Potential to include dedicated VLBI transmitters on board of:

- The subsequent generation of Galileo satellites
- Future co-location satellites at various altitudes
- CubeSats, see, e.g., VLBI observations of the APOD-A nano satellite (Hellerschmied et al. 2018, Hellerschmied 2018)

Summary

VGOS-type satellite observations in the GGOS era:

- Consistent determination of CRF, TRF, EOP, geocenter (to a certain extent) and satellite-based parameters
- Participation of VLBI in co-location in space
- **Technical aspects** (signal structure, signal strength, frequency bands and frequency setup) **of major importance**
- **Automated and optimised scheduling** of quasar and satellite obs. in order to **not degrade the standard parameters** that are **routinely** provided by conventional geodetic VLBI
- Satellite observations could be incorporated into regular geodetic sessions with no major effort and without **additional or dedicated** Earth-based equipment
- A multi-disciplinary topic that should involve various parties in order to fully benefit from the presented concept or similar ideas considered in the future...

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Stay Safe!

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