Deployment of GPS radio occultation instruments in the upcoming Strateole-2 equatorial superpressure balloon campaign to investigate tropical waves and their effects on circulation

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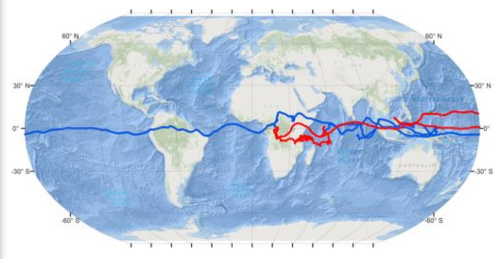
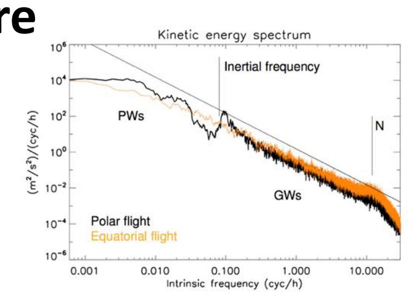
1. Science Objective



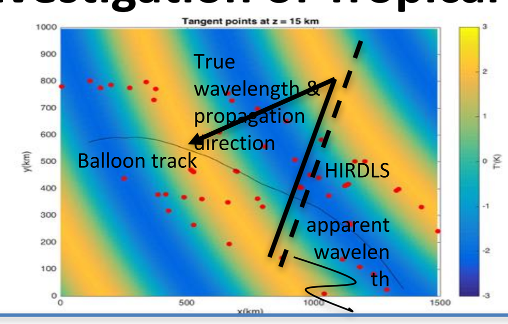
Early tropical test flights of the super-pressure balloon system during February-May 2010. The flight duration of the balloons was approximately 80 days near 20 km altitude. Clear **wave structure** is visible in the traces of the balloon paths, and the reversal of the balloon paths when the QBO changed phase is also visible.

Dynamics of the Equatorial Stratosphere

Observations of GW momentum fluxes in the tropics are needed for waves of all scales as well as the intermittency of their occurrence. Momentum fluxes will be retrieved from in-situ 30s balloon observations (u', v', P', and z') based on the GW polarization relationship.



Investigation of Tropical Waves in 3D Space

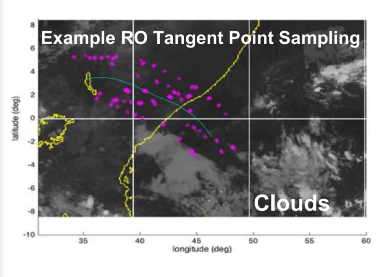


Current methods sample apparent wavelength and phase speed, so observed momentum flux is biased. The Radio Occultation (ROC) profiler attempts to sample large horizontal scale, fine vertical scale waves in 3D space.

Wave Influences on CPT, Dehydration, Cirrus Formation

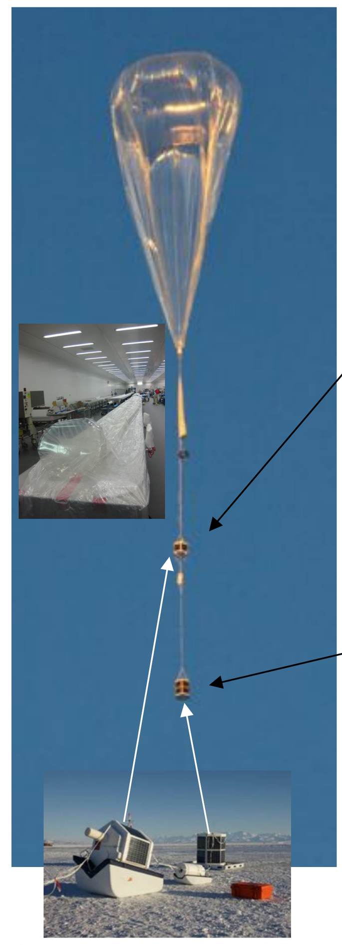
FLOATS will resolve CPT structure with high temporal and spatial/vertical resolutions and quantify fine-scale waves from a suspended 2 km fiber optical cable. RACHuTS will link temperature structure to dehydration processes through continuous measurements of water vapor, cloud particles, and temperature across the cold-point during night time. BeCOOL will detect cirrus below ROC profiles.

Relation between Gravity Waves and Convection

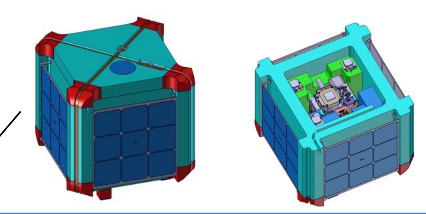


Parameterization schemes for GWs generated from convection require momentum flux phase speed spectra at cloud tops which depends on convective latent heating. Observations of waves and clouds are needed for these schemes to behave realistically both in present day and future climate simulations, especially in the poorly sampled equatorial region.

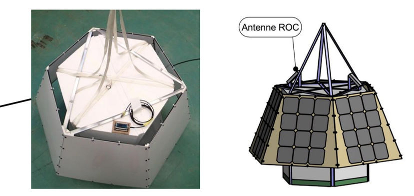
2. Overview of Strateole-2 Instruments



Spherical Super Pressure Balloon, Helium, 11 or 13 -m diameter.



Gondola: EUROS , ~13 kg
Flight Monitoring/Control
Scientific Instrument: TSEN
Control/Operation Center : CNES

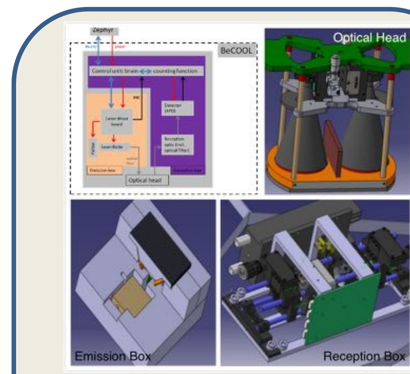


Gondola: ZEPHYR, ~22kg
Various combinations of 3 scientific instruments.
Science Mission Control Center : CNRS-LMD

- The balloon gondola provides Iridium data telemetry, power, and temperature regulation as well as integrated in-situ meteorological measurements.
- Each balloon is designed to fly for 3+ months, and circumnavigate the equatorial belt 2-3 times.
- 4 balloon configurations will be flown:
- STRAT1 – 4 balloons, 20 km alt, 13m diam., **ROC, BeCOOL, TSEN, BOL-DAIR**
- TTL1 – 4 balloons, 18 km alt., 11m diam., **TSEN, SAWfPHY, B-Bop, LOAC**
- TTL2 – 3 balloons, 18km alt., 11m, **TSEN, PicoSDLA, FLOAT**
- TTL3 – 3 balloons, 18 km al., 11m, **TSEN, LPC, RACHuts**

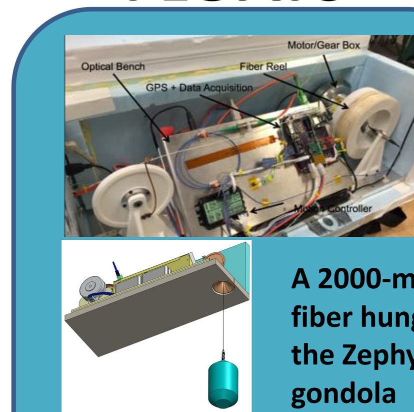
The Stratole-2 will begin with a 5-balloon technology validation campaign launched from the Seychelles Islands in boreal fall-winter 2018-2019, followed by 20-balloon flights in boreal fall-winter 2020-2021. A final 20-balloon campaign in 2023-2024 is planned for the opposite phase of the QBO.

BeCOOL



Balloon-borne Cloud Overshoot Observing Lidar: a micro-lidar to measure the geometry and optical properties of clouds.

FLOATS



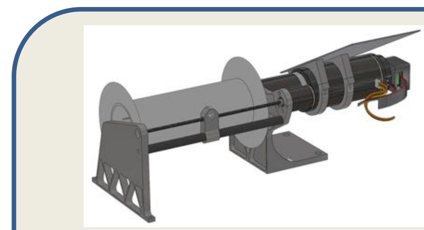
A 2000-m fiber hung on the Zephyr gondola

Fiber-optic Laser Operated Atmospheric Temperature Sensor: Provides high resolution temperature profiles.

TSEN

Thermodynamic Sensor: Measure the in-situ temperature and pressure.

RACHuTS

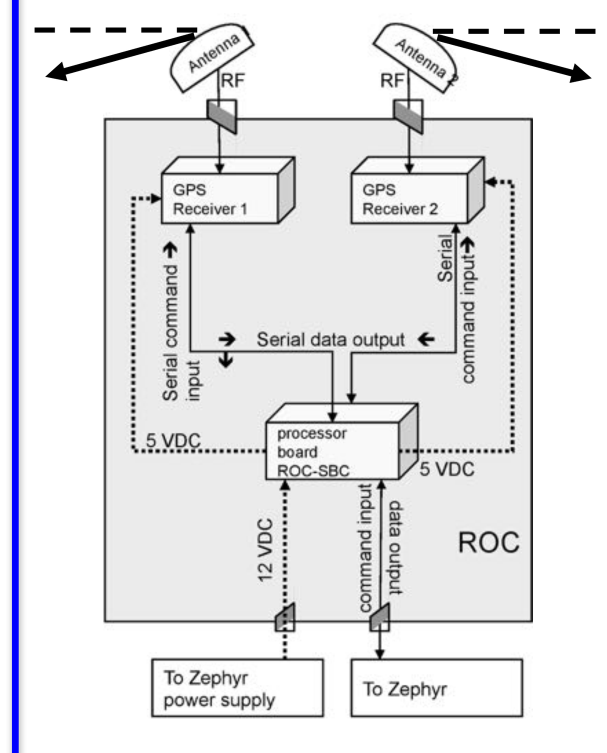


Reeldown Aerosol Clouds and Humidity Sensor: Obtain profiles of Humidity, Clouds and Temperature in the TTL.

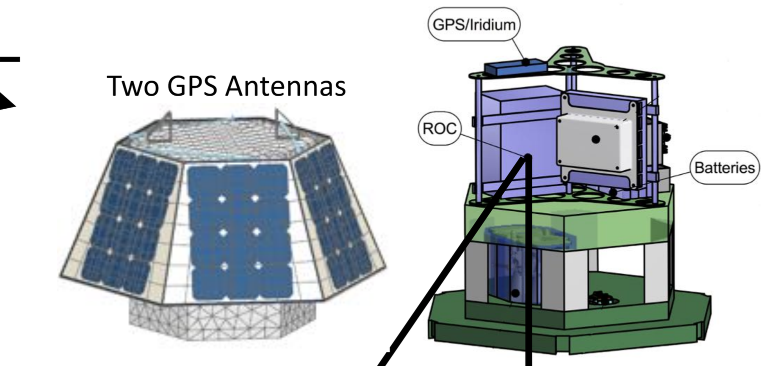
Additional Instruments

- **LPC** – LASP Particle Counter LPC **(Aerosols)**
- **LOAC** – Light Optical Aerosol Counter **(Aerosols)**
- **SAWfPHY** – Surface Acoustic Wave frost Point Hygrometer **(H_2O)**
- **BOL-DAIR** – BOLometer Determining Albedo and InfraRed flux **(solar/IR flux)**
- **Pico-SDLA ($H_2O/CO_2/CH_4$)**
- **B-Bop (O_3)**
- **GPS** Positioning

3. Radio OCcultation (ROC) Instrumentations



ROC Block Diagram



ROC in Zephyr

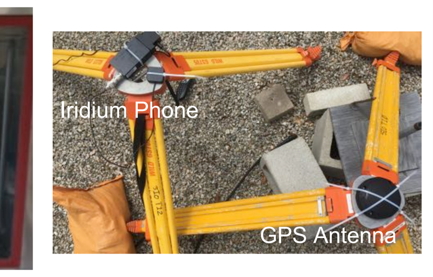
ROC Receiver

- The balloon-borne radio occulation instrument contains a multi-frequency Septentrio AsteRx4 GNSS receiver and two side-looking Aero avionics antennas.
- The instrument will interface with the new Zephyr gondola designed by the LMD and an Iridium RUDICS communication modem for data transmission to the Mission Control Center.
- The receiver is capable of tracking all GNSS signals (GPS, GLONASS, Galileo, Beidou). However, tradeoffs will have to be made based on data rates.

GPS Receiver: Septentrio/AsteRx4

Aero Avionics Antennas (L:GNSS R:GPS)

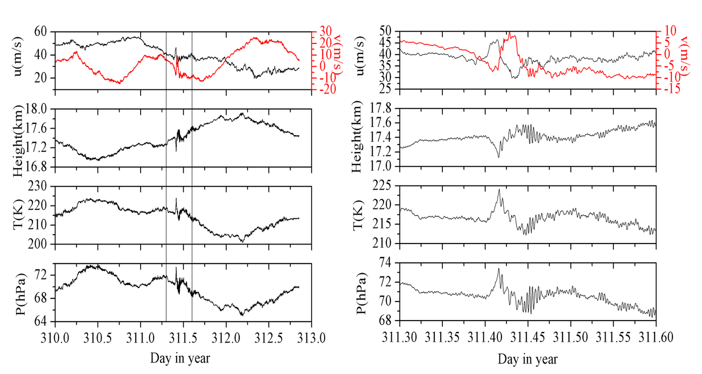
Cold Chamber Test



Iridium Interference Test

4. Example of GW Observations from High Precision GPS Positioning in a Previous Superpressure Balloon Campaign in Antarctica

- Wave signatures when the super-pressure balloon passed over the Antarctic Peninsula from Nov 6 to Nov 8, 2010.
- The real time positions recorded by the single-frequency receivers and the derived velocities (RTP solutions) are compared with solutions derived from the high-accuracy GPS receivers based on the PPPAR method in order to evaluate the improvements from using the high-accuracy GPS receivers.

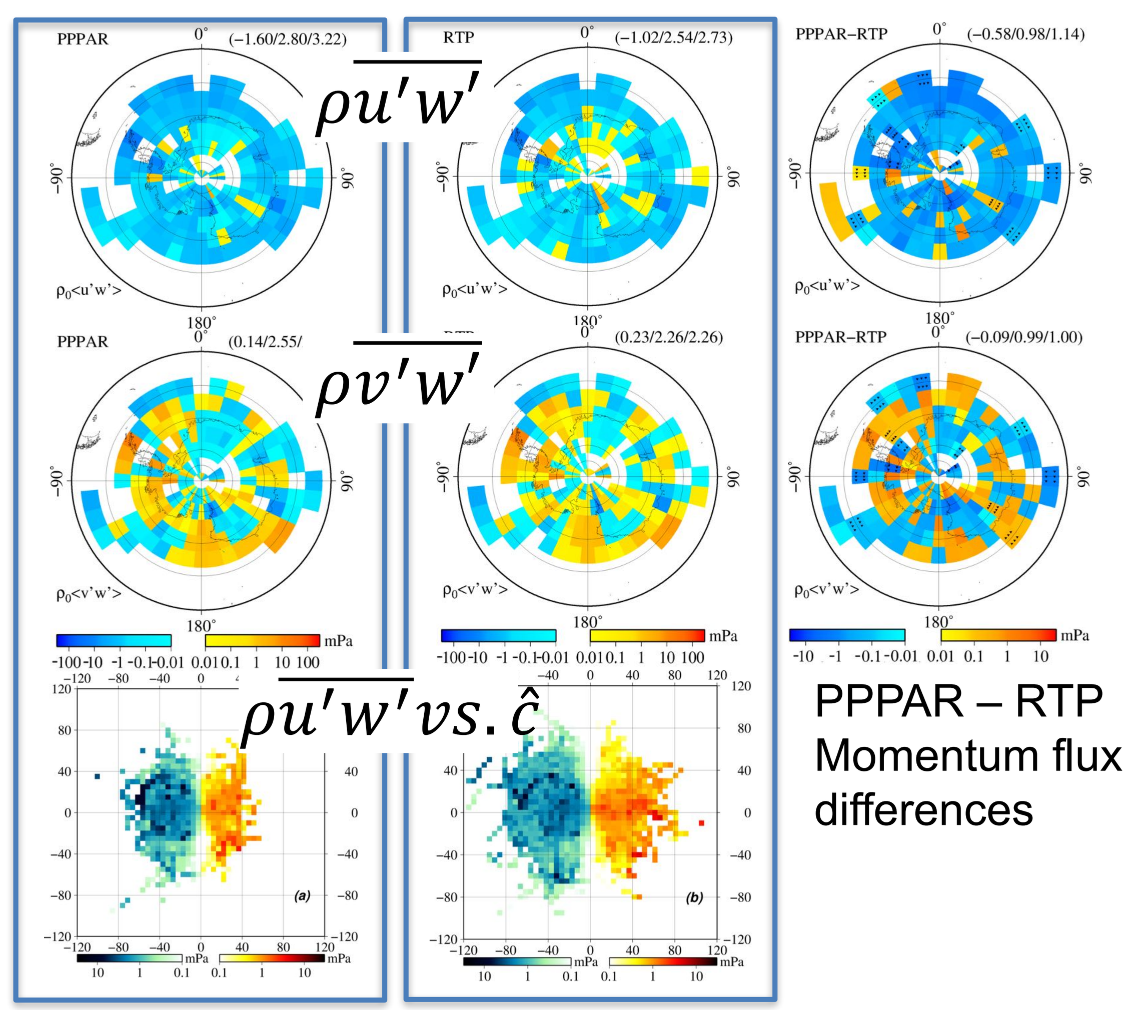


Conclusions and Remarks:

- **High-accuracy receivers enable us to significantly improve the estimated balloon position accuracy with the method.**
- **The results will significantly improve the GW parameterization in GCMs due to more precise flux estimates for high frequency GWs from PPPAR solutions when P' and z' can be determined independently.**

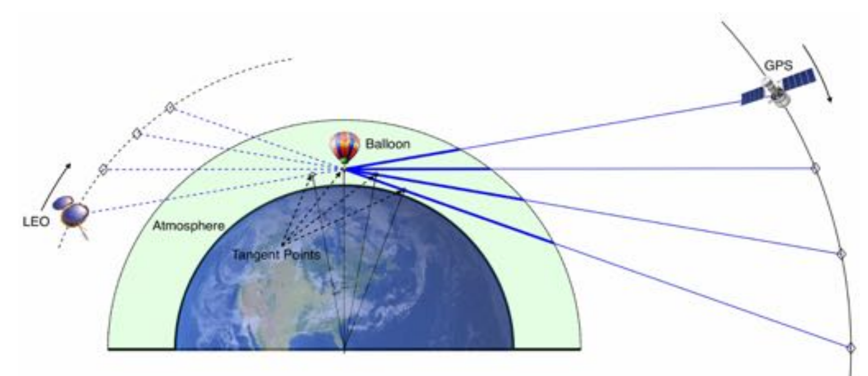
Momentum flux
Precise point positioning with ambiguity resolution using high-accuracy receivers.

Momentum flux
Traditional real time positioning using single-frequency receivers.



- For high frequency gravity waves, the differences between PPPAR and RTP have an RMS of 1.00 mPa, which represents variations 5 times the mean meridional flux of 0.14 mPa and ~40% of intra-bin variations of ~2.55 mPa.
- The PPPAR phase speed distributions have more momentum flux at lower phase speeds and less momentum flux at higher phase speeds.

5. Balloon-borne Radio Occultation



Geometry of Balloon-borne Radio Occultation

- Unlike the space-borne RO where the GPS signals are tracked by receivers outside the Earth atmosphere, the air-borne or balloon-borne RO signals are received within the atmosphere and require an additional correction to retrieve refractivity, N.

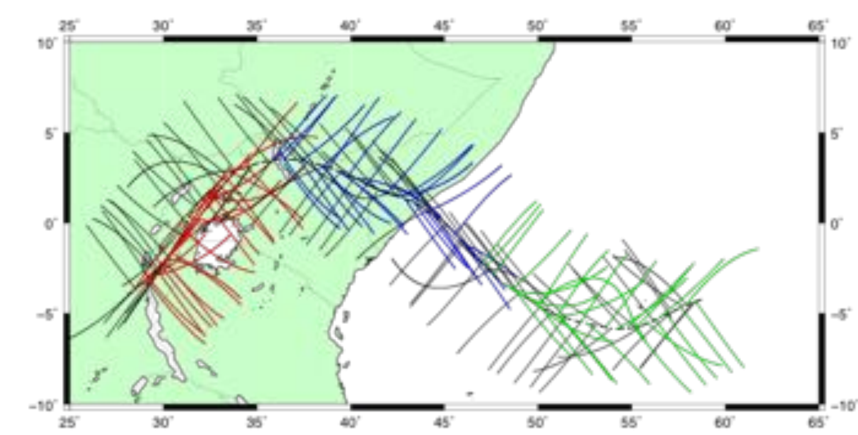
$$N = (n-1)\times 10^6 = 77.6\frac{P}{T} + 37.3\times 10^5\frac{P_w}{T^2}$$

- The bending is an integral along the ray path from the receiver to the tangent point altitude, continuing back up to the altitude of the receiver, and then continuing from the altitude of the receiver to the GPS satellite.

$$\alpha(a) = -2a\int_{r_t}^{r_R}\frac{1}{n}\frac{dn}{dr}\frac{dr}{\sqrt{n^2r^2-a^2}} - a\int_{r_R}^{r_T}\frac{1}{n}\frac{dn}{dr}\frac{dr}{\sqrt{n^2r^2-a^2}}$$

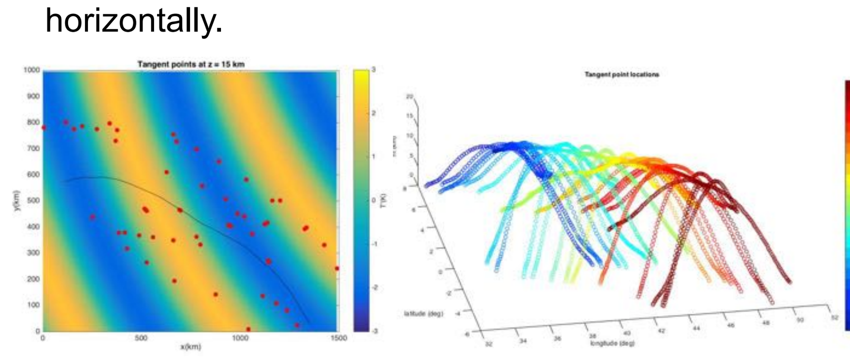
- The partial bending angle corresponds to the accumulated bending from the segment of the ray path below the altitude of the receiver. The partial bending angle (difference between positive and negative elevation angle bending) is inverted using the Abel transform to retrieve the refractive index.

$$n(a) = n_R\cdot\exp\left(\frac{1}{\pi}\int_a^{n_R r_R}\frac{\alpha'(x)dx}{\sqrt{x^2-a^2}}\right)$$



Prediction of occultations to be obtained over 3 days for an equatorial balloon flight such as the 2010 PreConcordiasi flight.

- The profiles of refractivity extend from the balloon flight altitude (20 km) down to ~7-8 km with an accuracy <2%.
- Expect 30 setting and 10 rising GPS occultations per day.
- Rising occultations are less likely to be recorded.
- The occultation (for one profile measurement) takes about 20 min to complete.
- The tangent point drifts as much as 350 km horizontally.



- Because of the tangent point drift, the ROC samples a 3D volume of space around the balloon flight track.
- Wave structures can be studied comprehensively in both horizontal and vertical directions.

6. Summary

- Stratéole-2 is an international project supported by NSF, CNES, and CNRS-LMD involving many research groups in France, USA, Italy, India, and Australia.
- Stratéole-2 will use long-duration balloon campaigns
  a) to address dynamics, transport, microphysics, and dehydration processes as well as their interactions in the deep tropics,
  b) to contribute to operational meteorology and satellite wind lidar calibration and validation.
- Balloons at 20-km altitude will carry the Radio OCcultation (ROC2) instrument. The ROC2 instrument is developed to record and derive:
  a) precise positions for Quasi-lagrangian gravity wave measurements and
  b) radio occultation vertical profiles of temperature variations associated with equatorial waves at different scales, continuously along the trajectory of the balloons.
- Balloon-borne RO measurements provide dense, high vertical resolution sampling contiguous in space and time, which will provide new information on gravity wave characteristics in 3D, as well as their relation to tropical convection and clouds, and will provide insight for GW parameterizations in climate models.

References
Haase et al., 2017, Stratéole-2 – Around the world in 84 days, EOS, in press, http://agsweb.ucsd.edu/strateole2/publications/strateole2_eos.pdf
Zhang et al., 2016. Position Improvements and impacts on GWs, J. Geophys. Res. Atmos., 121, 9977–9997, doi:10.1002/2015JD024596.

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