GEODESY FOR A RESILIENT AFRICA

# 1.The DORIS system and its principles

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DORIS special session

DORIS IDS

# What we will cover

### Why DORIS?
The reference frame, orbits and sea level — the motivation

### The system
Space segment, ground segment and the global network

### The measurement
Doppler shift, the observation equation, corrections

### Science & future
Applications, the Genesis mission, how to get involved

DEFINITION

# What is DORIS?

**D**

**Doppler**

frequency shift is the observable

**O**

**Orbitography**

built to compute precise orbits

**R**

**Radiopositioning**

radio signals position the stations

**I+S**

**Integrated on Satellite**

the receiver flies on the satellite

### The key idea — an inverted GNSS

**Ground beacons transmit; the satellite receives.** A worldwide network of ~60 beacons emits two stable radio frequencies. A receiver on board each satellite measures the Doppler shift of these signals every 10 seconds — from which we recover orbits, station positions and Earth orientation. Developed by CNES, IGN and CLS (France); one of the four space-geodetic techniques alongside GNSS, SLR and VLBI.

# Why do we need DORIS?

### The reference frame

One of the four techniques contributing to the ITRF — weekly station coordinates and Earth Orientation Parameters since 2005 (IDS).

### Precise orbits (POD)

Centimetre-level orbits for altimetry satellites. Without the orbit, the altimeter range is meaningless: SSH = orbit height – range.

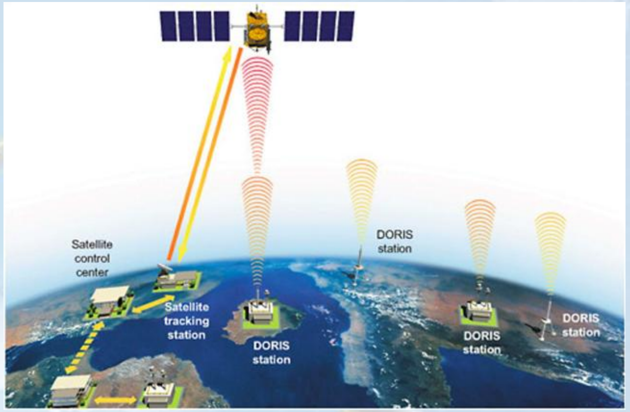
### Sea level & climate

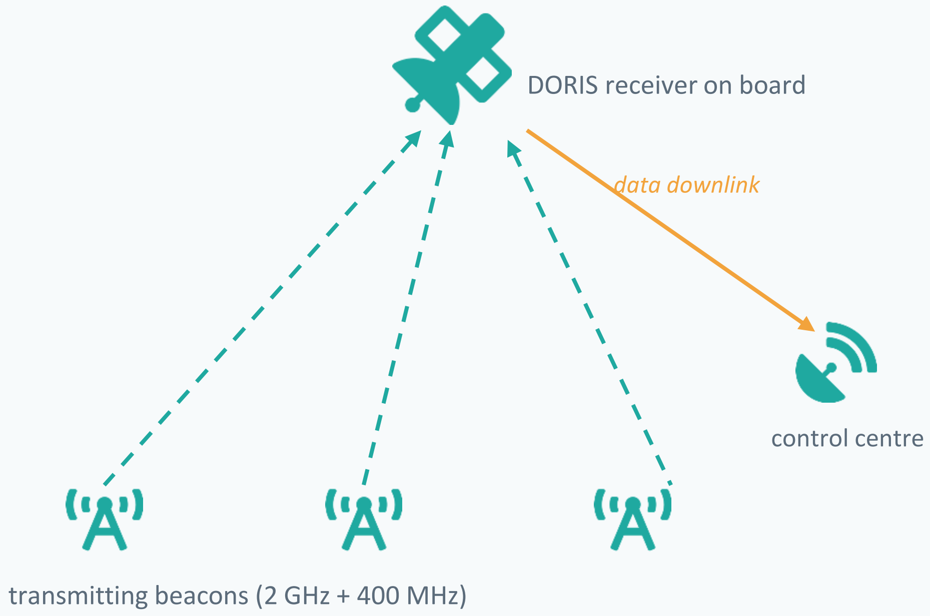
Underpins the global mean sea-level record: a rise of 3.0 ± 0.4 mm/yr measured by TOPEX and the Jason series — orbits flown on DORIS.

### Geophysics

Station time series reveal plate tectonics, post-seismic motion — and even uncovered a submarine volcanic eruption at Socorro Island.

# The DORIS system — four building blocks




**1 · Global beacon network**
~60 autonomous transmitting stations, evenly spread over the

**2 · The DORIS signal**
Two modulated frequencies: 2.03625 GHz and 401.25 MHz.

**3 · On-board receivers**
Every host satellite carries the same receiver + ultra-stable oscillator.

**4 · Control centre**
Receives the satellite observations, monitors and commands the network.

SPACE SEGMENT

# The host-satellite constellation, 1990–2035+

| Era | Missions (DORIS on board) | Agencies |
|---|---|---|
| Past | SPOT-2/3/4/5, TOPEX/Poseidon, Jason-1/2, Envisat, HY-2A | CNES · NASA · ESA · CNSA |
| Current | Cryosat-2, SARAL, Jason-3, Sentinel-3A/3B, Sentinel-6A, SWOT, HY-2C/2D | ESA · NASA · CNES · ISRO · CNSA |
| Future | Sentinel-3C/3D, Sentinel-6B, HY-2E…H, Genesis (ESA, dedicated to the ITRF) | ESA · CNSA |

**35+ yr**
continuous Doppler
data record since 1990

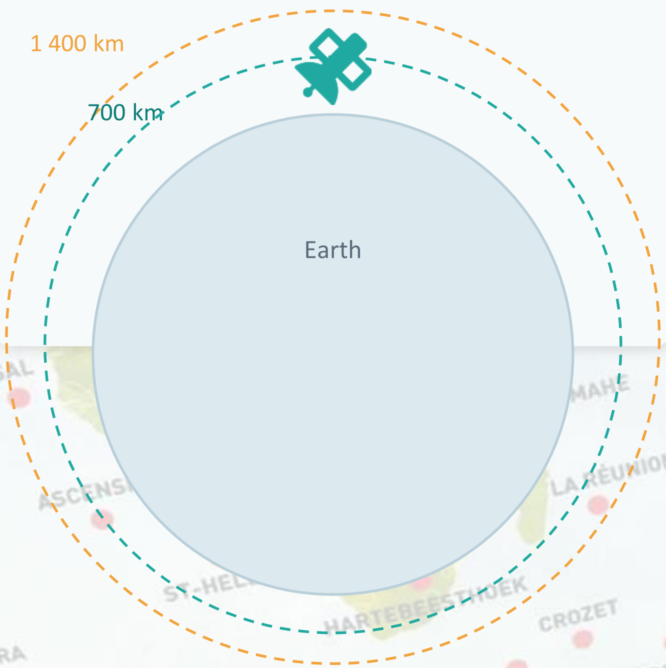
**10+**
satellites currently flying
a DORIS receiver

**S / G**
most hosts also carry SLR
and GNSS — co-location in space

# The orbits of the host satellites

- Low Earth Orbit: altitudes from 700 km to 1 400 km
- Inclinations 66° (Sentinel-6A), 77° (SWOT), 92° (Cryosat-2), 98° near-polar (Sentinel-3B)
- Main perturbations: atmospheric drag (LEO) and solar radiation pressure (satellite shape)
- Ground tracks densely cover the globe — every beacon is seen many times per day

LEO shell hosting the DORIS constellation



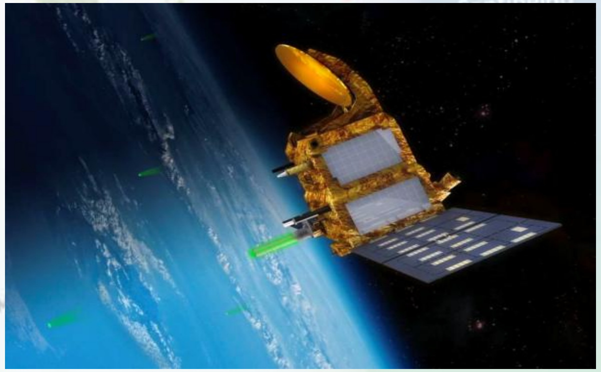

**Quick check — how fast is it going?**

$v = \sqrt{GM/R}$ with $R = R_\oplus + 800$ km $\rightarrow$ **$v \approx 7.5$ km/s**

Kepler's third law — this enormous relative velocity is exactly what makes the Doppler shift measurable.

Sentinel-6A


SWO



Saral



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# The DORIS on-board instrument

**Dual-frequency omnidirectional antenna**
Receives 2 GHz and 400 MHz simultaneously from all beacons in view — up to 7 beacons tracked at once.

**Receiver with two chains**
A nominal and a redundant receiving chain for reliability over a 10+ year mission.

**Two Ultra-Stable Oscillators (USO)**
One per chain. The on-board frequency reference — its stability (ADEV ~$5\times10^{-13}$ at 1000 s) drives the measurement quality.

**DIODE navigator software**
Real-time on-board orbit determination — DORIS is also an autonomous navigator.

*5th-generation DORIS receiver currently under development at CNES.*

# Inside a DORIS ground station

**1** **Beacon 4.0 (indoor)**

Generates the two modulated signals (401.25 MHz / 2.03625 GHz); houses the reference oscillator, synthesizer, management board and power.

**2** **Starec C antenna**

Omnidirectional — transmits the beacon signal towards every satellite above the horizon, with a well-defined phase-centre.

**3** **MGM box (external)**

Remote control, Iridium modem, a GPS sensor, and meteorological sensors (pressure, temperature, humidity — used for the troposphere correction).

**4** **Amplifier box (external)**

Signal amplification plus remote-control electronics.

## Site requirements

- Continuous service: 24/7, 365 days
- Clear view of the sky — visibility from LEO satellites
- Stability of the antenna monument
- Sites run for decades: Everest, Ny-Ålesund, Socorro, Arequipa…

# The DORIS network — even global coverage

**~60**

beacon sites worldwide, remarkably even distribution

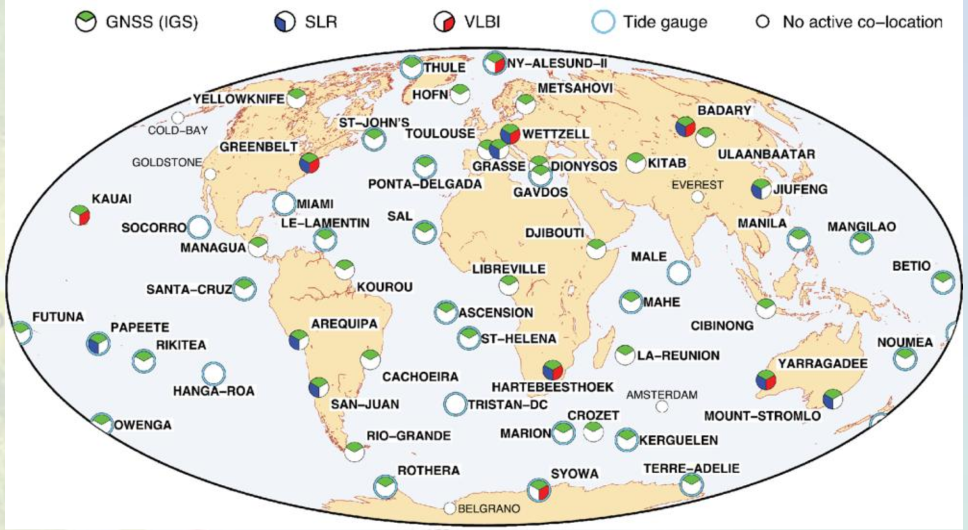
**35+**

co-located with GNSS, SLR, VLBI and/or tide gauges

**3**

master / time beacons class: Toulouse, Kourou, Hartebeesthoek…

- Southern hemisphere and ocean islands are well covered (Kerguelen, Crozet, Betio, Rikitea, Terre-Adélie…) — unlike any other technique
- Co-location with the other techniques provides the local ties that glue the ITRF together
- Master beacons are synchronised to TAI and broadcast the timing reference for the whole system
- Africa hosts key sites: Hartebeesthoek (master beacon, co-located with VLBI/SLR/GNSS), Libreville, Djibouti, La Réunion, Sal, St-Helena, Ascension



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| Station | Country/Territory | Code | Approx. Latitude | Approx. Longitude | Co-located Techniques / Remarks |
|---|---|---|---|---|---|
| Djibouti | Djibouti | DJIB | 11.5° N | 42.9° E | GNSS co-location; East African Rift region |
| Hartebeesthoek | South Africa | HBKB | 25.9° S | 27.7° E | Co-located with VLBI, SLR and GNSS; major geodetic observatory |
| Libreville | Gabon | LIBB | 0.4° N | 9.7° E | GNSS co-location; equatorial Africa |
| Mahé | Seychelles | MAHB | 4.7° S | 55.5° E | Island station; Indian Ocean coverage |
| Marion Island | South Africa | MARB | 46.9° S | 37.9° E | Remote sub-Antarctic island; important southern hemisphere coverage |
| La Réunion | France (Réunion) | REUB | 21.2° S | 55.5° E | GNSS co-location; volcanic island in Indian Ocean |
| Sal | Cape Verde | SALB | 16.7° N | 22.9° W | Atlantic island station; GNSS co-location |
| St Helena | UK Territory | HELB | 15.9° S | 5.7° W | South Atlantic island station |
| Tristan da Cunha | UK Territory | TRIB | 37.1° S | 12.3° W | One of the world's most isolated DORIS sites |
| Ascension Island | UK Territory | ASEB | 7.9° S | 14.3° W | Strategic Atlantic station; GNSS co-location |
| Crozet | France (Crozet Islands) | CRRC | 46.4° S | 51.9° E | Southern Indian Ocean island station |
| Amsterdam Island | France (TAAF) | AMVB | 37.8° S | 77.6° E | Remote southern Indian Ocean site |

# The Doppler principle

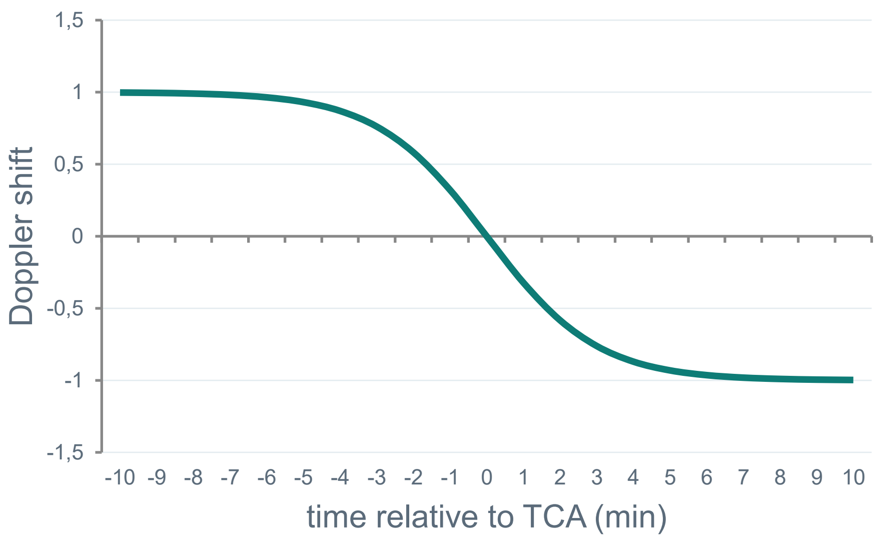
$$f_r = f_e\,(1 - v / c)$$

fe: beacon frequency · fr: received frequency
v: relative (line-of-sight) velocity · c: speed of light

**Approaching**
received frequency HIGHER than transmitted

**TCA — closest approach**
received = transmitted; satellite passes overhead the beacon

**Receding**
received frequency LOWER than transmitted




*The slope of the curve at TCA gives the beacon–satellite distance — one pass already constrains the geometry.*

# What the receiver actually records

**10 s**
one Doppler / phase measurement every 10 seconds (3 or 7 s on some missions)

**2.036 GHz**
the precise measurement frequency

**401.25 MHz**
second frequency — used to correct the ionosphere

**7**
beacons tracked simultaneously by modern receivers

## From RINEX file to science product

Data are distributed as DORIS RINEX files: **ambiguous phase L1, L2 · pseudo-ranges C1, C2 · receiver frequency offset F · in-situ pressure, temperature, humidity** — time-tagged in the on-board (DIODE) timescale with an offset to TAI. The analysis centres turn these into Precise Orbit Ephemerides, station coordinates and EOP, all expressed in the ITRF.

# The DORIS observation equation

- Between two events the beacon emits Ne cycles at frequency fe
- Over the same interval the receiver generates Nr cycles with its own oscillator at fr
- The receiver measures the phase difference between received and generated signals every Δt = 10 s
- Differentiating gives the Doppler count N_Dop → a range-rate (velocity) observable

*DORIS is a clock-comparison experiment: ground USO vs flying USO, linked by a radio signal.*

**Simplified velocity equation**

$$V_{\mathrm{E}\rightarrow\mathrm{R}} = (c / f_e) \cdot (f_e - f_r - N_{Dop} / \Delta t)$$

the relative velocity between emitter and receiver, projected on the line of sight (Lemoine et al., 2016)

**In reality: frequency offsets**

Replace $f_e \rightarrow f_e+\Delta f_e$ and $f_r \rightarrow f_r+\Delta f_r$. The two offsets cannot be separated: DIODE provides an approximate $\Delta f_r$, and $\Delta f_e$ is adjusted by least squares for every pass during orbit determination.

# Corrections — from raw Doppler to geodesy

### Ionosphere

Dispersive: removed to first order with the dual frequencies (next slide).

### Troposphere

Dry + wet delay from station met data or models (VMF-1); a zenith bias is still adjusted per pass.

### Time-tagging

Epochs in the on-board timescale; synchronised to TAI via master-beacon bits to 1–2 µs.

### Light-time effect

The signal needs ~2–4 ms to travel; emitter and receiver move meanwhile — must be modelled.

### Phase wind-up

Rotating circular-polarised antennas add phase; matters during attitude manoeuvres.

### Relativity

Clock rates depend on potential U and speed V; signal path is curved — both corrected.

**Plus a DORIS speciality — the South Atlantic Anomaly (SAA):** high-energy protons perturb the USO of some satellites (Jason-1, Sentinel-6); the effect must be modelled or it leaks into station heights.

# Why two frequencies? The ionosphere

- The ionosphere is dispersive — the delay depends on frequency
- Measure the same path at two frequencies and you can solve for both unknowns
- α converts to the Total Electron Content (TEC) along the path
- $r_0$ — the ionosphere-free range — is what goes into orbit determination

**Two equations, two unknowns**

$$r(f_1) = r_0 + \alpha / f_1^{\,2}$$
$$r(f_2) = r_0 + \alpha / f_2^{\,2}$$

$f_1$ = 2.03625 GHz, $f_2$ = 401.25 MHz → $\gamma = (f_1/f_2)^2 \approx 25.75$

## Caution from the experts

The 2 GHz and 400 MHz phase centres of any antenna do not coincide. The iono-free combination therefore has its own 'iono-free phase centre', a few mm from the 2 GHz one, opposite to the 400 MHz centre — forget this and you bias your orbits at the mm level.

# DORIS vs GNSS — siblings, not twins

| | DORIS | GNSS |
|---|---|---|
| **Signal direction** | Uplink: ground → satellite | Downlink: satellite → ground |
| **Frequencies** | 401.25 MHz & 2.03625 GHz (far apart) | L-band, ~1.2–1.6 GHz (close together) |
| **Observables** | Carrier phase + pseudo-range, 2 freq. — but no redundancy: no easy instant navigation | Pseudo-ranges to ≥4 satellites → instant point positioning |
| **Real-time orbits** | DIODE navigator on board | Receiver navigation solution |
| **Network control** | One agency, even global design | Heterogeneous, dense in the north |
| **Data flow** | Centralised, disseminated as RINEX | User-collected, RINEX |

# What DORIS delivers

### Global mean sea level

3.0 ± 0.4 mm/yr rise since 1992, from TOPEX → Jason-1/2/3 — every orbit computed with DORIS. Also tides, currents, ENSO.

### ITRF & EOP

Weekly station coordinates and polar motion in ITRF2020; DORIS contributes scale & translation parameters and its uniquely even network.

### Ever-improving precision

Station residuals fell from ~15–20 mm (1st-gen, 1 beacon) to ~5 mm (3rd-gen, 7 beacons). EOP scatter shrank accordingly.

### Unexpected geophysics

Socorro Island time series revealed a submarine volcanic eruption — cm-level deformation captured by a beacon doing its routine job.

# An exciting future

### ESA Genesis mission

One satellite carrying ALL FOUR techniques — DORIS, GNSS, SLR, VLBI — co-located in space, dedicated to the ITRF. Goal: 1 mm accuracy, 0.1 mm/yr stability

### Missions to 2035 and beyond

Sentinel-3C/3D, Sentinel-6B already agreed; HY-2E…H pending. The DORIS data record will exceed 45 years.

### New hardware & sites

5th-generation receiver in development at CNES; new ground beacons joining the network.

# Key points to take home

- DORIS is one of the four space-geodetic techniques — Doppler measurements at 401.25 MHz and 2.03625 GHz
- The signal goes UP: transmitted by ~60 evenly-distributed ground beacons, received on board the satellites
- The observable is a phase / Doppler count every 10 s → line-of-sight velocity: $V = (c/fe)(fe - fr - N\_Dop/\Delta t)$
- Corrections matter: ionosphere (dual frequency), troposphere, frequency offsets, light-time, relativity, phase wind-up, SAA
- Products: precise orbits in the ITRF, weekly station coordinates, Earth Orientation Parameters — feeding altimetry and sea-level science
- The future is bright: missions to 2035+, a 5th-generation receiver, and ESA's Genesis mission dedicated to the ITRF

**Self-test**

Can you explain to a colleague why DORIS needs two frequencies, and why a frequency bias is estimated every pass?

# Thank you — questions?

*Get involved with the International DORIS Service (IDS)*

- Data, products & documentation:  ids-doris.org
- Meetings: DORIS Analysis Working Group (2×/yr) · IDS Workshop (every 2 yrs) · DORIS Days hands-on school
- Meet IDS members at AGU, EGU and IAG assemblies
- Contact:  ids-central.bureau@ids-doris.org