FUTURE CIRCULAR COLLIDER

COORDINATE REFERENCE AND NETWORKS

FCC week 2022, June 1st, 2022, Paris, France

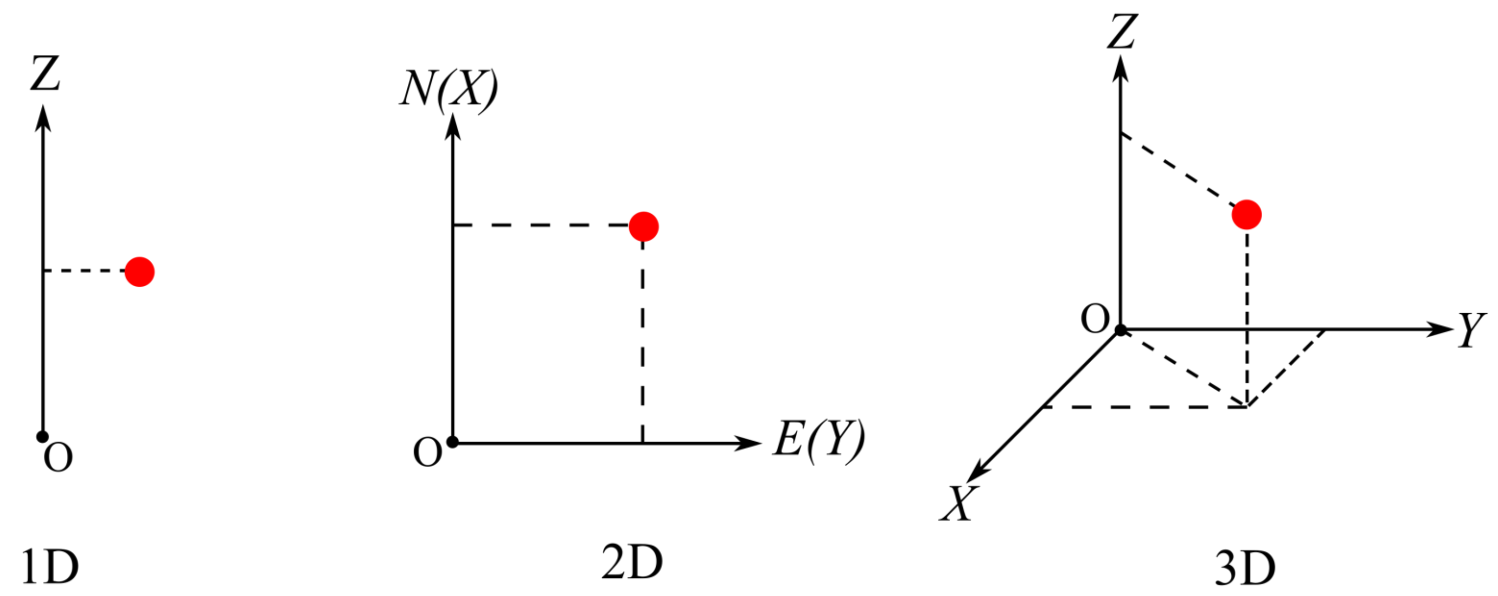
Dr. Matej Varga
ETH Zürich
Institute of Geodesy and Photogrammetry
Geosensors and Engineering Geodesy

Outline

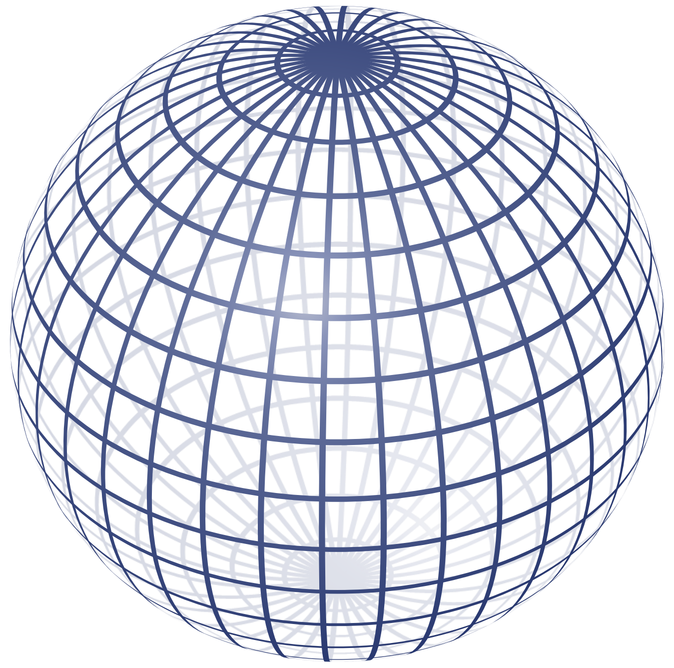
1. **Why coordinate reference systems and geodetic networks are needed for FCC**

2. **Summary of CERN's existing solutions**

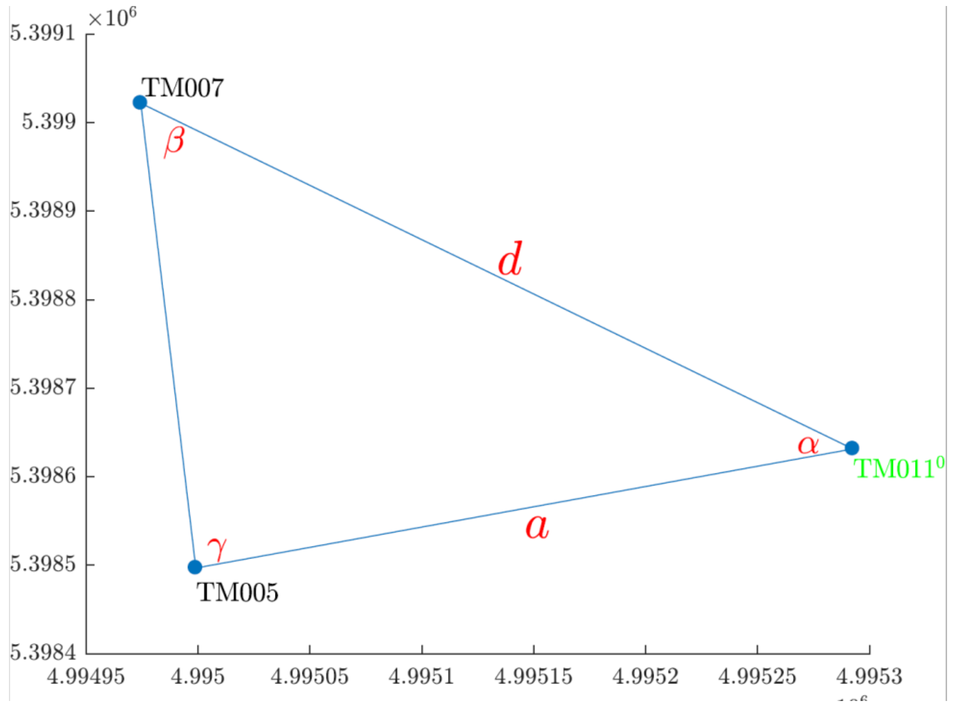
3. **How coordinate reference systems and geodetic networks should be designed and implemented**



Cartesian coordinate systems



An ellipsoid: the fundamental geodetic surface



The example of simple geodetic network consisting from 3 points

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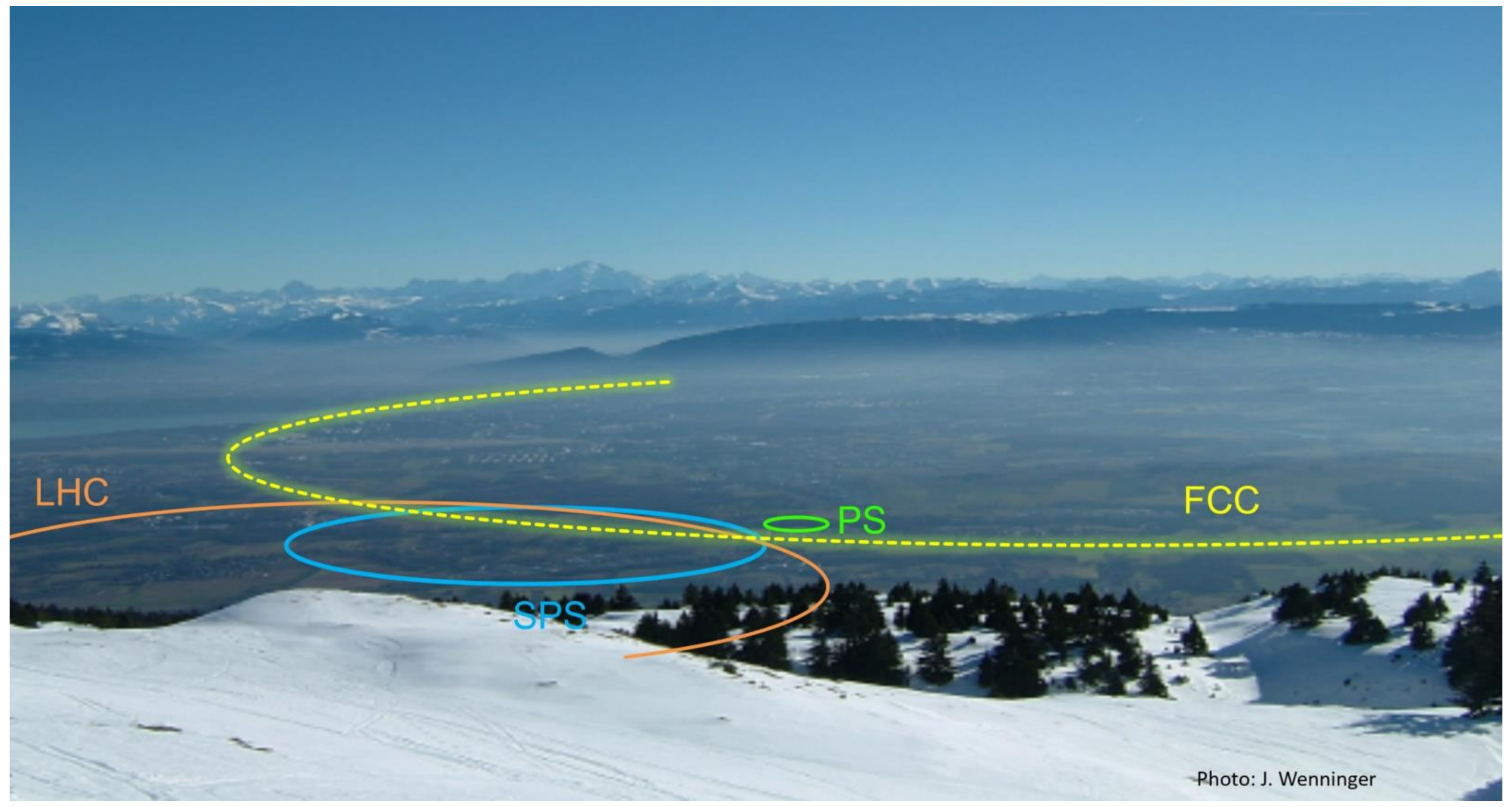
Background: FCC-Geodesy project

- Project of CERN, ETHZ, HEIG-VD and swisstopo (2021-2024)
- French and Swiss national mapping agencies in Advisory Board
- Main objective: **propose solutions and conceptually develop geodetic infrastructure for the construction, operation and maintainance of the FCC**
- **Geodetic infrastructure includes:**
  1. Coordinate reference system (CRS)
  2. Geodetic networks (GN)
  3. Documentation
  4. Tools



The illustration of the FCC tunnel over the wider Geneva area

Geodetic equipment, @GSEG, ETHZ

Use of CRS at CERN

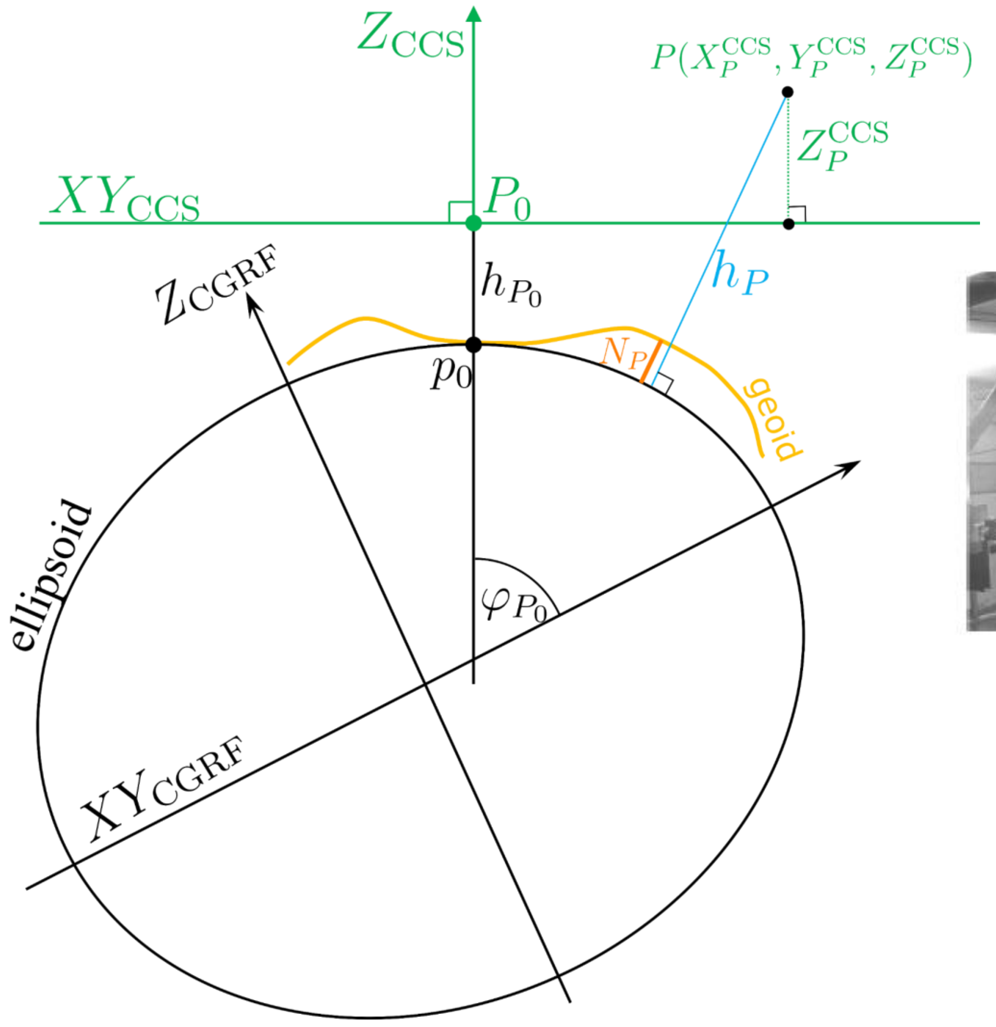
Purposes

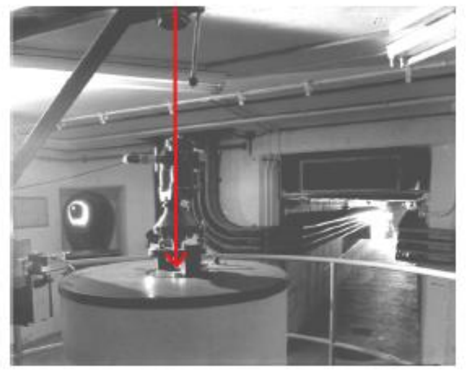
1. Civil engineering including tunnelling
2. Installation and maintenance of infrastructure above/below ground
3. Monitoring crustal deformations
4. Connecting facilities to others (locally, nationally, internationally)
5. Accelerator alignment

Practical requirements

1. Reusability of existing infrastructure and solutions
2. Unambiguous conversions and transformations between all systems
3. Update possible if needed
4. Complete and clear definition according to international standards

CRS at CERN: current situation

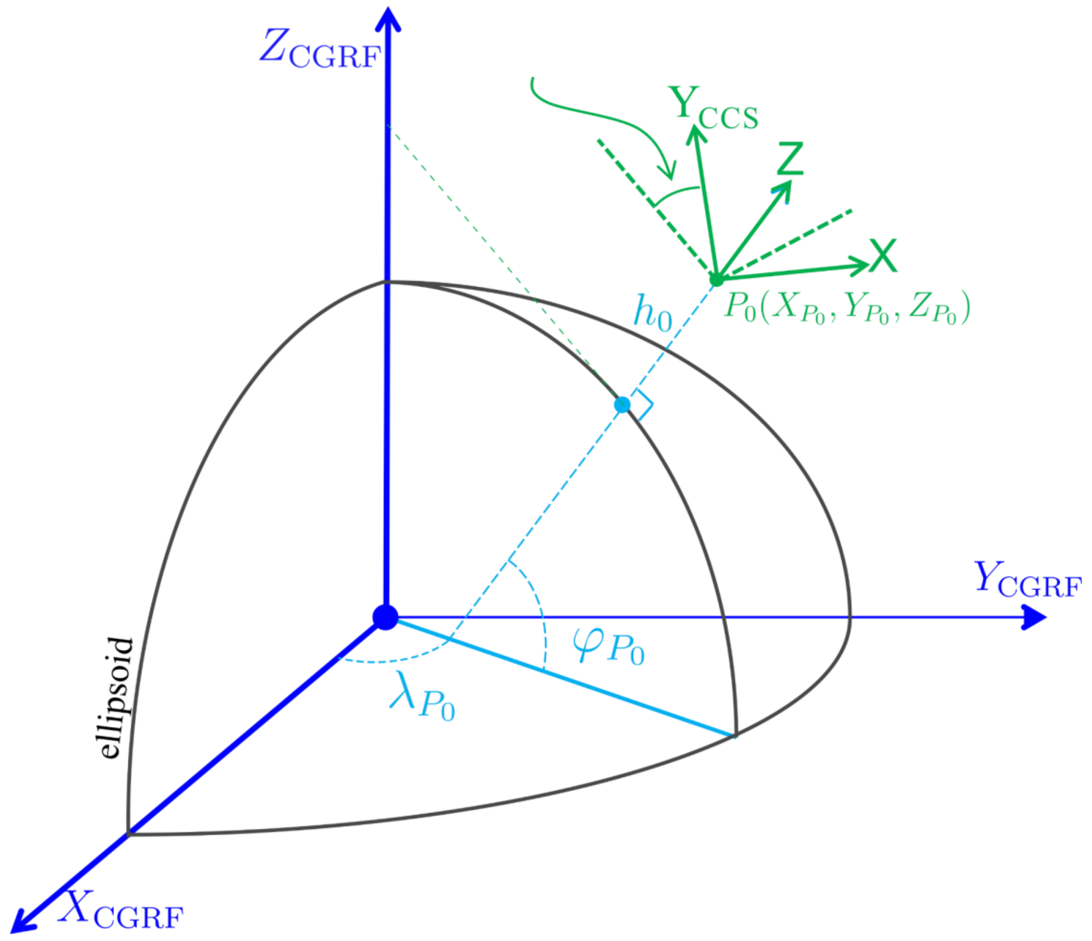




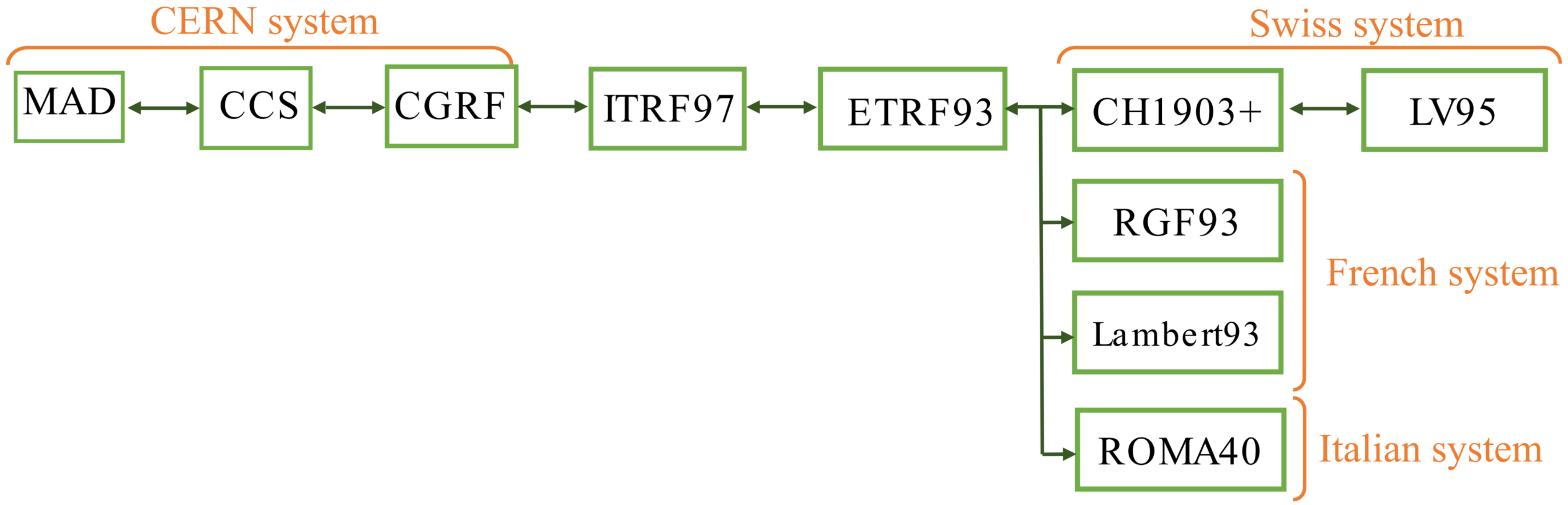
The geometric relations between plane, ellipsoid, and geoid in CCS-e.

Parameter	Symbol	CERN coordinate system			
		CCS-plane (CCS-p)	CCS-sphere (CCS-s)	CCS-ellipsoid (CCS-e) [est. in 2001]	CCS-e [est. in 2016]
Datum for horizontal coordinates	X, Y	plane	plane	plane	plane
Datum for vertical coordinates	Z	plane	plane	plane	plane
Datum for vertical coordinates	h	plane	sphere	ellipsoid	ellipsoid
Datum for vertical coordinates	H	plane	geoid/pseudo-geoid	geoid/pseudo-geoid	geoid/pseudo-geoid
Local topocentric Cartesian coordinates of P_0		in CCS			
	X_{P_0} [m]	2000.00000	2000.00000	2000.00000	2000.00000
	Y_{P_0} [m]	2097.79265	2097.79265	2097.79265	2097.79265
	Z_{P_0} [m]	2433.66000	2433.66000	2000.00079	2000.00079
Global geodetic Coordinates of P_0 in CGRF					
Datum	—	—	sphere	ellipsoid	ellipsoid
Geodetic latitude of P_0	φ_{P_0} [^{g}]	—	—	51.36920	51.36734
Geodetic longitude of P_0	λ_{P_0} [^{g}]	—	—	6.72124	6.722515
Geodetic height of P_0	h_{P_0} [m]	433.65921	433.65921	433.65921	433.65921
Geoid undulation of P_0	N_{P_0} [m]	—	—	0.00000	0.00000
Orientation of reference surface (sphere, ellipsoid)					
Azimuth of the Y-axis CERN :	α_{P_0} [^{g}]	—	—	37.77864	37.779033
N-S component of DOV in P_0	ξ_{P_0} [^{cc}]	—	0.00000	0.00000	0.00000
W-E component of DOV in P_0	η_{P_0} [^{cc}]	—	0.00000	0.00000	0.00000

Numerical definition of CERN coordinate system (CCS) and CERN Geodetic Reference Frame (CGRF)



The geometric relations between CCS-e and CGRF



Different coordinate reference systems (CRS) in use by CERN

CRS for FCC: proposed conceptual solution

CTRS
terrestrial reference system

- connection to CERN, national, and international reference frames
- monitoring crustal deformations

CKM
kinematic model

CPS
projected reference system

- civil engineering
- alignment

CVS
vertical reference system

CLS/MAD
local reference system

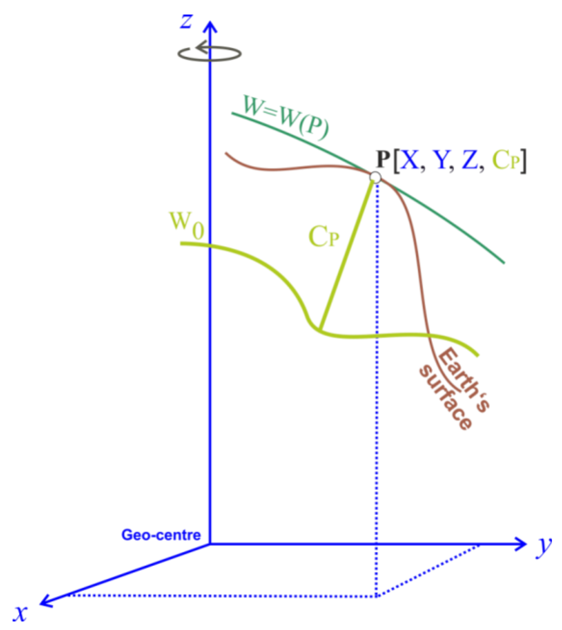
- machine design
- physics

Proposed coordinate reference systems

```
GEOGCS["CTRS21",
  DATUM["CERN_Terrestrial_Reference_System_2021",
    SPHEROID["GRS 1980",6378137,298.257222101,
      AUTHORITY["EPSG","7019"]],
  PRIMEM["Greenwich",0,
    AUTHORITY["EPSG","8901"]],
  UNIT["degree",0.0174532925199433,
    AUTHORITY["EPSG","9122"]],
  AUTHORITY["EPSG","NNNNN"]]
```

```
PROJCS["CPS21",
  GEOGCS["CTRS21",
    DATUM["CERN_Terrestrial_Reference_System_2021",
      SPHEROID["GRS 1980",6378137,298.257222101,
        AUTHORITY["EPSG","7019"]],
    PRIMEM["Greenwich",0,
      AUTHORITY["EPSG","8901"]],
    UNIT["degree",0.0174532925199433,
      AUTHORITY["EPSG","9122"]],
    AUTHORITY["EPSG","NNNNN"]],
  PROJECTION["Transverse_Mercator"],
  PARAMETER["latitude_of_origin",0.00],
  PARAMETER["central_meridian",6.14],
  PARAMETER["scale_factor",1.00006],
  PARAMETER["false_easting",0.0],
  PARAMETER["false_northing",0.0],
  UNIT["metre",1,
    AUTHORITY["EPSG","9001"]],
  AXIS["Easting",EAST],
  AXIS["Northing",NORTH],
  AUTHORITY["EPSG","NNNNN"]]
```

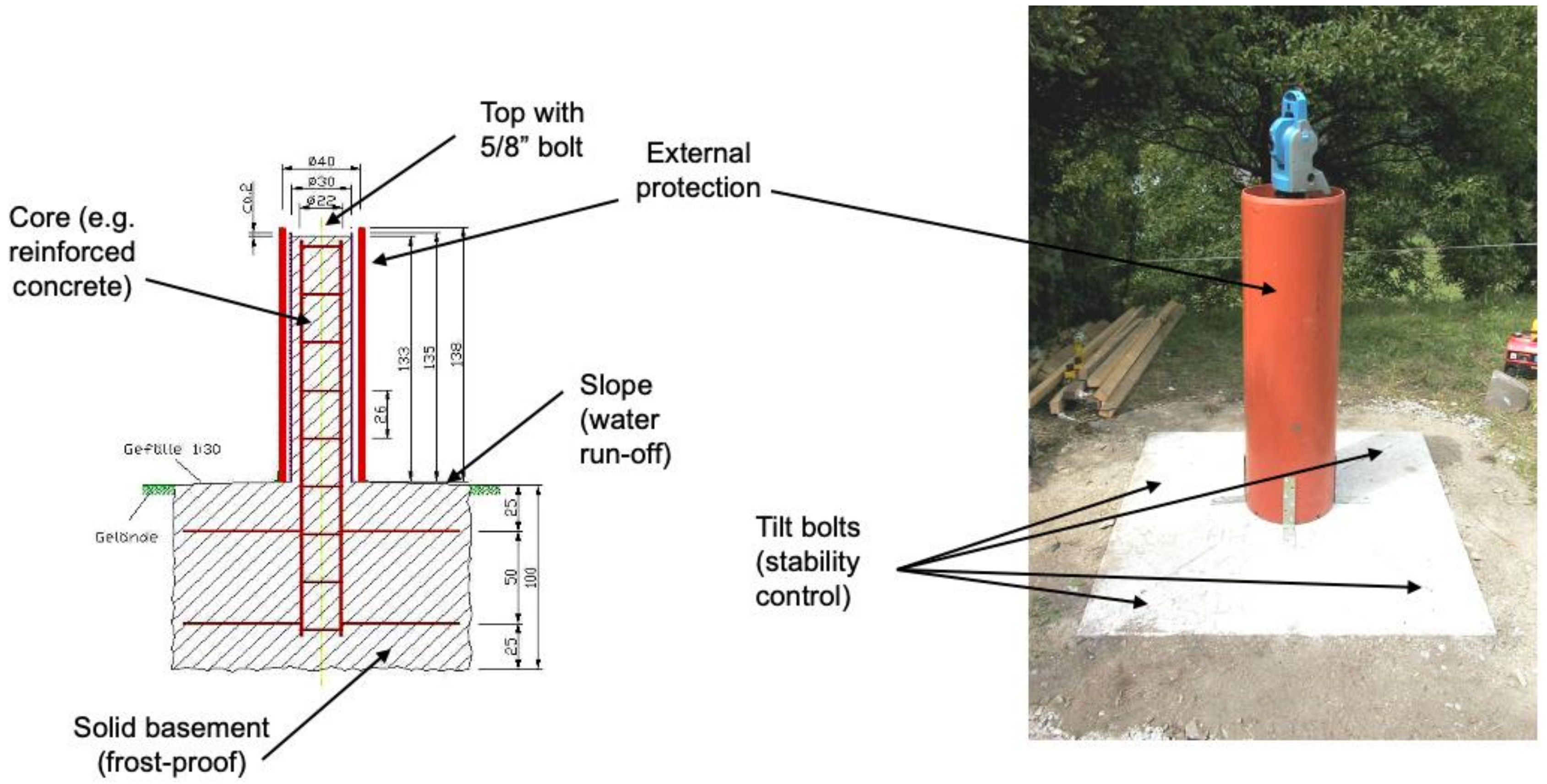
GIS-format (well-known-text) representation of coordinate reference systems



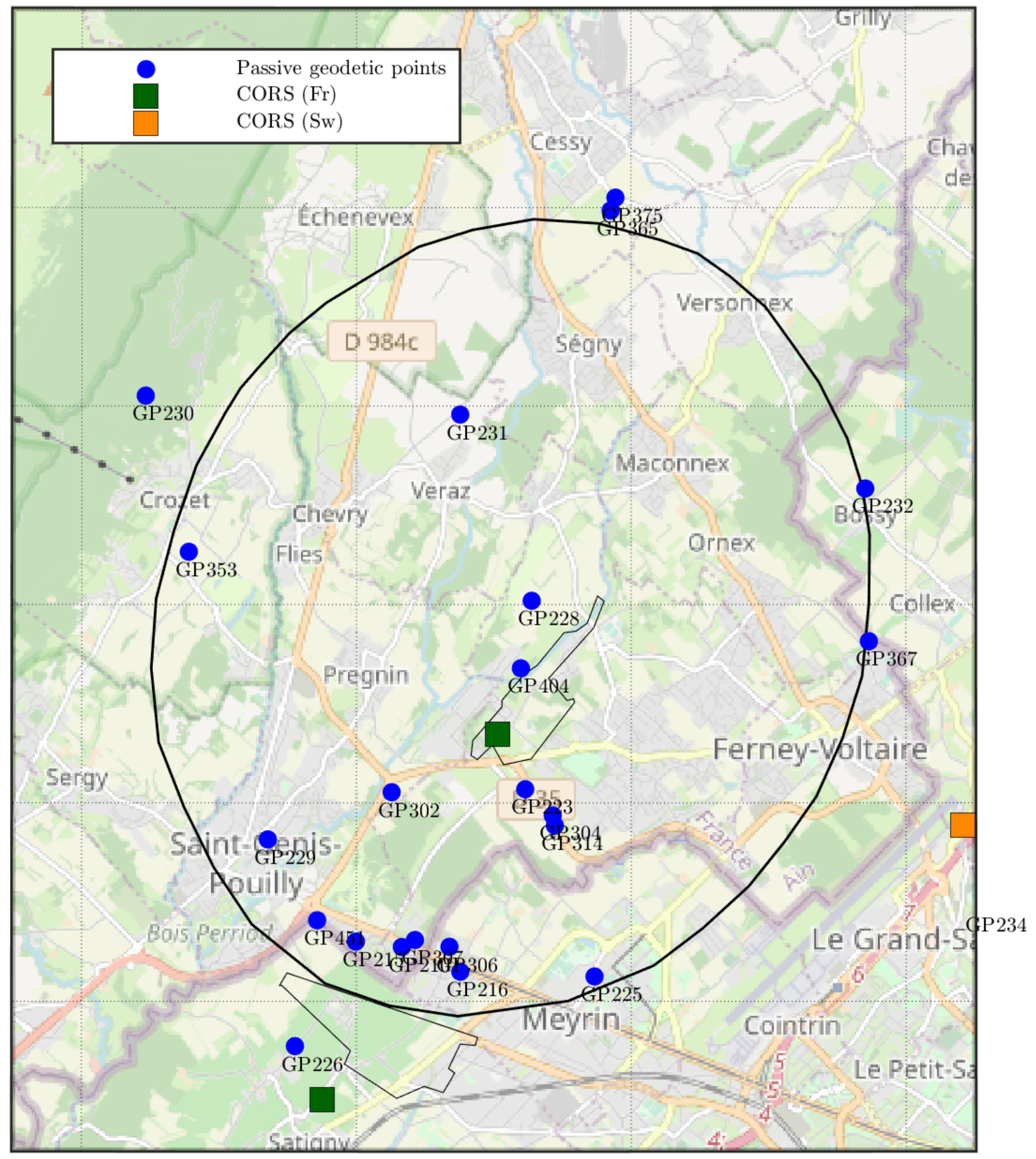
Acronyms: CTRS: CERN terrestrial reference system, CKM: CERN kinematic model, CPS: CERN projection system, CVS: CERN vertical system, CLS: CERN local system, MAD: Machine Aided Design

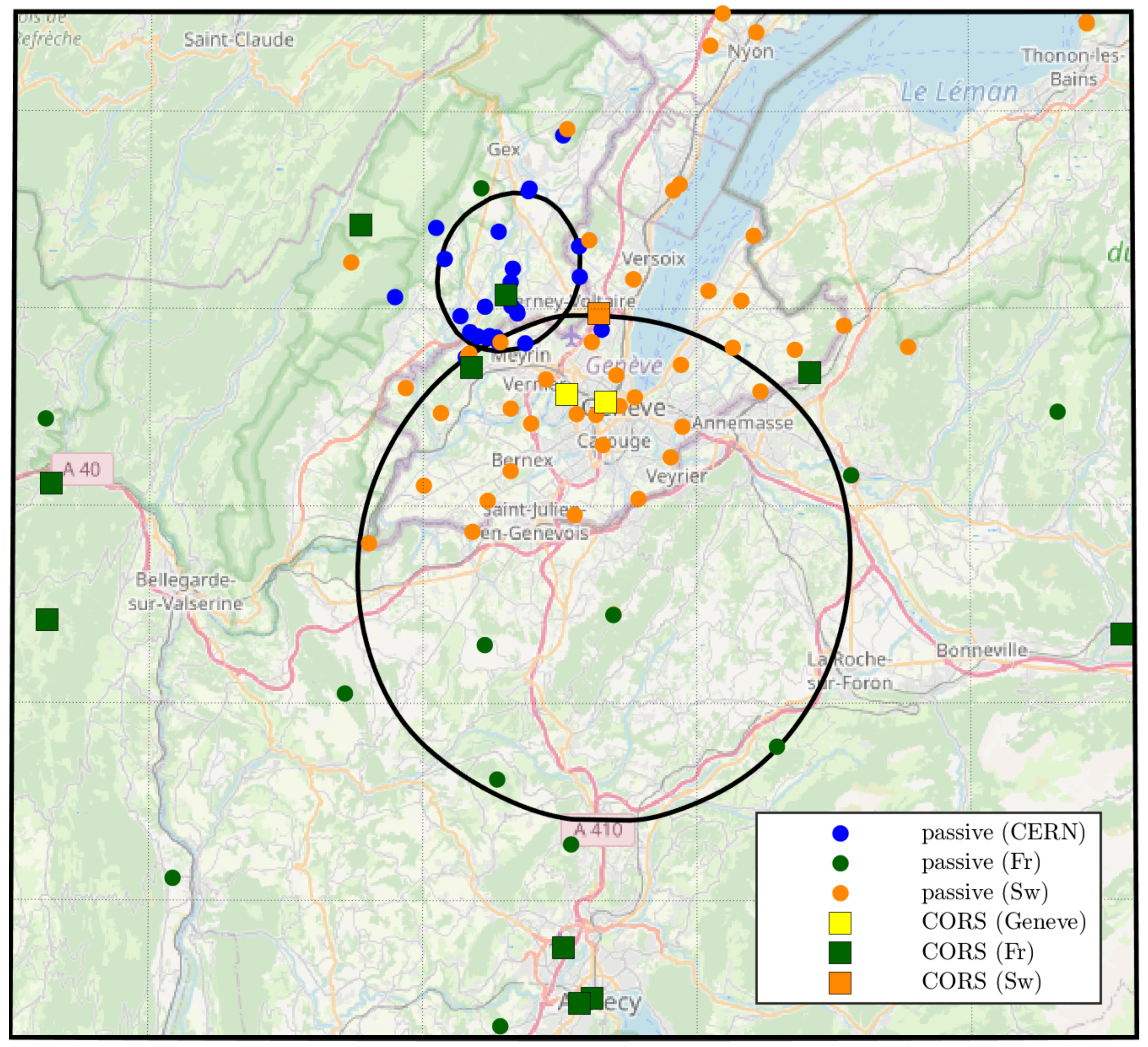
Geodetic networks: introduction

- Geodetic networks enable users an access to coordinates
- Consist from physically materialized points with precisely determined coordinates
- Basis: geodetic instruments and techniques (total-stations, GNSS, levels, laser trackers, …)

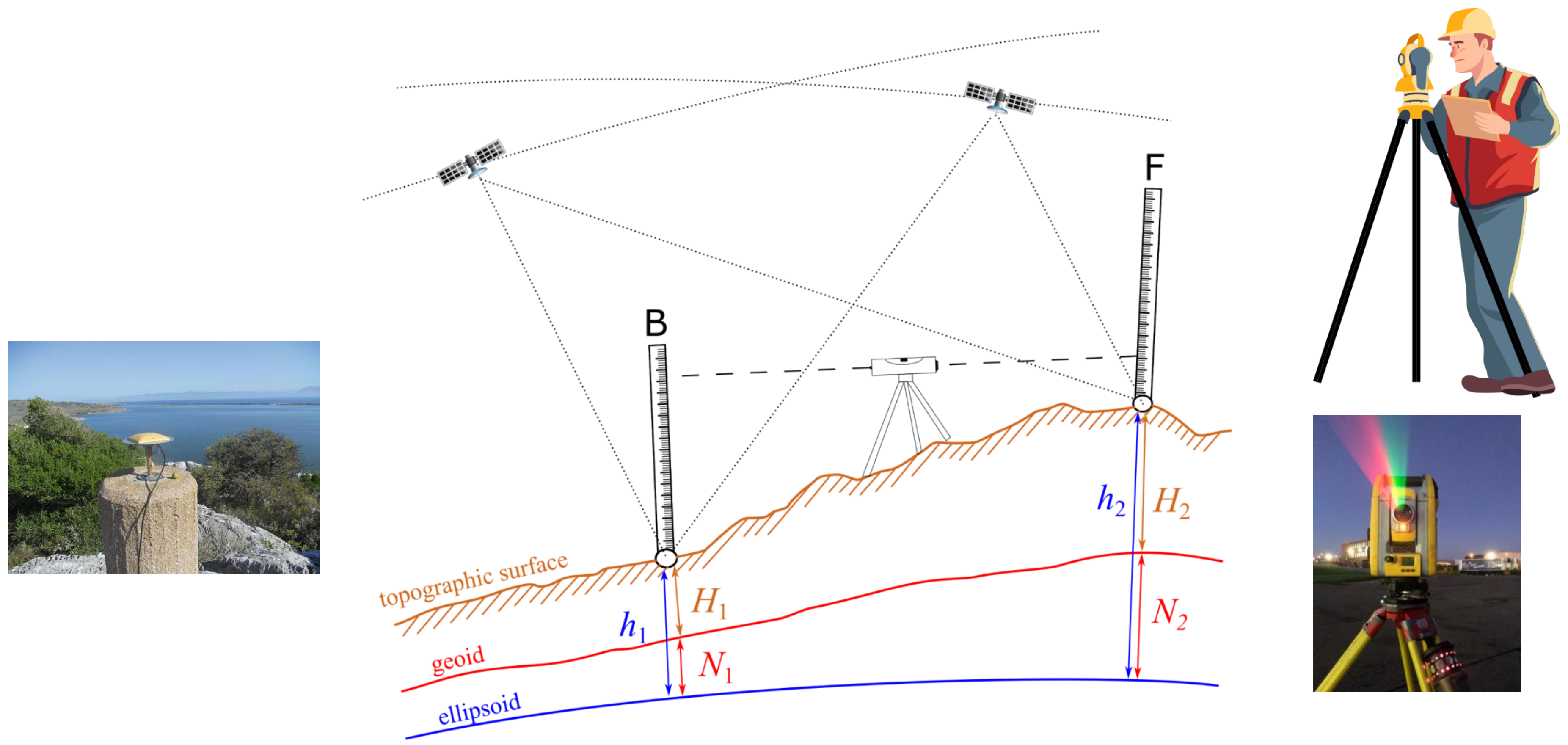


Example of geodetic pillars (source: TU Graz, Institute for Engineering Geodesy and Measurement Systems)





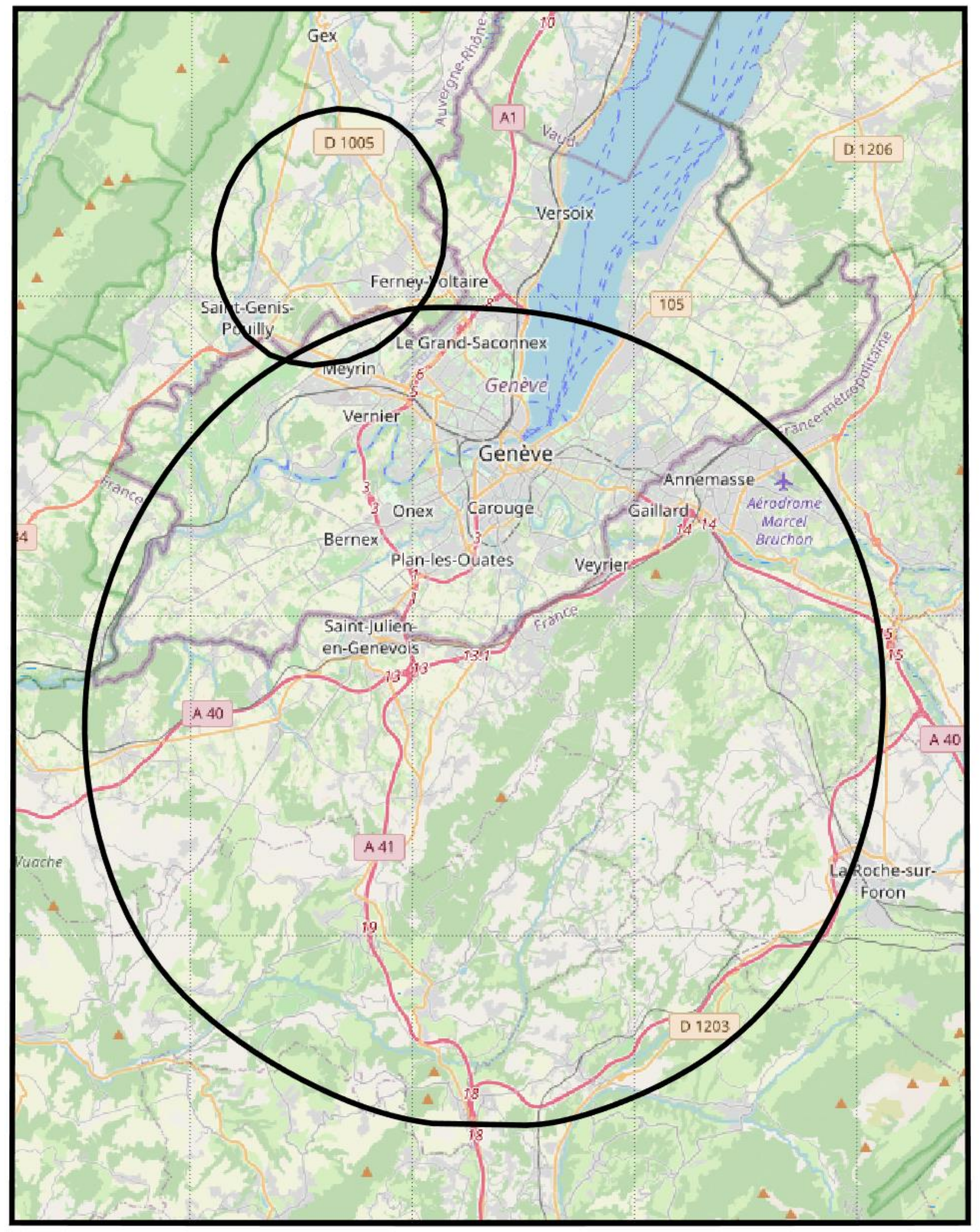
Passive and active geodetic points over the CERN area



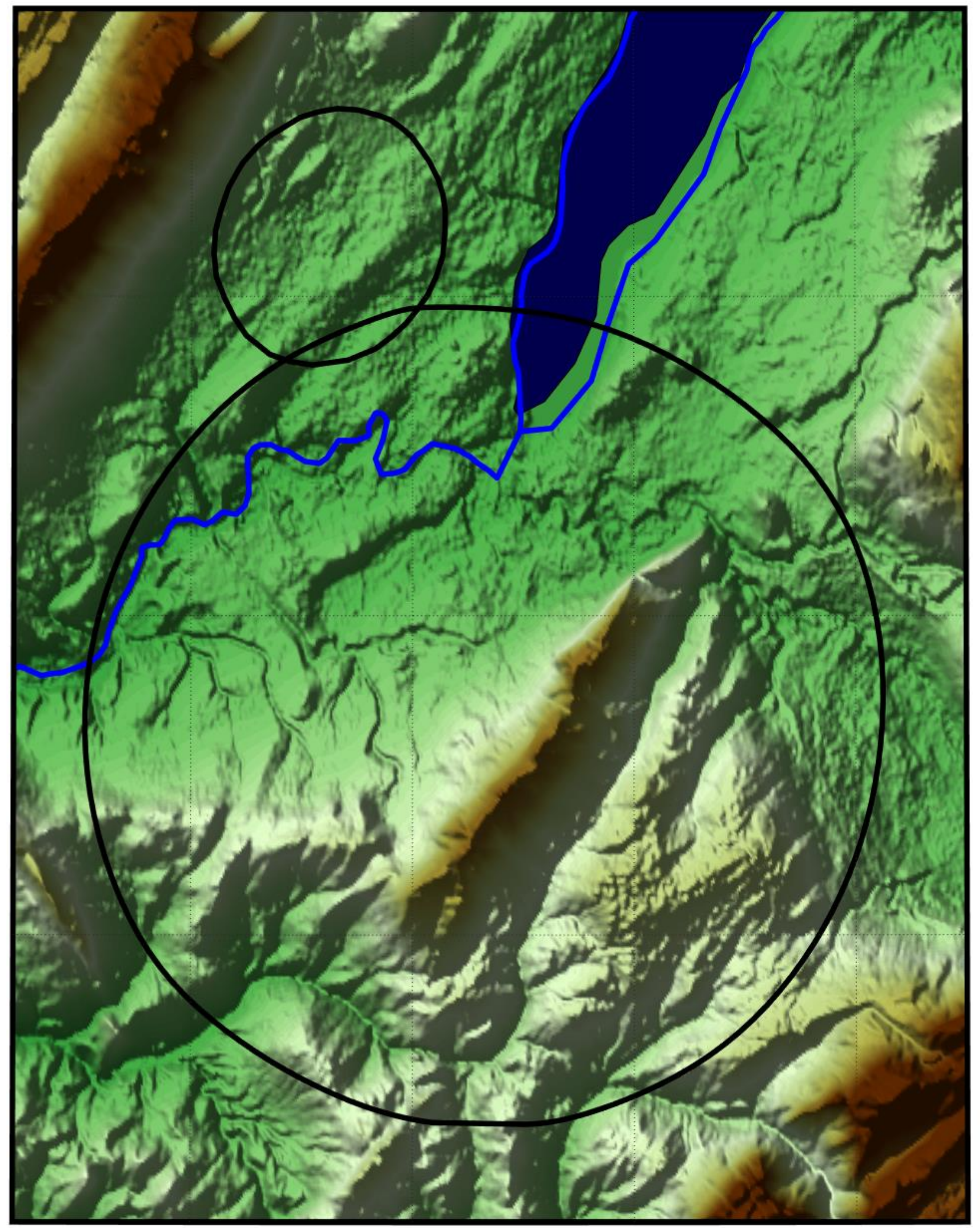
Tachymmetry, GNSS and levelling as precise geodetic measurement techniques

Geodetic networks: design constraints

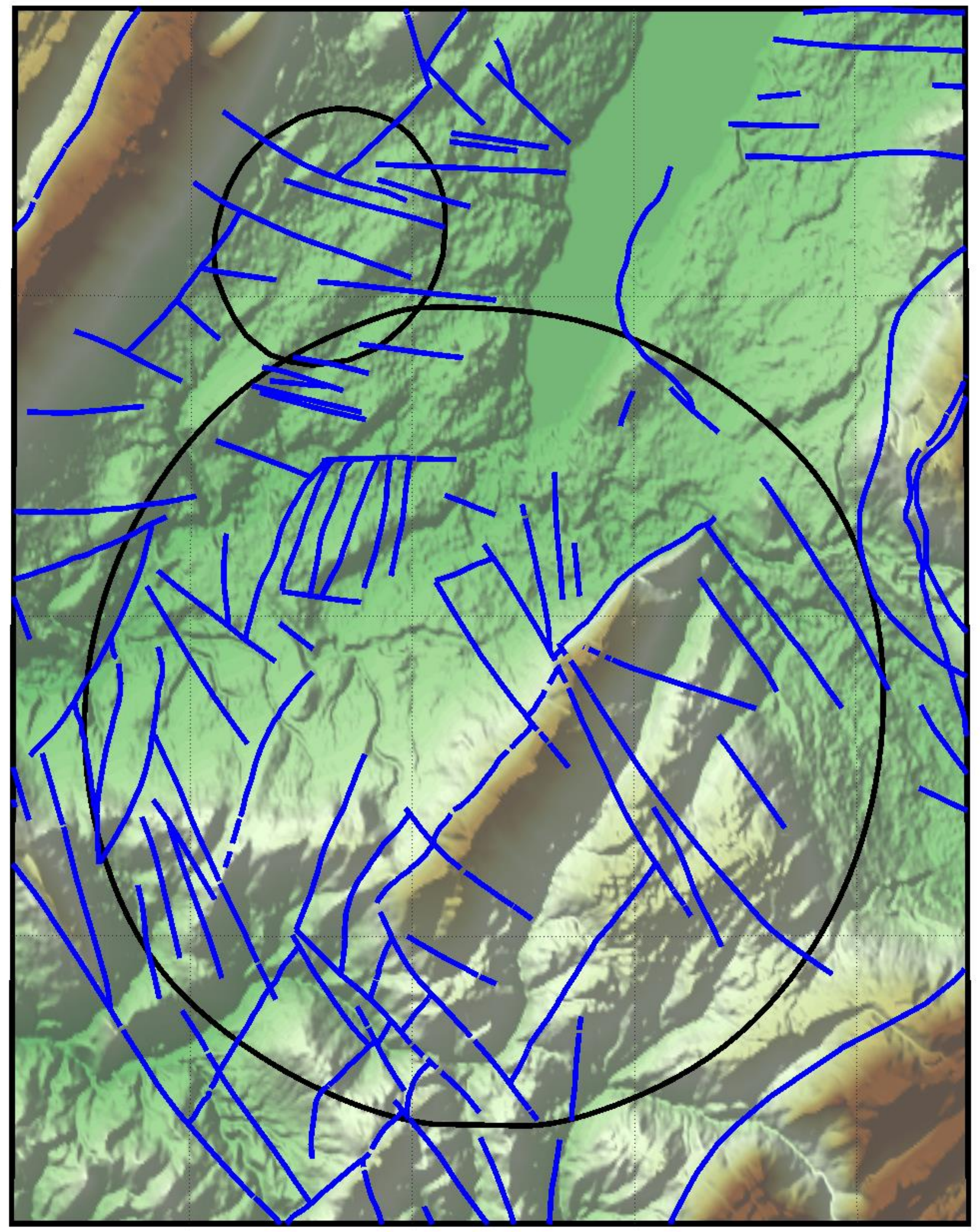
- many constraints exist when choosing locations of geodetic points
- optimal configuration for geodetic network have to be found



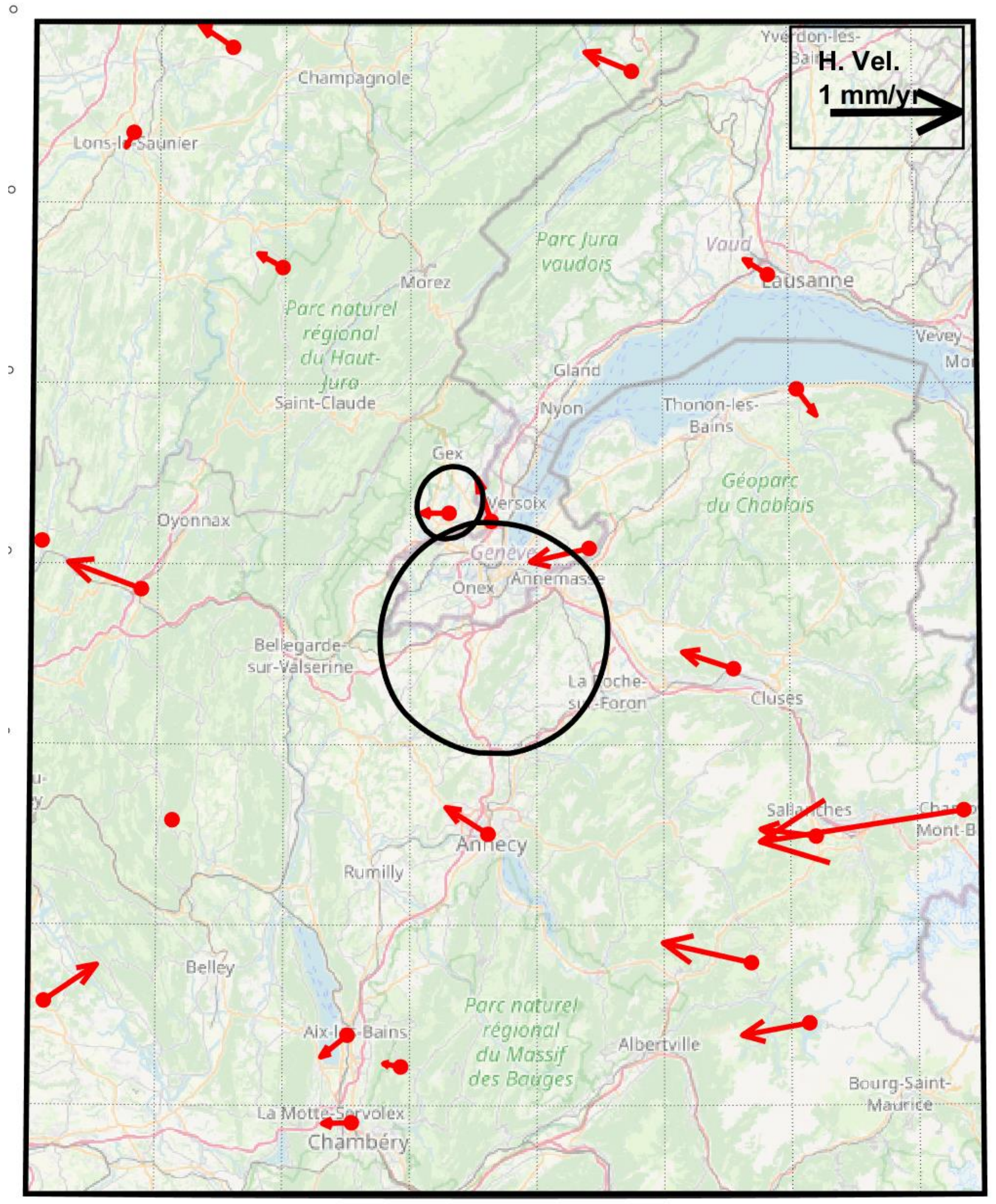
Geographic features (borders, municipalities, roads, ...)



Topographic features (mountains, lakes, rivers, valleys, ...)



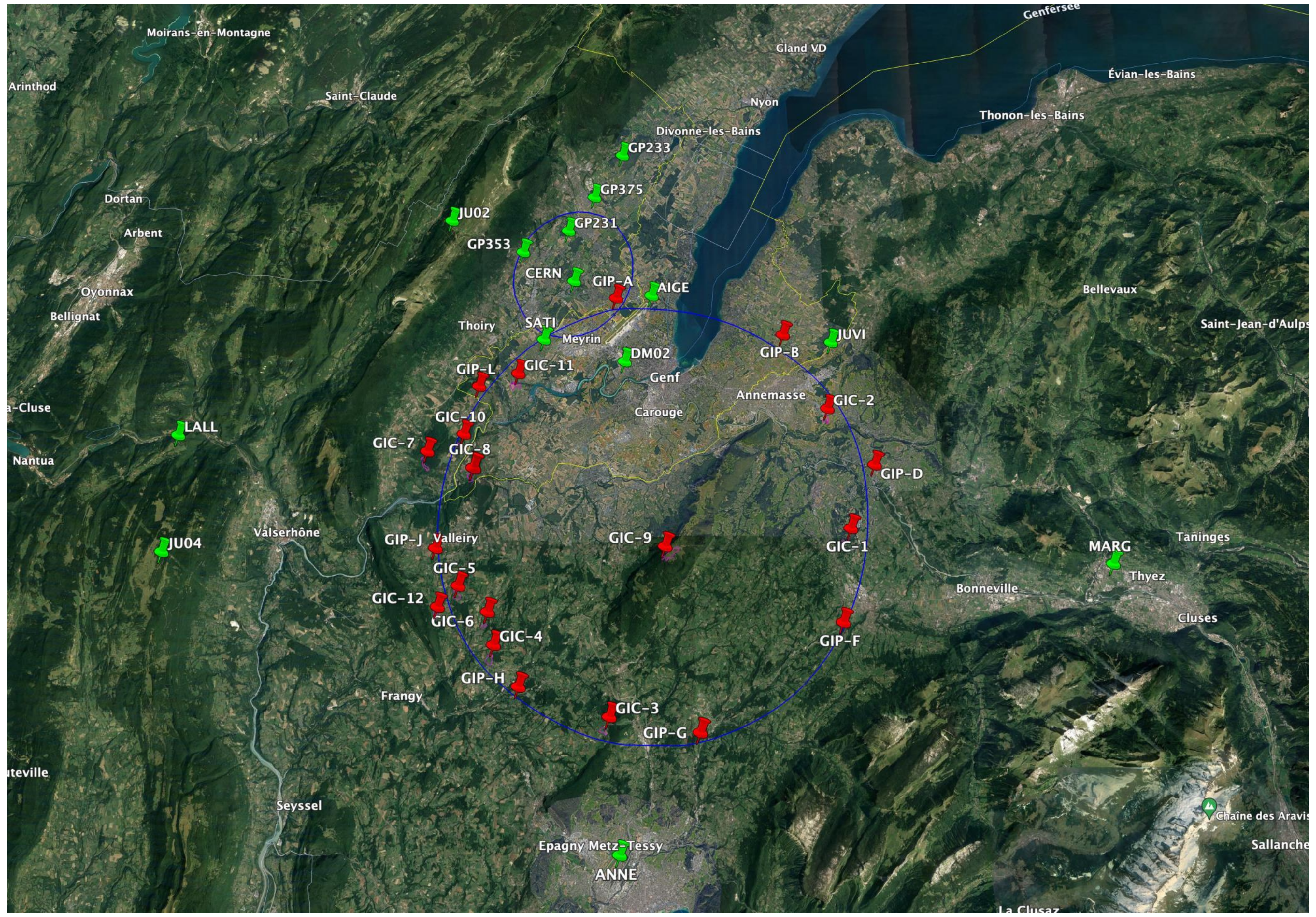
Geological faults



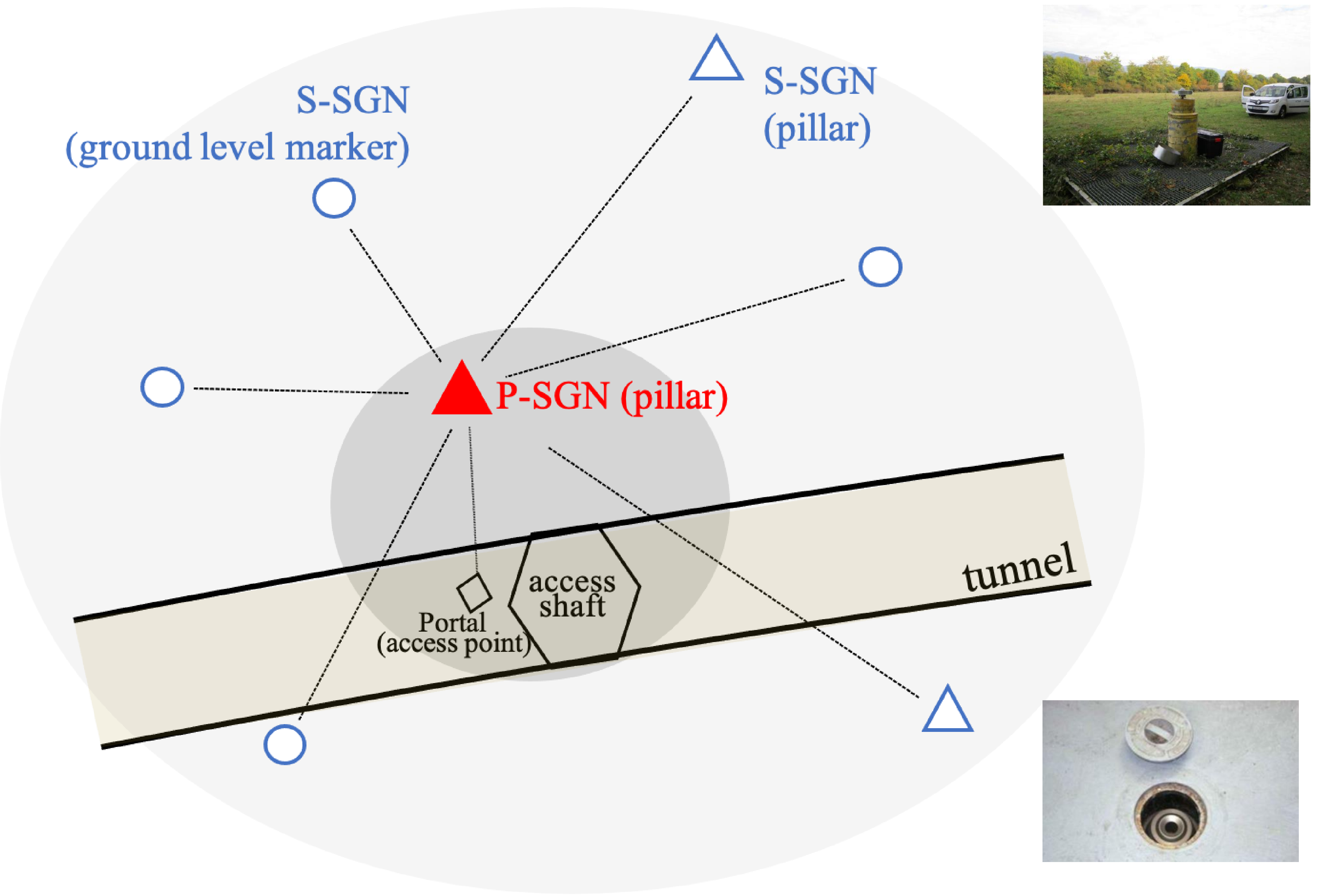
Surface kinematics

Geodetic network for FCC: conceptual solution (1)

- Active, semi-active (campaign) and passive geodetic points
- Strategically distributed in important locations (e.g. around tunnel access shafts)
- Ensure ideal support during pre-construction and construction phases, as well as full life-time of the FCC



Proposal for newly established (red) and existing (green) surface geodetic points (note: locations are only approximate and may change).



Schematic layout of a portal surface geodetic network for one tunnel access shaft

Acronyms: P-SGN: primary surface geodetic network, S-SGN: secondary surface geodetic network

Geodetic network for FCC: conceptual solution (2)

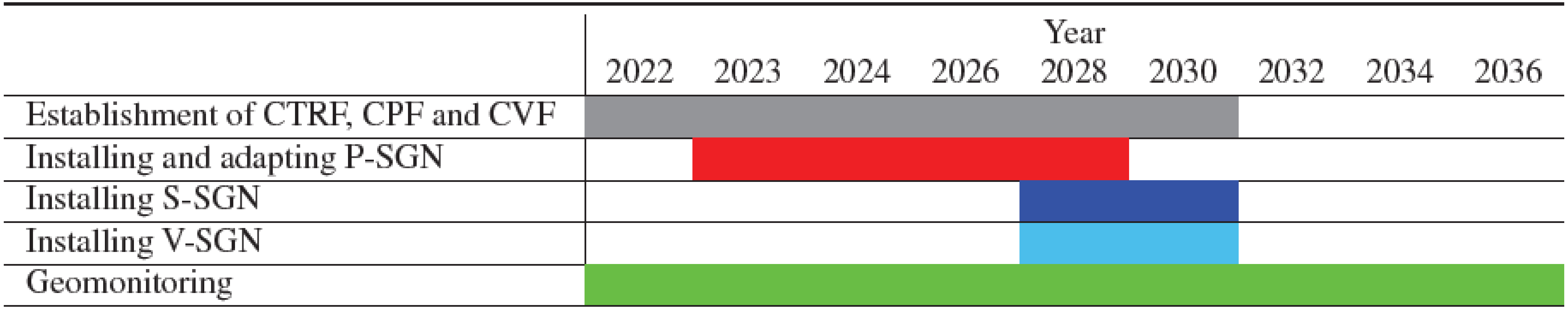
Key characteristics of the various types of surface geodetic network (SGN) points

	P-SGN	S-SGN	V-SGN
Purposes	Realize CTRF Determine CKM Main tunnel network	Densification Geomonitoring Construction Portal networks	Realize CVF Geomonitoring Construction
Coordinates	3D in CTRF 2D in CPF option: 1D in CVF	3D in CTRF 2D in CPF option: 1D in CVF	1D in CVF
Materialization	Pillar, or ground level foundation with precision marker	Various, typically ground level marker	Height bolt
Suitability	GNSS optionally also other surveying equipment	various surveying equipment	geometric levelling
Precision	individually specified all: $\sigma_{N,E} \leq 3.5\,\text{mm}$ $\sigma_U \leq 5.0\,\text{mm}$ in CTRF	individually specified typ.: $\sigma_{N,E} \leq 3.5\,\text{mm}$ $\sigma_U \leq 5.0\,\text{mm}$ in CTRF	individually specified all: $\sigma_{\Delta H} \leq 0.5\,\text{mm/km}^{\frac{1}{2}}$ w.r.t. V-SGN (up to 5 km)
Reliability	AZ≤ 3 for $\alpha_0 = 1\%, \beta = 10\%$	AZ≤ 3 for $\alpha_0 = 1\%, \beta = 10\%$	AZ≤ 3 for $\alpha_0 = 1\%, \beta = 10\%$

Acronyms: P-SGN primary SGN, S-SGN secondargy SGN, V-SGN vertical surface geodetic network, GNSS: Global Navigation Satellite System

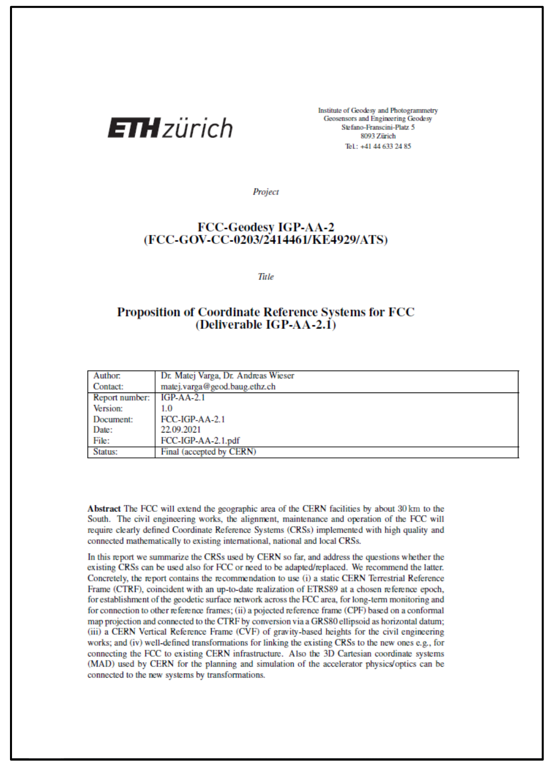
Theoretically proposed timeline for implementation

- Relative time-periods between activities can be predicted more reliable than absolute time-periods.
- Possible delays in each activity can be expected due to many reasons.



Conclusion

1. Conceptual solutions of CRS and geodetic networks have been proposed
2. The practical solutions planned to be implemented in the next few years
3. Two scientific reports summarize the proposed concept of CRS and surface network
    - Varga M., Wieser A. (2021): ***Proposition of Coordinate Reference Systems for FCC***
    - Varga M., Wieser A. (2021): ***Conceptual design report for the establishment of a surface geodetic reference network including control baseline***
4. Presented information have mainly scientific and consultative value
5. Decisions on adoption and details of practical (*real-world*) implementation are made by CERN
6. The results will have positive impact on everyday work of many other participants (physicists, metrologists, civil-engineers, etc.)


ETH zürich

Institute of Geodesy and Photogrammetry
Geosensors and Engineering Geodesy
Stefano-Franscini-Platz 5
8093 Zürich
Tel.: +41 44 633 24 85

Project

FCC-Geodesy IGP-AA-2
(FCC-GOV-CC-0203/2414461/KE4929/ATS)

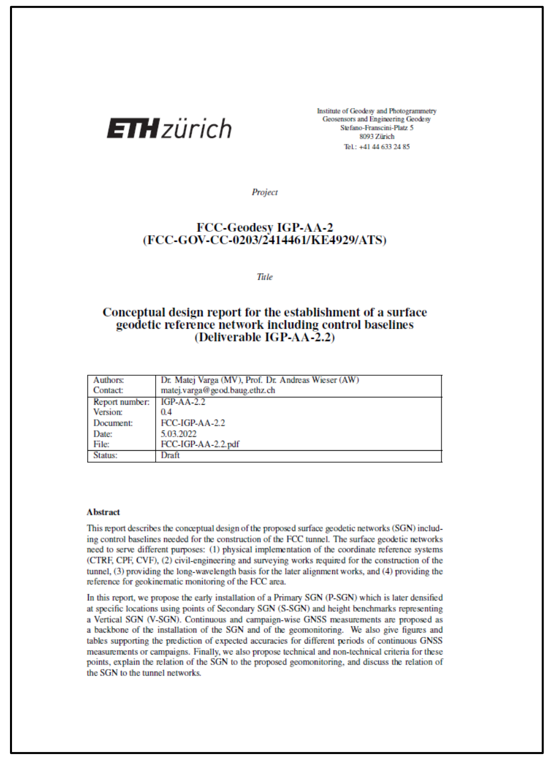
Title

Proposition of Coordinate Reference Systems for FCC
(Deliverable IGP-AA-2.1)

Author:	Dr. Matej Varga, Dr. Andreas Wieser
Contact:	matej.varga@geod.baug.ethz.ch
Report number:	IGP-AA-2.1
Version:	1.0
Document:	FCC-IGP-AA-2.1
Date:	22.09.2021
File:	FCC-IGP-AA-2.1.pdf
Status:	Final (accepted by CERN)

Abstract The FCC will extend the geographic area of the CERN facilities by about 30 km to the South. The civil engineering works, the alignment, maintenance and operation of the FCC will require clearly defined Coordinate Reference Systems (CRSs) implemented with high quality and connected mathematically to existing international, national and local CRSs.

In this report we summarize the CRSs used by CERN so far, and address the questions whether the existing CRSs can be used also for FCC or need to be adapted/replaced. We recommend the latter. Concretely, the report contains the recommendation to use (i) a static CERN Terrestrial Reference Frame (CTRF), coincident with an up-to-date realization of ETRS89 at a chosen reference epoch, for establishment of the geodetic surface network across the FCC area, for long-term monitoring and for connection to other reference frames; (ii) a pojected reference frame (CPF) based on a conformal map projection and connected to the CTRF by conversion via a GRS80 ellipsoid as horizontal datum; (iii) a CERN Vertical Reference Frame (CVF) of gravity-based heights for the civil engineering works; and (iv) well-defined transformations for linking the existing CRSs to the new ones e.g., for connecting the FCC to existing CERN infrastructure. Also the 3D Cartesian coordinate systems (MAD) used by CERN for the planning and simulation of the accelerator physics/optics can be connected to the new systems by transformations.


ETH zürich

Institute of Geodesy and Photogrammetry
Geosensors and Engineering Geodesy
Stefano-Franscini-Platz 5
8093 Zürich
Tel.: +41 44 633 24 85

Project

FCC-Geodesy IGP-AA-2
(FCC-GOV-CC-0203/2414461/KE4929/ATS)

Title

Conceptual design report for the establishment of a surface geodetic reference network including control baselines
(Deliverable IGP-AA-2.2)

Authors:	Dr. Matej Varga (MV), Prof. Dr. Andreas Wieser (AW)
Contact:	matej.varga@geod.baug.ethz.ch
Report number:	IGP-AA-2.2
Version:	0.4
Document:	FCC-IGP-AA-2.2
Date:	5.03.2022
File:	FCC-IGP-AA-2.2.pdf
Status:	Draft

Abstract

This report describes the conceptual design of the proposed surface geodetic networks (SGN) including control baselines needed for the construction of the FCC tunnel. The surface geodetic networks need to serve different purposes: (1) physical implementation of the coordinate reference systems (CTRF, CPF, CVF), (2) civil-engineering and surveying works required for the construction of the tunnel, (3) providing the long-wavelength basis for the later alignment works, and (4) providing the reference for geokinematic monitoring of the FCC area.

In this report, we propose the early installation of a Primary SGN (P-SGN) which is later densified at specific locations using points of Secondary SGN (S-SGN) and height benchmarks representing a Vertical SGN (V-SGN). Continuous and campaign-wise GNSS measurements are proposed as a backbone of the installation of the SGN and of the geomonitoring. We also give figures and tables supporting the prediction of expected accuracies for different periods of continuous GNSS measurements or campaigns. Finally, we also propose technical and non-technical criteria for these points, explain the relation of the SGN to the proposed geomonitoring, and discuss the relation of the SGN to the tunnel networks.

Thank you for your attention.