Geodetic Reference
via
Precise Point Positioning - RTK

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Contents

Terms and Abbreviations

Terms and Abbreviations

- **RTCM** – **R**adio **T**echnical **C**ommission for **M**aritime Services
- **SSR** – "**S**tate **S**pace **R**epresentation"
  - error components affecting positioning application are represented as parameters of state vector
- **OSR** – "**O**bservation **S**pace **R**epresentation"
  - "lump sum" of error components are represented in observation space
- **RT** - "**R**eal **T**ime" vs
- **PP** - "**P**ost **P**rocessing"
- **PPP** – "**P**recise **P**oint **P**ositioning" – Using **SSR** parameters to determine precise position of **single points** – In use since many years for post-processing applications utilizing IGS state parameters (orbits, clocks) PP-PPP
- **RTK** – "**R**eal **T**ime **K**inematic" – Carrier phase based positioning yielding centimeter accuracy with very short observation time on rovers through carrier phase *ambiguity resolution* (AR): "**Centimeters in Seconds**". In use since approx. 20 years utilizing OSR from single reference stations and networks (Network – RTK)
- **PPP-RTK** – achieve RTK performance for single points using SSR

Terms and Abbreviations

- **AR** – “**A**mbiguity **R**esolution”
- **DF** – **D**ual **F**requency
- **SF** – **S**ingle **F**requency
- **VTEC/STEC** – Ionospheric **V**ertical/**S**lant **T**otal **E**lectron **C**ontent
- **TTFA** – **T**ime **T**o **F**ix **A**mbiguities
- **WL** – **W**ide **L**ane
- **NL** – **N**arrow **L**ane
- **MW** – **M**elbourne-**W**übbena WL-AR method

Real Time GNSS Applications – RTCM Standards

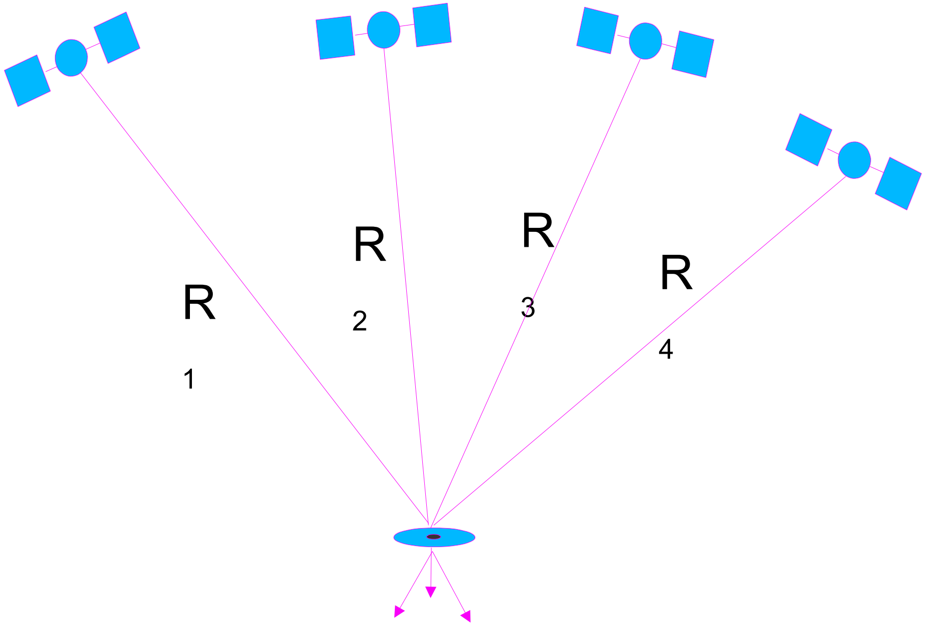
- DGPS (DGNSS) RTCM V1 – 198?
  - Accuracy 5 m
  - Long range
  - V2.0 – 1990
    - Accuracy 1m ...
- Single Base RTK – V2.1 - 1994
  - Accuracy 2..3 cm
  - Short Range <10 km
  - GLONASS – V2.2 - 1998
  - Antenna + Improvements – V2.3 – 2001
  - Compression V3.0 - 2004
- Network RTK – since 2006
  - Accuracy 1..3 cm
  - Interstation Distances 50..70 km
- PPP-RTK – 2007 – SSR Working Group established
  - SSR Stage 1 - 2010

GNSS Principle

GNSS principle

- Measurement of pseudoranges (Pr_X) (i.e. signal propagation time)
- 3 frequencies (L1, L2, new: L5)
- Use PRN Codes (P-Code, C/A-Code) for navigation

$$\sigma_p^2 = PDOP\, \sigma_l^2$$



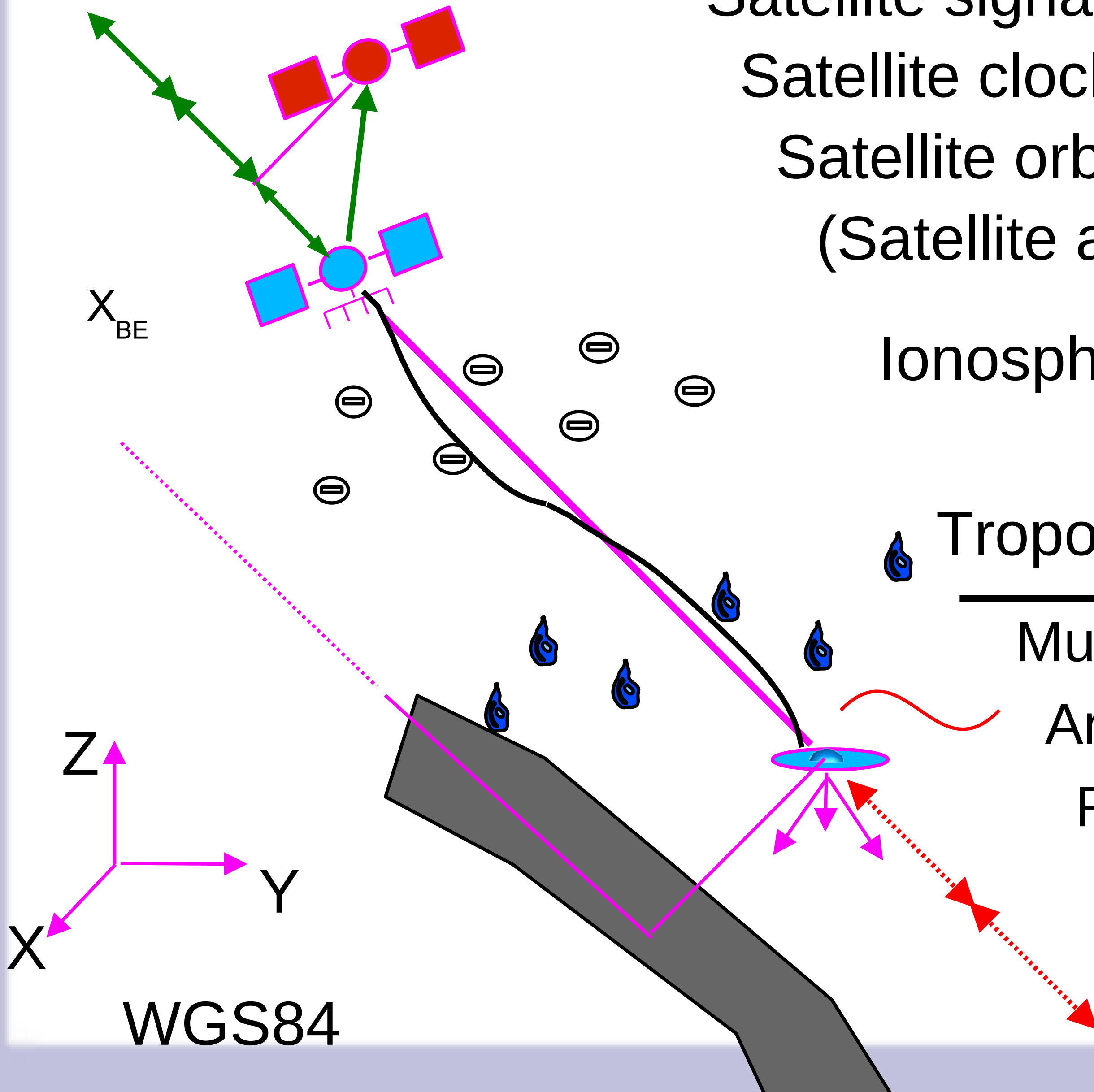
- Use of carrier phase for geodetic (high-accuracy) applications

n ≥ 4 Observations: { PR_1 PR_2 PR_3 PR_4 ... PR_n}

4 Unknowns: { X Y Z Δt }

GNSS Error Sources

Major GNSS Error Sources



Satellite signal delay+bias
Satellite clock error
Satellite orbit error
(Satellite antenna PCV)

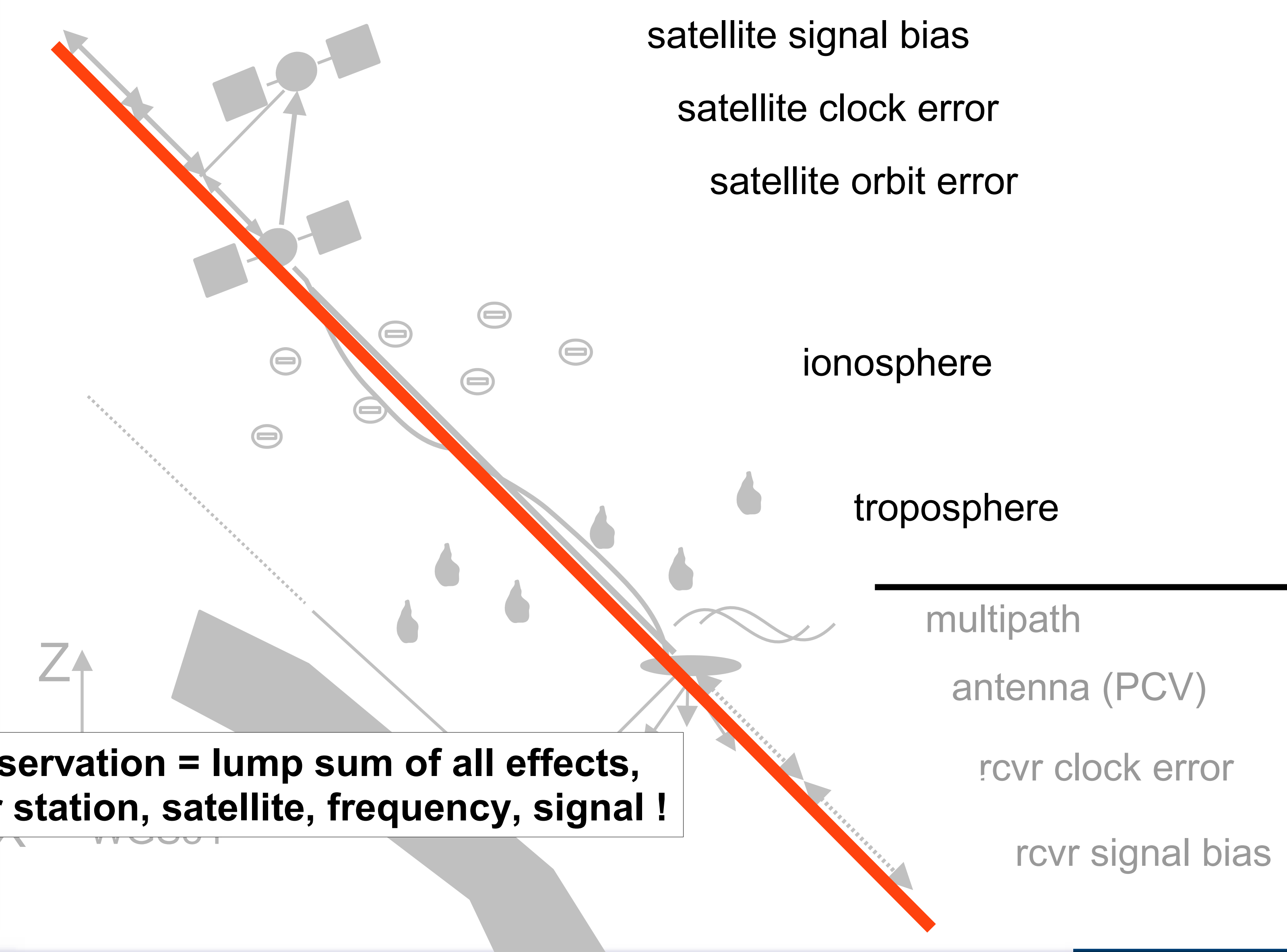
Ionosphere

Troposphere

Multipath
Antenna (PCV)
Rcvr clock error
Rcvr signal delay+bias

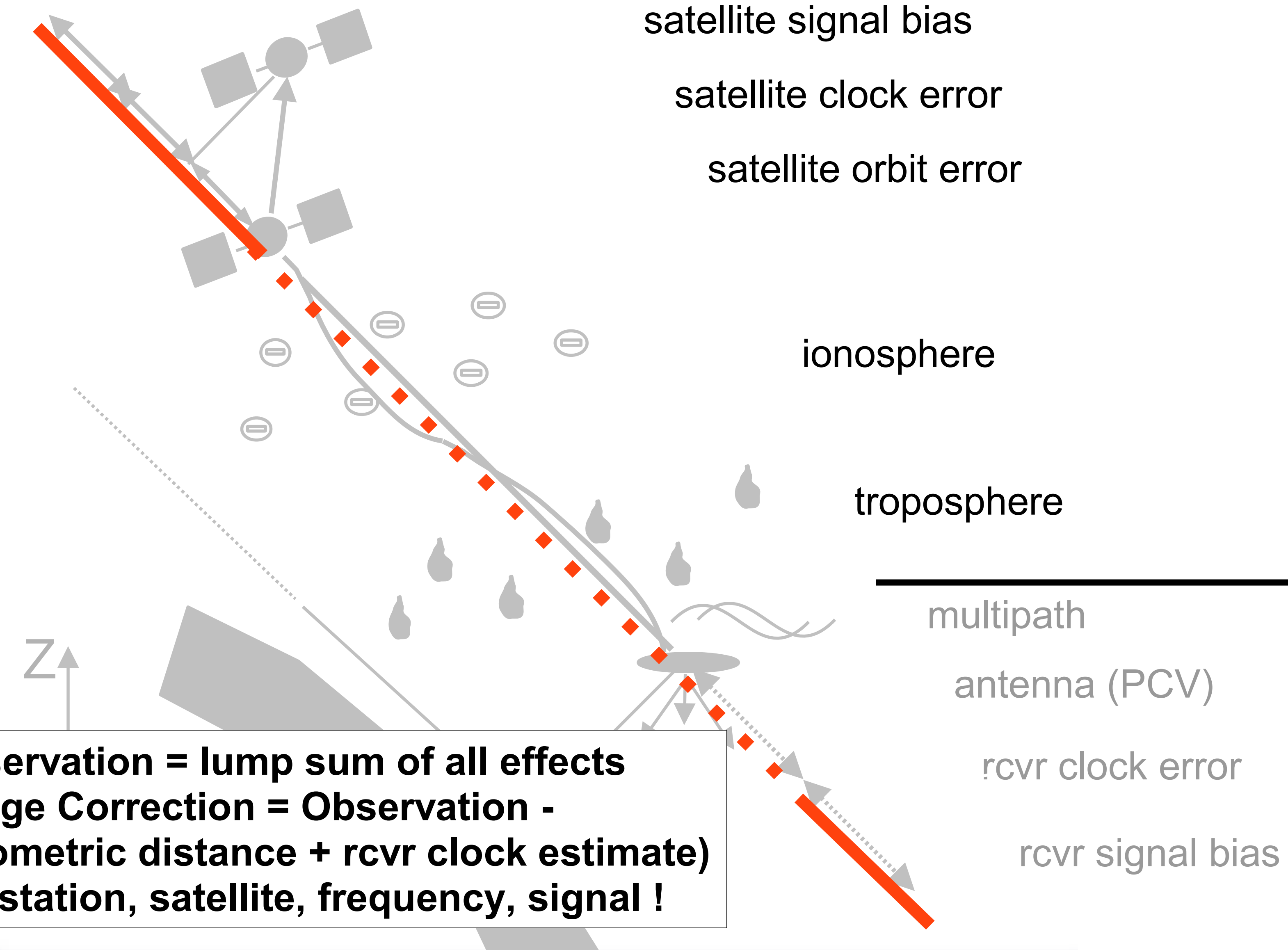
OSR
DGNSS
Single Base RTK

Observation Space Representation – Raw Observation



Observation = lump sum of all effects, per station, satellite, frequency, signal !

Observation Space Representation – Range Correction



Observation = lump sum of all effects
Range Correction = Observation - (geometric distance + rcvr clock estimate)
per station, satellite, frequency, signal !

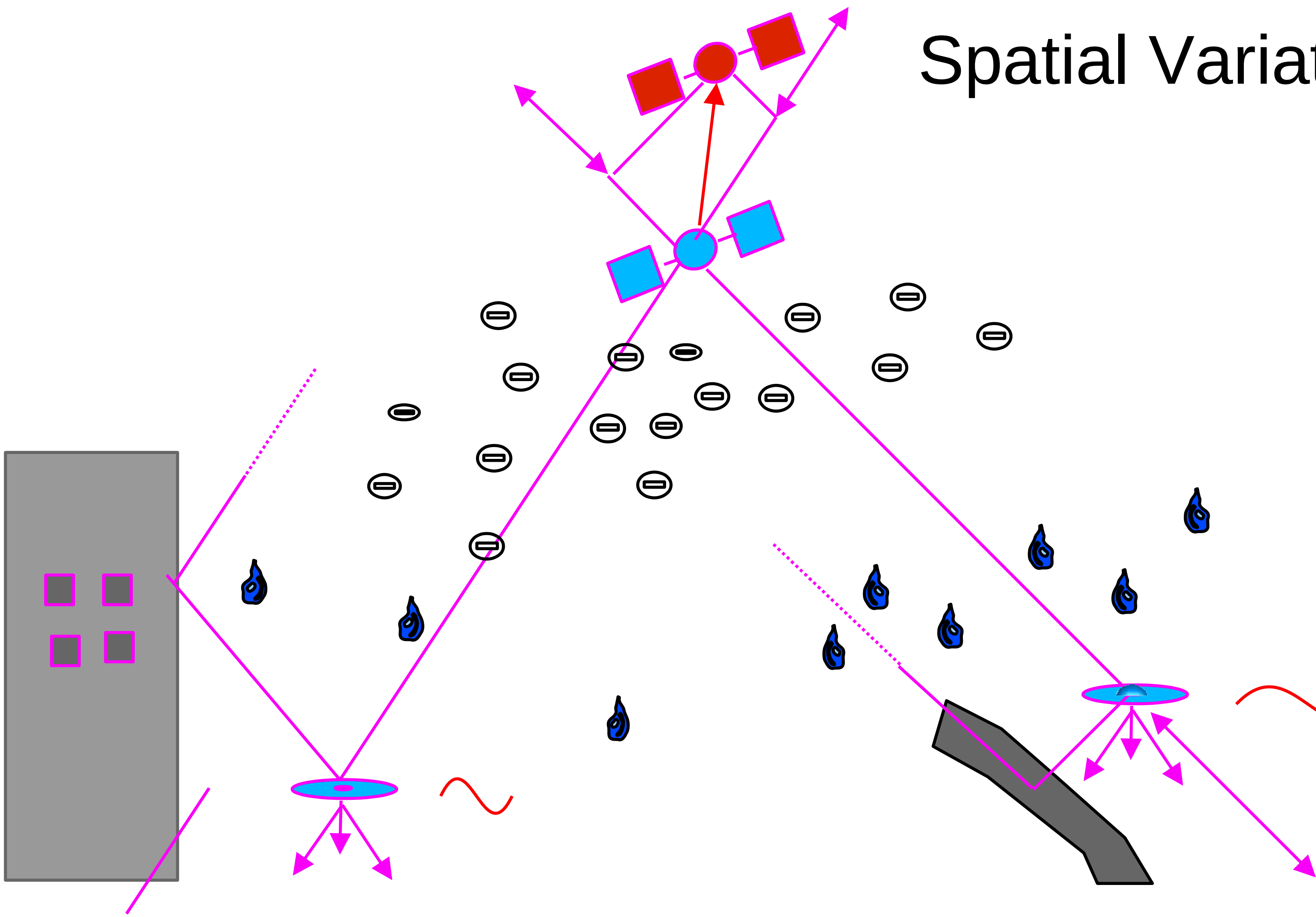
DGNSS (OSR)

- **Application of Range Corrections to Rover Observations**
  - Elimination/reduction of satellite dependent errors
  - Elimination/reduction of atmospheric errors
  - Remaining receiver signal delay/receiver clock bias is common to all satellites and thus appears in the estimate of corresponding rover parameters
  - Limitations:
    - Degradation with increasing distance between RS and Rover
    - Requires tracking of same signals at RS and Rover
    - Remaining local errors at RS (Antenna, MP, Diffraction, ..)
    - Missing satellites due to RS obstructions

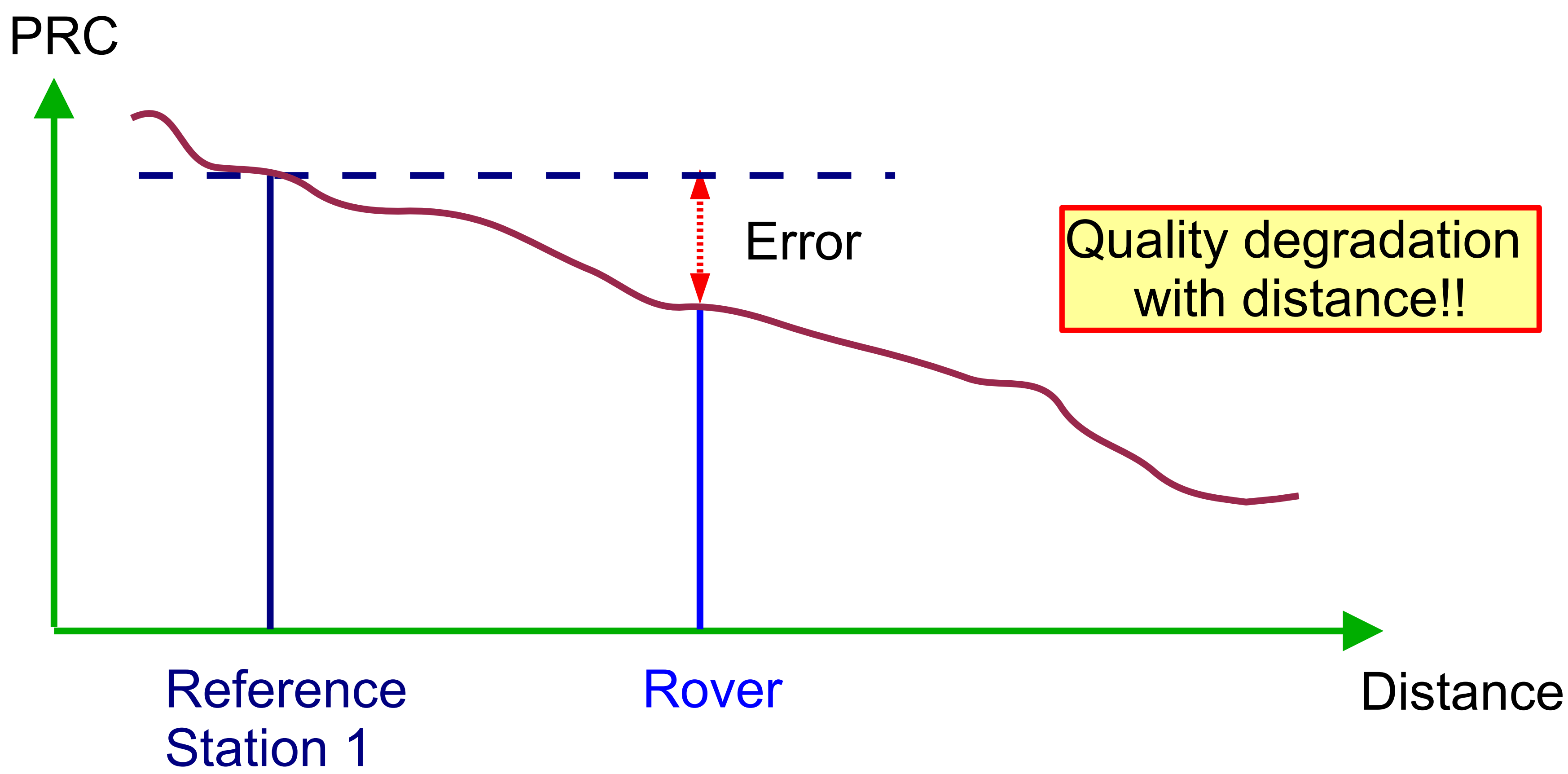
Network RTK

GNSS Errors – Spatial Variations

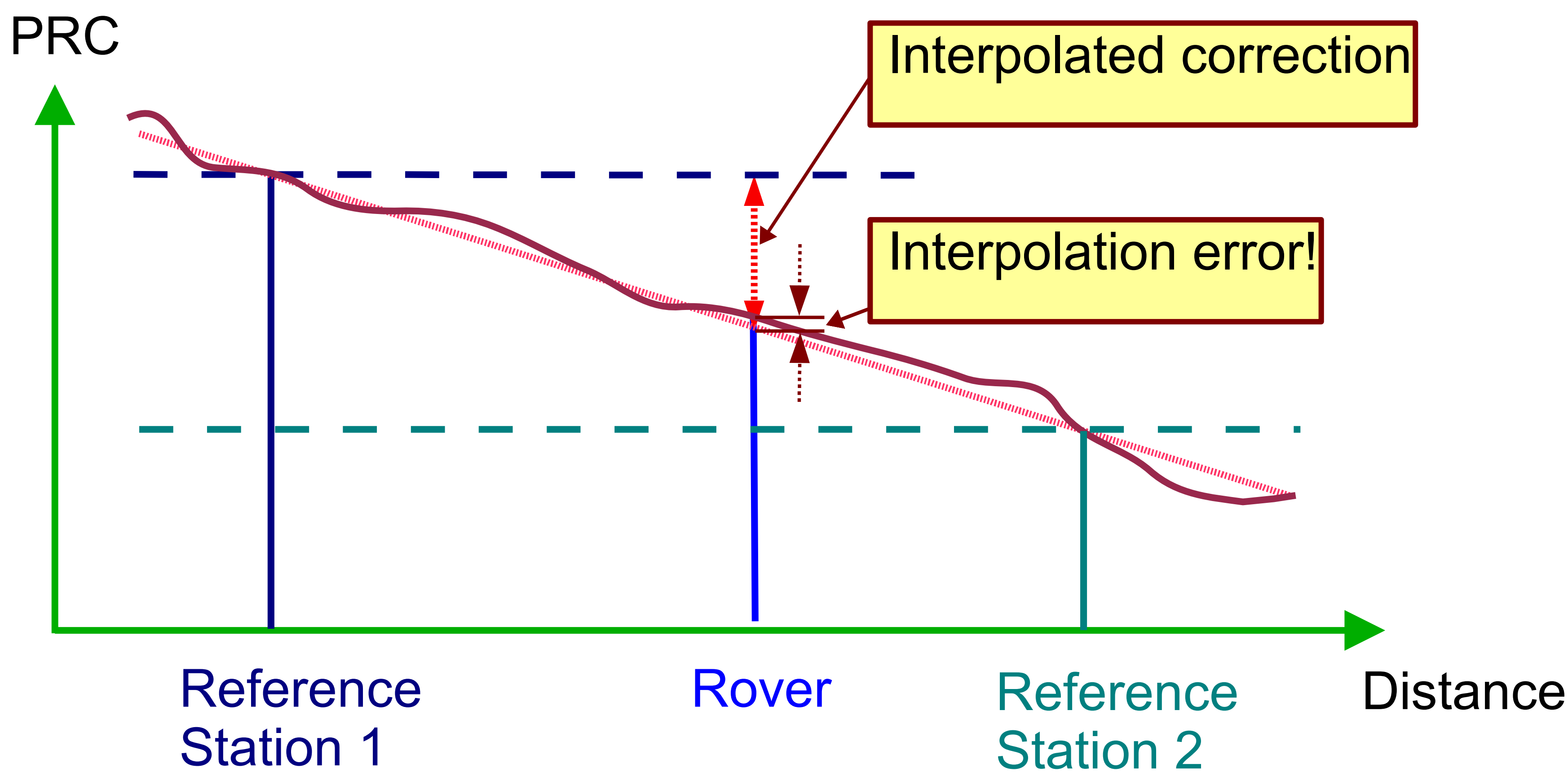
Spatial Variations



Distance Dependent Error: Single RS (single base)



Distance Dependent Error: RTK Network

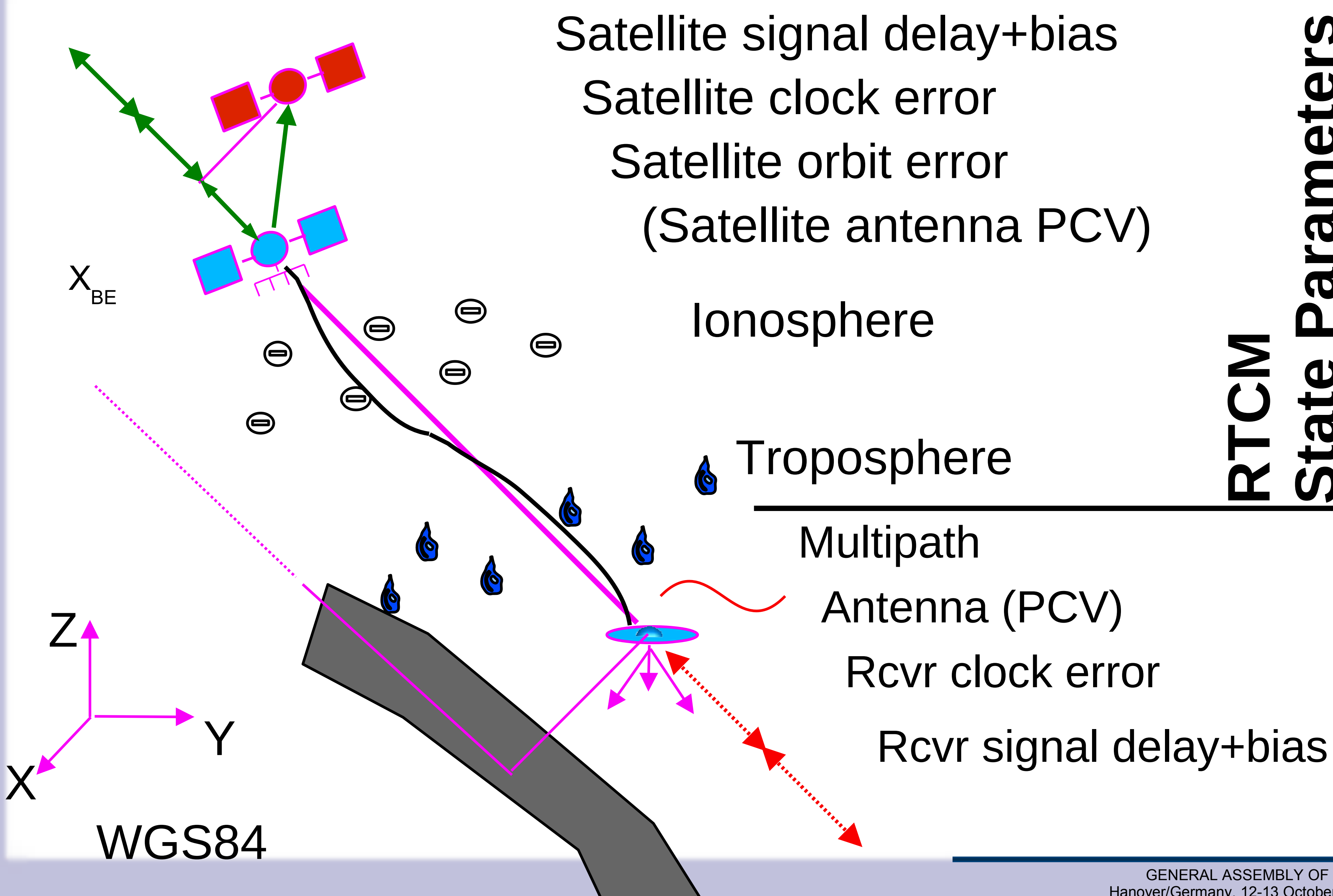


Network RTK

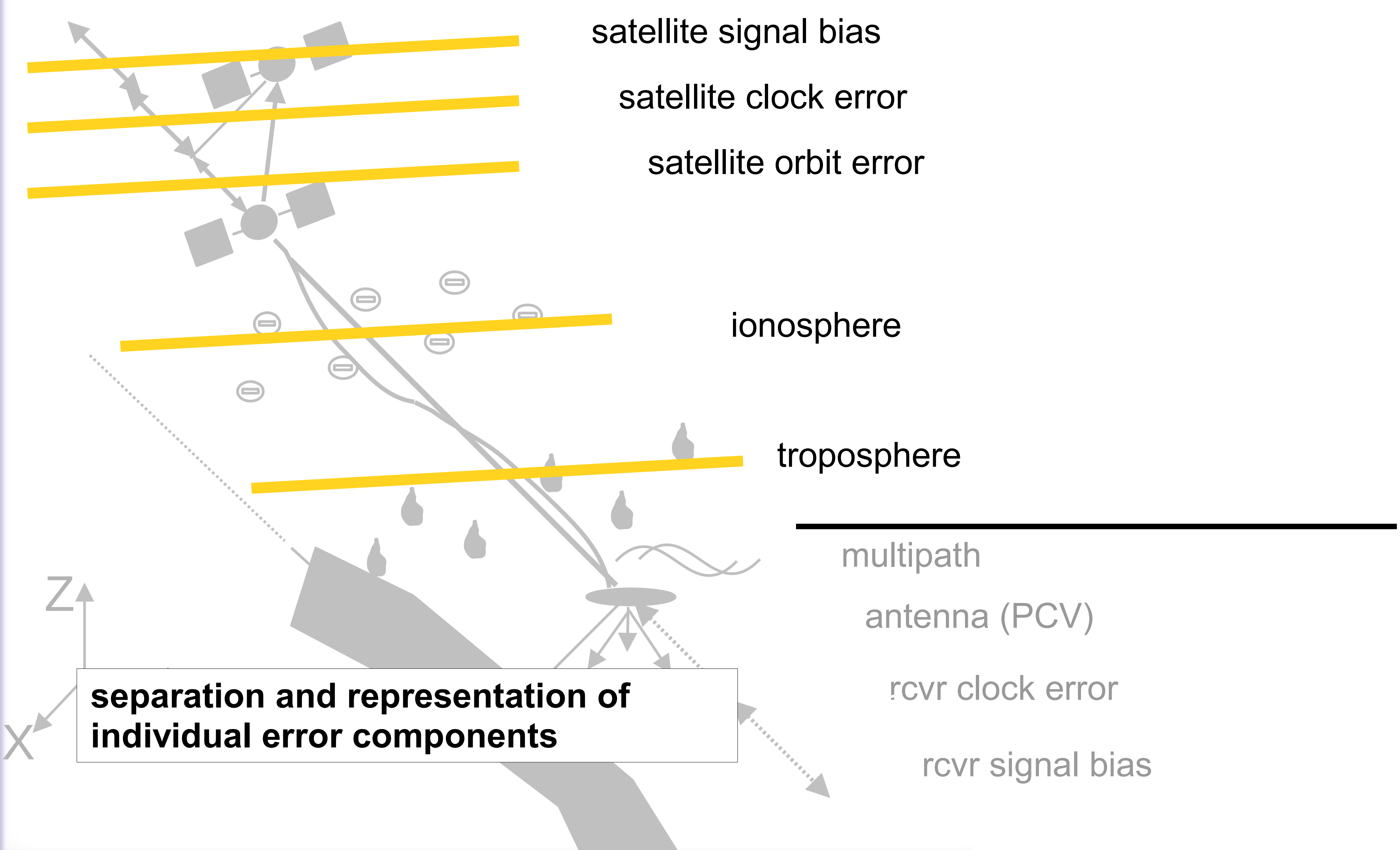
- Different approaches
  - FKP – provide single RS + gradients of phase corrections
  - VRS/PRS – interpolate phase corrections at rovers position
  - MAC – provide correction differences between master RS and auxiliary RS's
- Widely available operational services
- Elimination/reduction of distance dependent errors (in addition to single RS operation)
  - Satellite orbit errors
  - Atmospheric errors
- Limitations:
  - Residual interpolation error (small degradation with increasing distance between RS and Rover)
  - Requires tracking of same signals at RS's and Rover
  - Remaining local errors at RS (Antenna, MP, Diffraction, ..)
  - Missing satellites due to RS obstructions

SSR

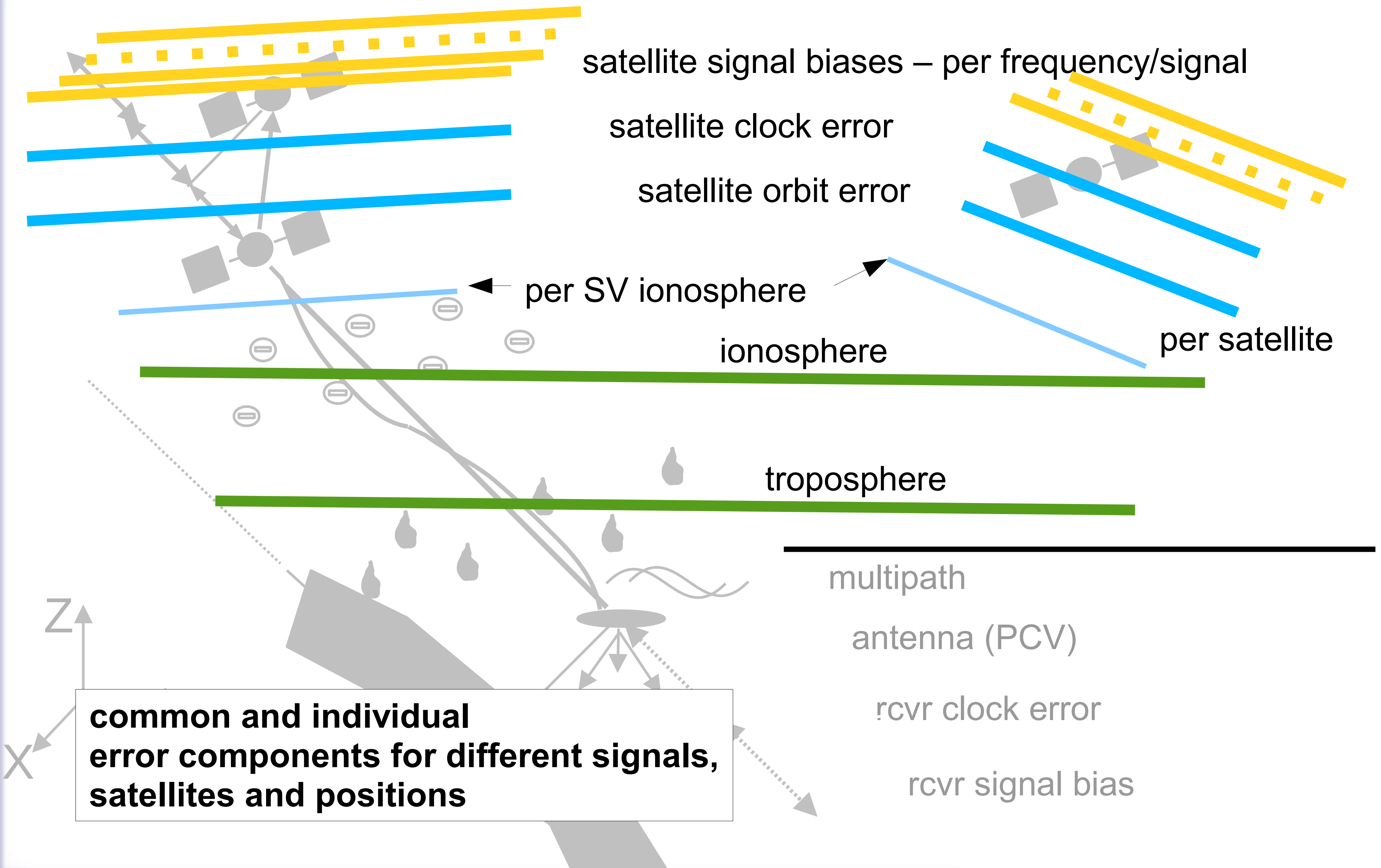
Major GNSS Error Sources / RTCM State Parameters



State Space Representation – Error States

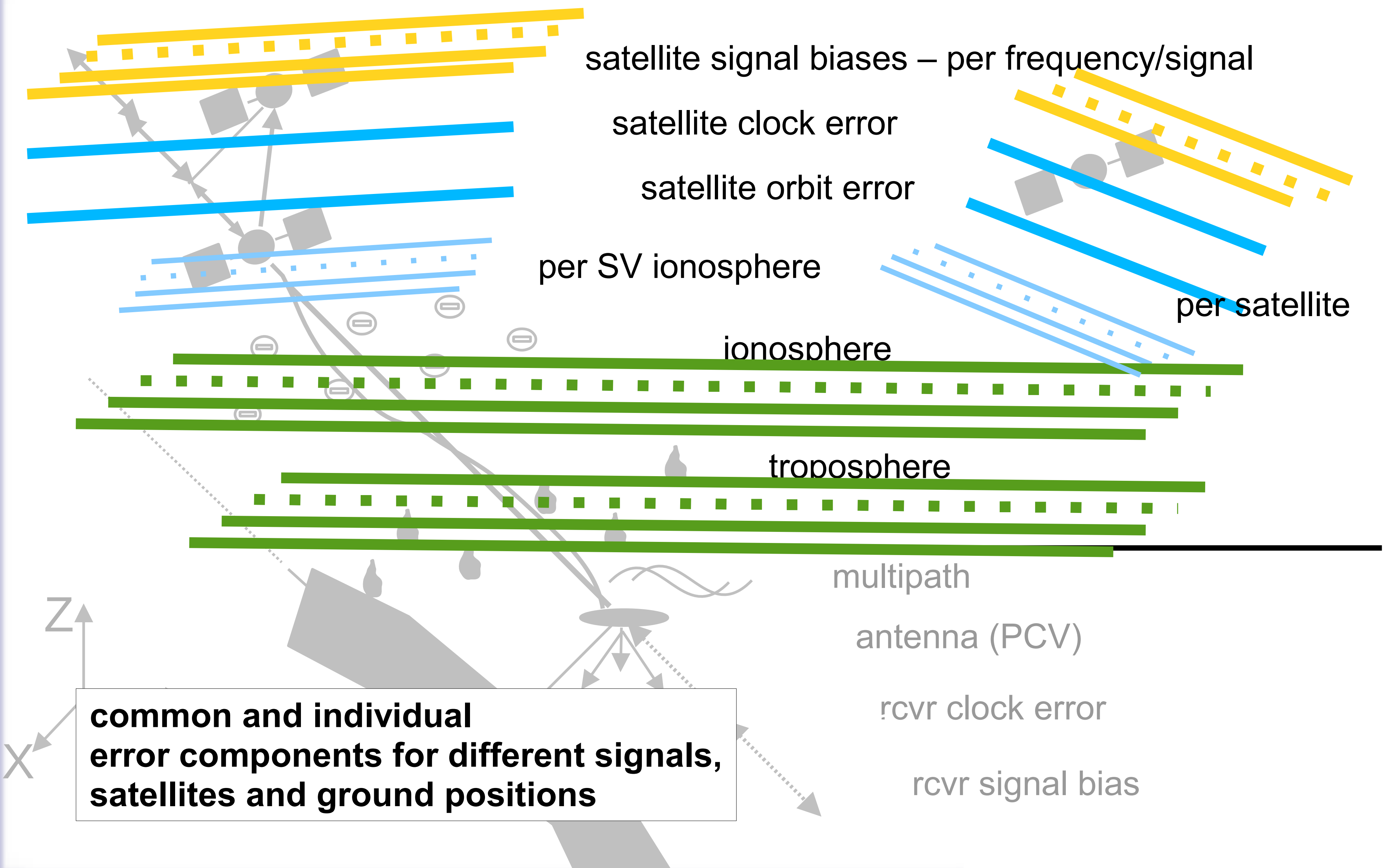


SSR – Common and Individual States



common and individual
error components for different signals,
satellites and positions

SSR – Spatial Variations of Atmospheric States



common and individual error components for different signals, satellites and ground positions

RTCM – SSR Working Group

- **Primary goal**:
  - Development of messages to exchange information about GNSS error states (SSR) for **precise positioning** applications **including RTK**
  -
- Working Group established in 2007
  - ~15 members

- 3 Stage Development Plan
  1. Satellite Orbits, Clocks, Satellite Code Biases
     - Code Based DF-RT-PPP
  2. Vertical Ionosphere (VTEC), Satellite Phase Biases
     - Code Based SF-RT-PPP, Carrier based DF-RT-PPP with AR
  3. Slant Ionosphere (STEC) and Troposphere
     - RTK

Carrier Phase Ambiguity Resolution

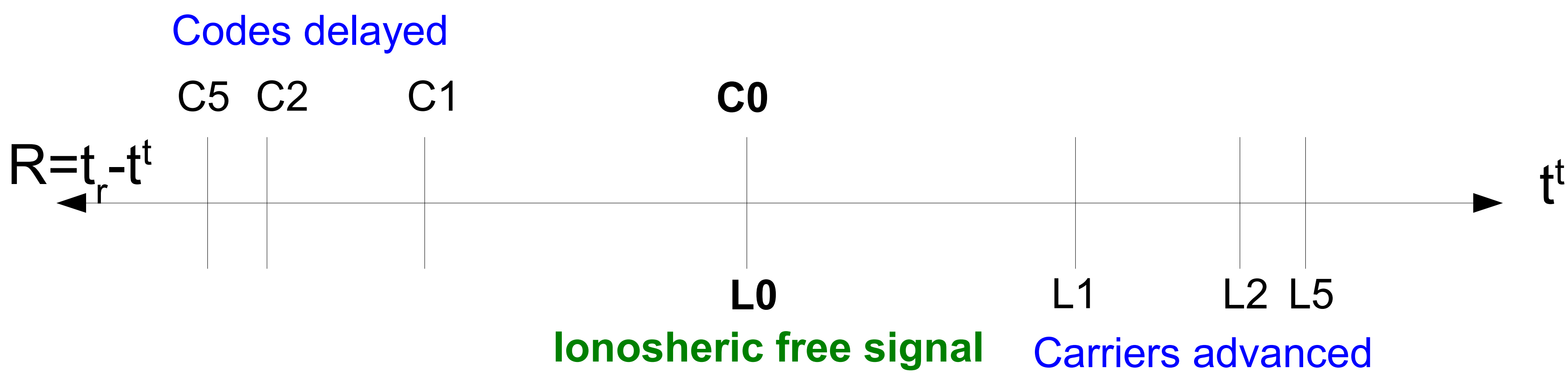
Ambiguity Resolution

- RTK ("Centimeters in Seconds") requires resolution of carrier phase ambiguities
- Different techniques have been developed in the past
  - **GFAR** – **G**eometry **F**ree **AR**
    - Linear combinations of different code and carrier signals are used to determine ambiguities
    - Often used: **Melbourne-Wübbena** - **MW**
      - Combines carrier wide lane and code "narrow lane" to resolve wide lane ambiguity
  - **GBAR** – **G**eometry **B**ased **AR**
    - Utilizes redundant satellites to find the optimal integer ambiguity vector
    - Often used: **Lambda** method (Teunissen (1993) Technical University of Delft)
  - Combinations of GFAR and GBAR

First Order Ionospheric Effect on Signal Components

- Signal components received at the same time have different „apparent“ transmission times
  - biases, higher order ionospheric and multipath effects ignored:

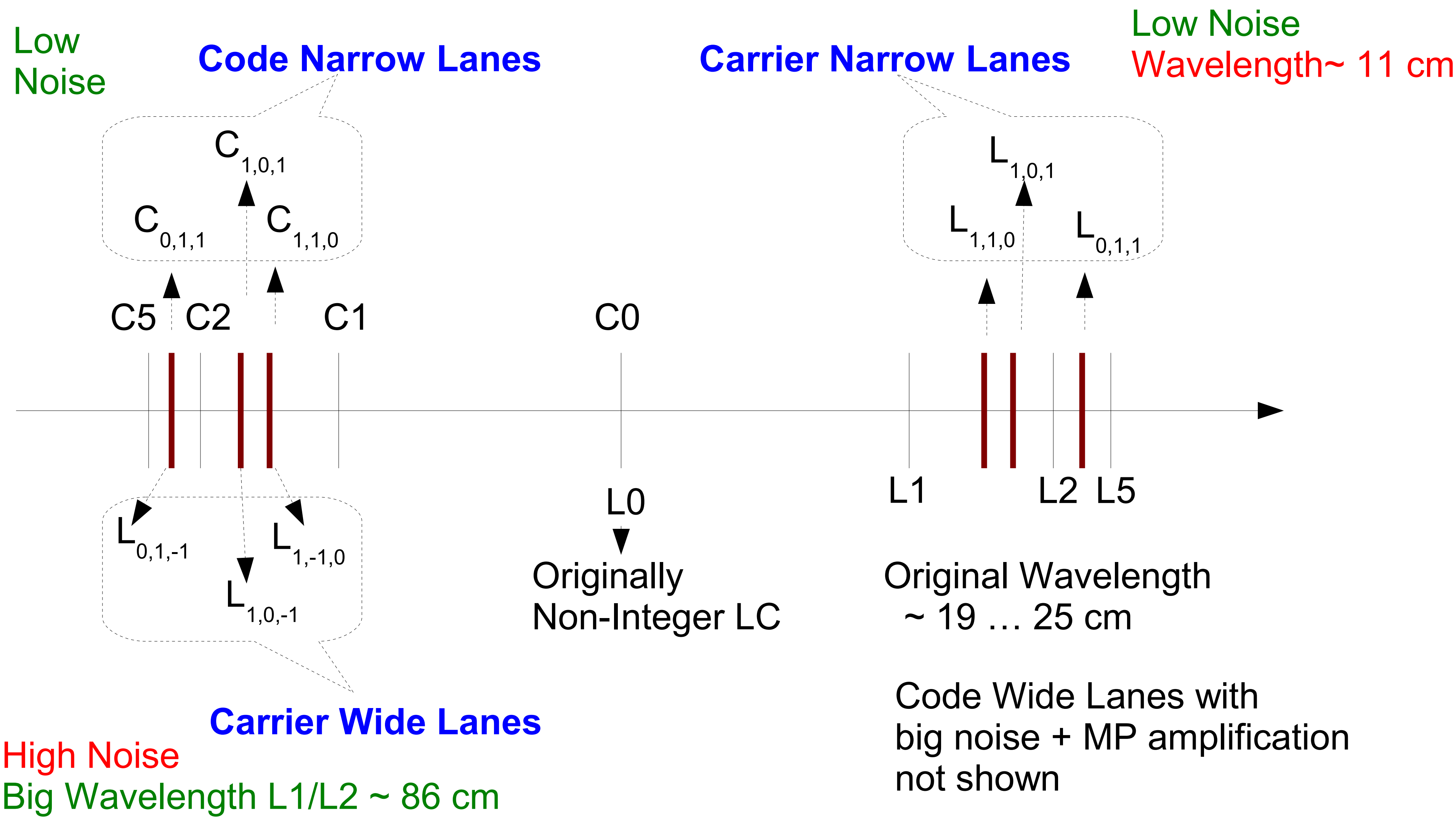
Apparent GPS Signal transmission Times (First order Iono Effect):



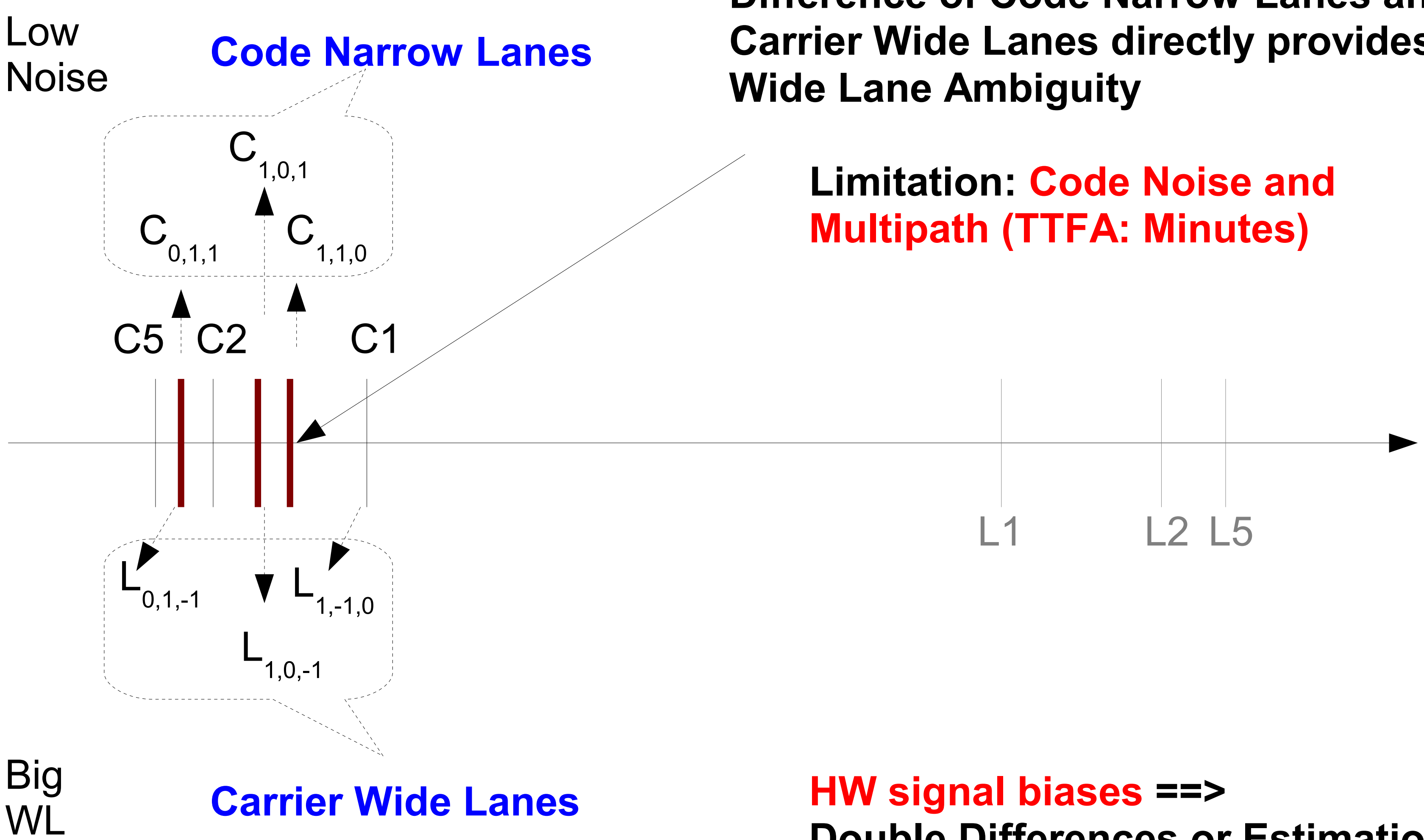
- C1, C2, C5 – Code Epochs on L1, L2, L5 Carrier
- L1, L2, L5 – Carrier Phase Epochs
- C0, L0 – Ionospheric free (First Order) Linear Combination for Code (C0) and Carrier (L0)
- RTK requires ambiguity free L0 or elimination of ionospheric effect

Narrow and Wide Lanes

Apparent Signal Transmission Times:



GFAR Principle: Step 1: Solve n-1 Wide Lanes



Melbourne-Wübbena MW-AR:

Difference of Code Narrow Lanes and Carrier Wide Lanes directly provides Wide Lane Ambiguity

Limitation: Code Noise and Multipath (TTFA: Minutes)

HW signal biases ==>
Double Differences or Estimation

GFAR Principle: After Step 1: Even-Odd Condition

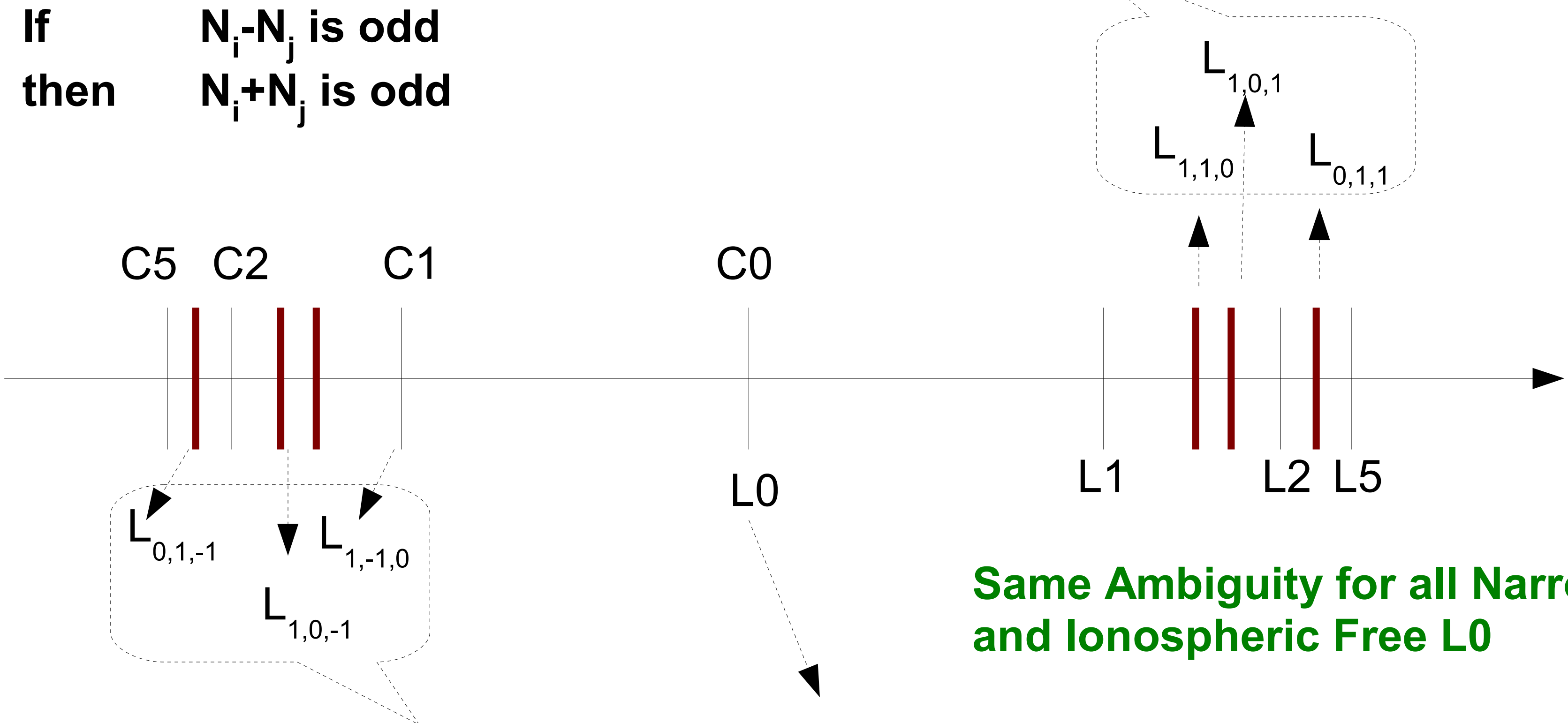
If $N_i - N_j$ **is even**
then $N_i + N_j$ **is even**

If $N_i - N_j$ **is odd**
then $N_i + N_j$ **is odd**

Effective Narrow Lane WL increases by Factor: 2

Low Noise
WL ~ 21 cm

Carrier Narrow Lanes



Same Ambiguity for all Narrow Lanes and Ionospheric Free L0

High WL

Carrier Wide Lanes Ambiguities Resolved

Integer LC WL ~ 11 cm!
Noise and MP of original signals amplified by factor of ~3 in L0

Ambiguity Resolution for L0

- With resolved Wide-Lane ambiguities the ionospheric free signal (L0) has integer ambiguity with a wavelength of approx. 11 cm.
- L0 noise+MP ~ 3 * noise+MP in L1,L2,L5
- AR for L0
  - Wavelength of ~11 cm and amplified noise and MP do not allow fast AR
  - Long TTFA for reliable AR
    - not within seconds or few minutes
    - L0-AR may not be feasible at all for kinematic applications
  - **==> No RTK performance!**
- Solution:
  - Ionospheric constraints to increase the "effective wavelength"
    - With no ionosphere the effective wavelength for AR increases to twice the wide lane wavelength (172 cm for GPS L1/L2) due to the even-odd condition between wide and narrow lane ambiguities
  - **==> key issue for RTK performance**

OSR Today

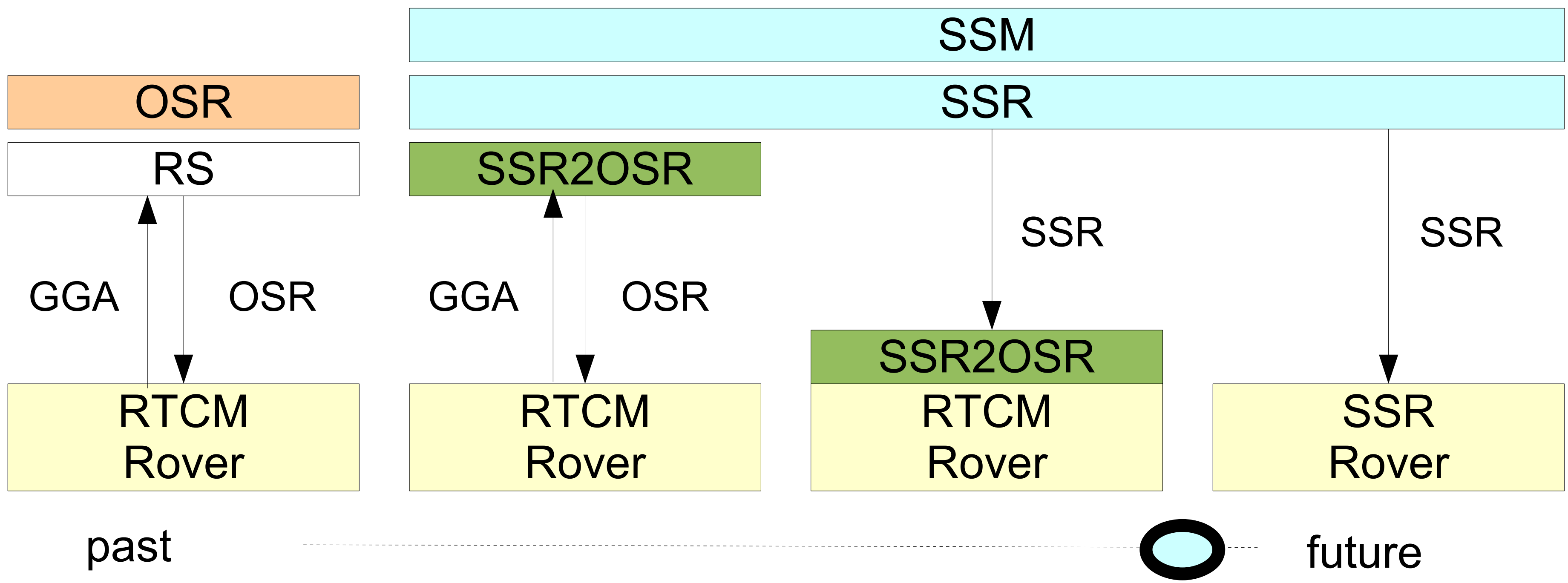
- OSR in operation in many applications and services
- **Network-RTK**
  - Well standardized methods
    - Non-physical reference station
      - PRS,VRS
    - MAC
      - Range correction differences
    - FKP
      - Range correction gradients
  - Network RTK services can fully or partly be derived from a State Space Model (SSM)
  - Problems
    - High ionospheric irregularities still cause ambiguity fixing problems for some rover types

VRS	Virtual Reference Station
PRS	Pseudo Reference Station
MAC	Master Auxiliary Concept
FKP	Flächenkorrekturparameter

SSR Today

- Different SSR services are in operation
  - **IGS Precise Point Positioning** (PPP) – Postprocessing
    - Main State Parameters (IGS products): Orbits, Clocks, (VTEC)
  - SBAS systems
    - State Parameters; Orbits, Clocks, VTEC
  - Proprietary systems with and w/o satellite communication
  - Japanese QZSS CMAS
    - Quasi Zenith Satellite System - Centimeter Augmentation System
    - Using Geo++-GNSMART software
  - Network-RTK services derived from SSM and converted to OSR
- Major Issue: Standardization for RT applications

Application to Rover System



GGA – NMEA Position Messsage

- SSM State Space Monitoring
- SSM/SSR concept operationally applied with Geo++ GNSMART

RTCM-SSR Development
Requirements, Strategy and Rules

General Requirements / Rules for RTCM-SSR Development

- RTCM-SSR shall be a **self-contained** format as far as possible.

  I.e. all necessary information for consistent processing of an RTCM-SSR stream shall be contained in the stream or shall be specified as part of the standard document. The need for external information should be avoided.
  - TBC: SV-PCV
- The definition of RTCM-SSR contents **shall not limit/restrict** the generation of SSR streams **to certain generation models or approaches**.

  Example: Conventional approaches with dynamic orbit modeling (IGS) as well as approaches with kinematic orbit modeling shall be supported.

- International **conventions for observation modeling and/or corrections** shall be applied **as far as necessary** and as long as they are well defined and documented and freely usable.

  Do not prevent new ideas, models or approaches.

General Requirements / Rules

- The standard shall allow **different update rates for different state parameters** in a flexible way.

  Different error states possess different variability with time. Slowly changing states need lower update rates as highly variable states. This is the key characteristic that allows minimization of stream bandwidth.
- **Self-consistency** of RTSM-SSR streams must be achieved.

- **Consistent processing** of SSR stream contents must be ensured.

  Consistency is one of the major requirements in order to achieve the desired performance. Consistency of algorithms and computations for reference models must be assured as well as consistency of state parameter sets.

- The RTCM-SSR standard shall support **scalable global, continental, regional and/or local applications**.

Standardization Issues
Consistency

Standardization Issues and Conventions

- Requirement: Consistent Modeling and Processing
  - Reference Frame(s) (Global, Regional,..)
    - Transformation into destination CRS
  - Site Displacements
    - Solid Earth Tides
    - Pole Tides
    - Ocean Loading
    - Atmospheric Loading
    - …
    - IERS conventions

Standardization Issues and Conventions

- Requirement: Consistent Modeling and Processing
  - Corrections and Reference Models
    - Reference orbit and clock computation (GNSS-ICDs)
    - Relativistic Effects (GNSS-ICDs, IERS conventions),
    - Phase Wind-Up (SV attitude),
    - Higher order ionosphere
    - Troposphere reference model
    - SV antenna PCO and PCV corrections
    - Signal dependent biases (phase shifts)
    - ...

Consistency

- Parameter Consistency
  - “static” parameters to be specified in the standard document
  - “non-static” parameters preferably to be included in the SSR stream (self-contained), alternatively to be referenced to external, freely accessible documents
- SSR Data Set Consistency
  - Self-Consistency of SSR parameters with different update rates must be ensured

Parameter Correlation and Self-Consistency

- Different state parameters are correlated.
- Example 1:
  - Satellite Clock and Satellite Signal Biases
    - Very high correlation / linear dependency
    - A different set of signal biases leads to different estimates for the satellite clock. Due to the linear dependency (correlation=1) between such parameters both estimates are equally valid.
    - A rover must use consistent set of state parameters. A mixing of parameters from non-consistent sources is not allowed.
    - RTCM-SSR shall be self-contained ==> clocks and biases are to be included into the streams.

Parameter Correlation and Self-Consistency

- Different state parameters are correlated.
- Example 2:
  - Satellite Orbit and Satellite Clocks
    - The effect of a radial satellite orbit error in the range and phase measurements can be calculated by
      - dobs=cos(nadir_distance)*dradial
    - In the vicinity of the earth the maximal nadir distance (satellite at 0° elevation) is about 14°, so cos(14°)~0.97. i.e. the influence of the radial orbit error is in the range of 0.97...1.
    - A 10 cm radial orbits error, compensated by a 10 cm clock error results in a maximum observation error of 3 mm at 0° elevation.
    -
- ==> State Parameters must be self-consistent.
- ==> Do not mix state parameters from different sources.

OSR vs SSR

OSR vs SSR

- Future variety of GNSS signals
  - OSR services must observe the different signals
    - Alternative: Mixture of OSR with satellite inter-signal biases taken from SSR
  - SSR services must determine/use inter-signal biases
- Spatial area of validity
  - OSR – limited area of validity
  - SSR – area of validity according to type of state parameter
    - Global: satellite state parameters (orbits,clocks,signal biases,...)
    - Global: coarse vertical ionosphere
    - Regional: dense vertical ionosphere, coarse troposphere
    - Local: precise slant ionosphere, dense troposphere
- Temporal validity
  - OSR – corresponding to validity of state parameter with highest variability
  - SSR – validity according to characteristics of parameters (low rate, medium rate, high rate parameters)

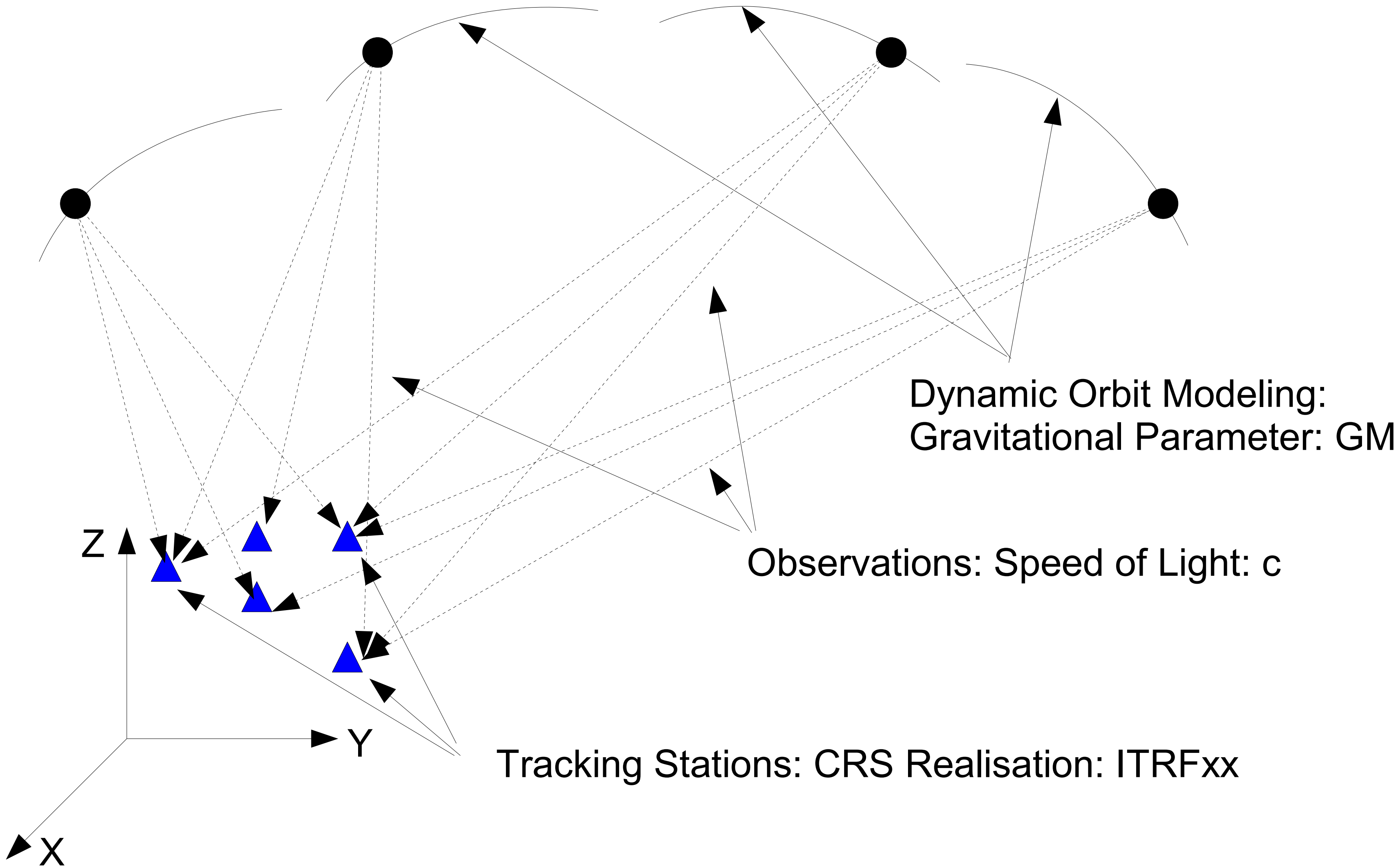
OSR vs SSR

- Performance Issues
  - OSR: performance is affected by local reference station antenna, near- and far-field multipath, signal diffraction and signal obstruction effects
  - SSR: local reference station effects are greatly reduced or eliminated
- "Scalability" of Services
  - OSR: limited scalability
    - omit observations
  - SSR: good scalability
    - Covered area
    - Performance (Accuracy, Initialization Time)
    - Positioning Mode
      - SF / DF / TF
      - PPP, PPP-RTK

OSR vs SSR

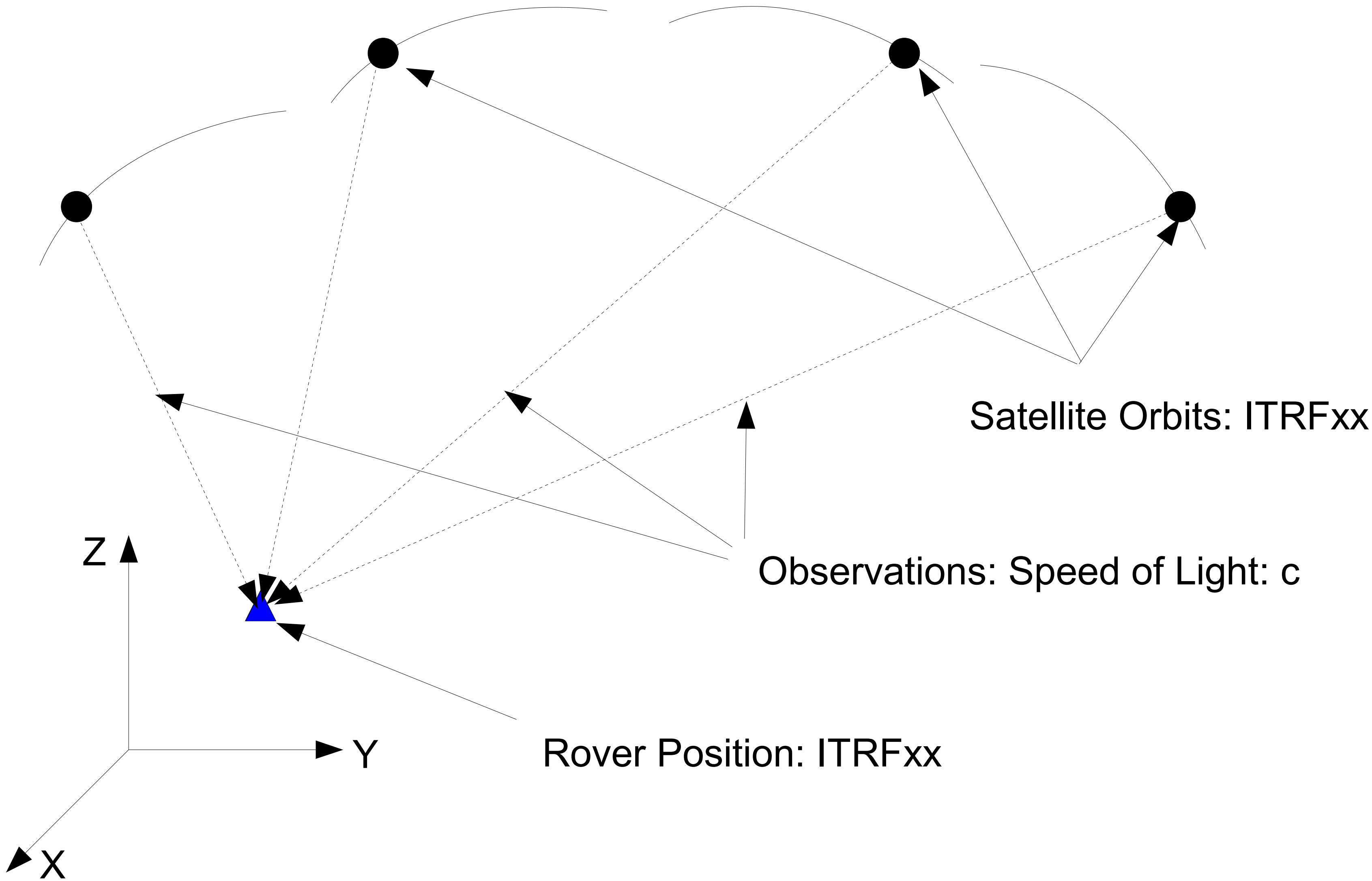
- Communication Issues
  - Bandwidth
    - OSR: high update rate for all observables (typically 1 Hz) ==> high bandwidth requirement
    - SSR: high update rates only for highly variable parameters (SV clocks, Slant Ionosphere) ==> low bandwidth requirement
  - Simplex or Duplex communication channels
    - OSR: Duplex communication is required
      - VRS computation, selection of nearest reference station
    - SSR: Simplex/Broadcast communication generally sufficient
      - Possibility of highly compressed streams for large areas
      - Variety of media

GNSS Positioning CRS Issues – Orbit Determination

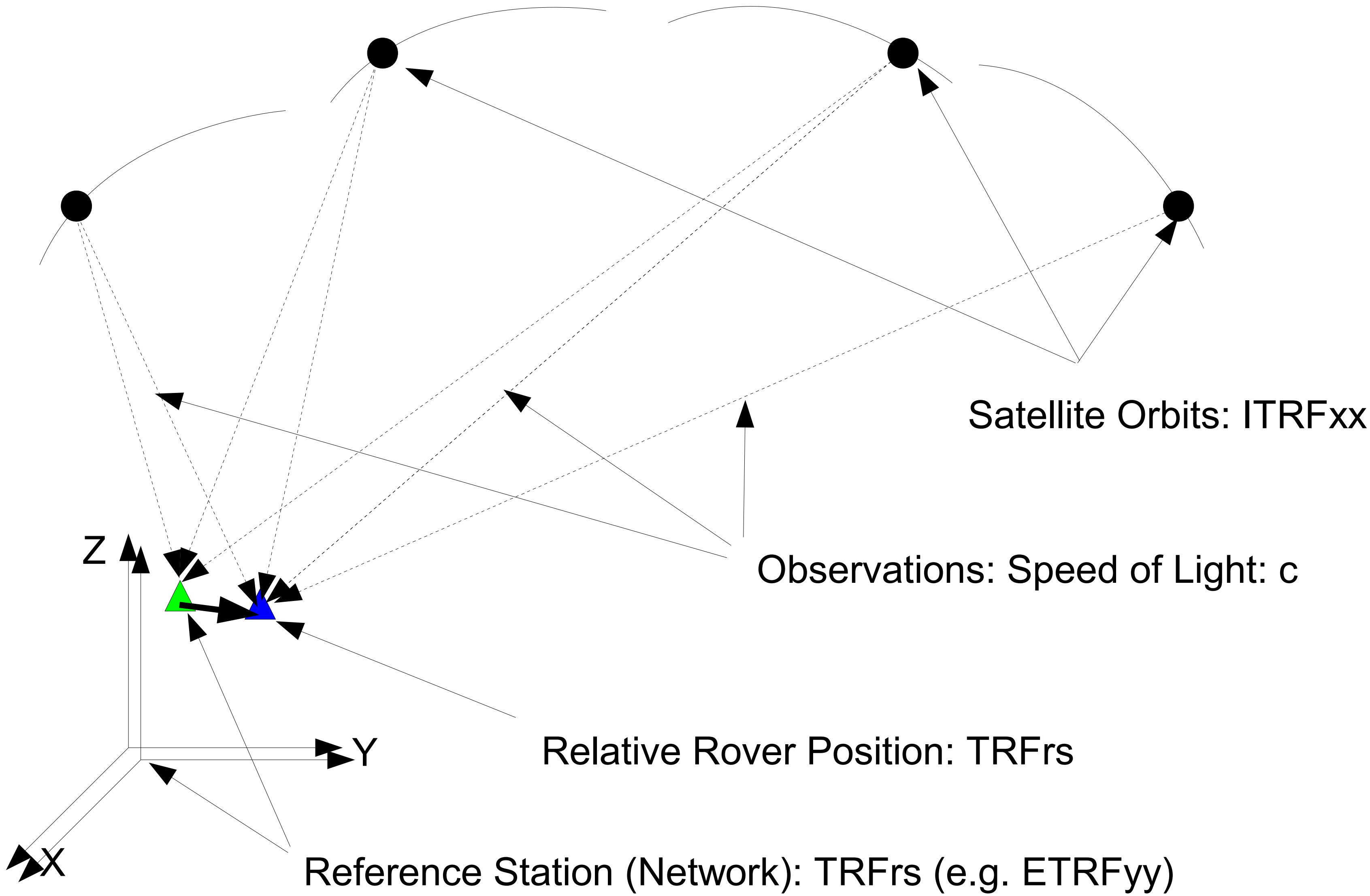


Consistency of CSR scale, c and GM requeired!

GNSS Positioning CRS Issues – Positioning



GNSS Positioning CRS Issues – Differential Positioning



OSR vs SSR

- Coordinate Reference Frame issues
  - OSR: global/continental/regional/local reference frames
    - Represented through reference station coordinates
    - Site displacements often neglected due to high correlation between RS and rover
    - “Inconsistency” of global (ITRF) and regional (ETRF) reference frames causes systematic errors in rover positions
      - problem increases with time due to plate motion
  - SSR: global/continental reference frames
    - Represented through satellite orbit
    - Regional and local frames through transformation
      - Dynamics of transformations!
    - Site displacements must be corrected

OSR vs SSR

- Service generation and infrastructure issues
  - OSR: Network-RTK services require homogeneous high quality RS equipment
  - SSR:
    - different state parameters may be derived from different sets of RS with different equipment
    - State parameters from different providers may be mixed as long as consistency is maintained
      - Example: Use IGS-IGU precise predicted orbits and determine satellite clock corrections
- Standardization issues
  - OSR: low standardization efforts
  - SSR: high standardization efforts

Summary

- SSR can/will replace OSR techniques for all types of GNSS positioning applications with better performance and less costs
- SSR standardization is challenging
- Status of RTCM-SSR and future steps:
  - Finished Stage 1: Satellite Orbits+Clocks+Code Biases ==> DF PPP
  - Stage 2: Phase Biases + Global Ionosphere ==> SF PPP
  - Stage 3: Regional and Local Ionosphere + Troposphere ==> RTK

Thank you for your attention


Thank you for your attention!