NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
U.S. DEPARTMENT OF COMMERCE

UTC(*k*) and its Realization and National Distribution

Andrew Novick
National Institute of Standards and Technology
Boulder, Colorado
tf.nist.gov
novick@nist.gov

BIPM Summer School
September 2025

Outline

- Lab setup and organization
- Equipment used in the lab
- Diagrams of lab configurations
- Steering of outputs
- Submitting data to BIPM Circular-T
- Indirect traceability
- National time distribution

Lab setup and organization

Starting with an empty room…

Considerations:

- Temperature and humidity control (and monitoring/logging)
- Vibration
- Power distribution (and backup)
- Signals coming into room (time, frequency, GNSS)
- Who has access, signage, etc.

Equipment used in the lab

Cables *
Clocks (time and frequency outputs – Cs, H)
Signal generators (function generators)
Time interval counters (TIC) *
Distribution for frequency and time
Time transfer GNSS receiver(s) *
Computer(s) – for logging, running statistics, etc.
Microstepper
Multi-channel measurement system

Equipment used in the lab

Cables *
Clocks (time and frequency outputs – Cs, H)
Signal generators (function generators)
Time interval counters (TIC) *
Distribution for frequency and time
Time transfer GNSS receiver(s) *
Computer(s) – for logging, running statistics, etc.
Microstepper
Multi-channel measurement system

BACKUPS

Equipment used in the lab

Time transfer GNSS receiver

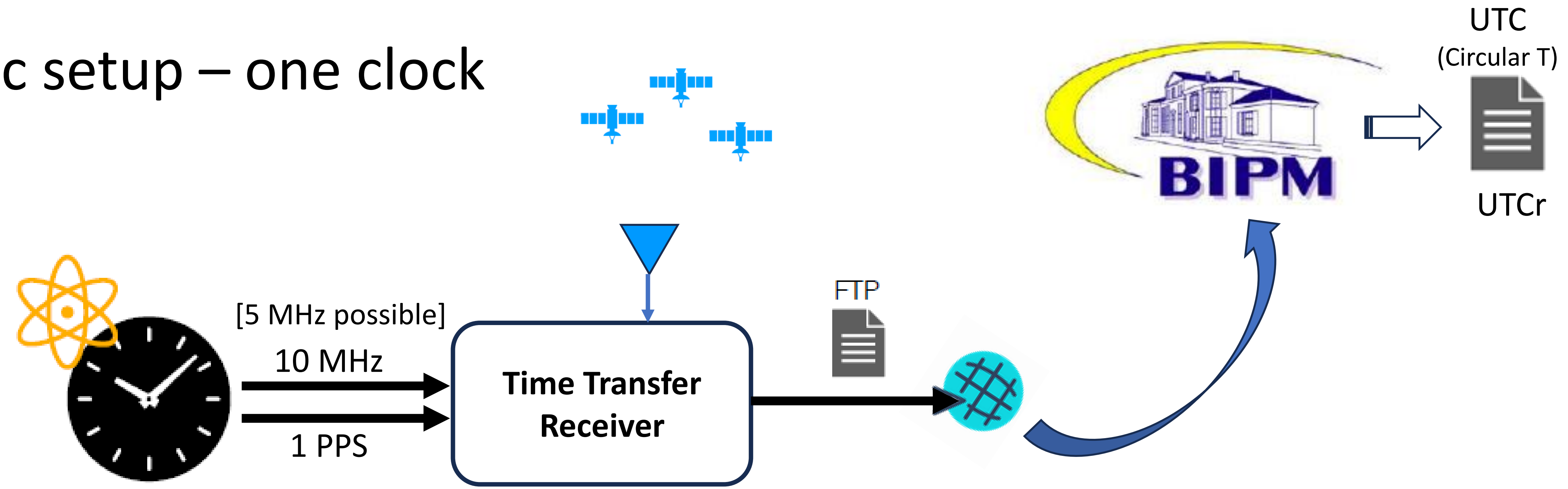
This is not a typical GNSS receiver of GPSDO.

It takes PPS and 10 MHz inputs and generates RINEX and CGGTTS files for BIPM.

There will be sessions on these file formats and the calibration procedure for these receivers

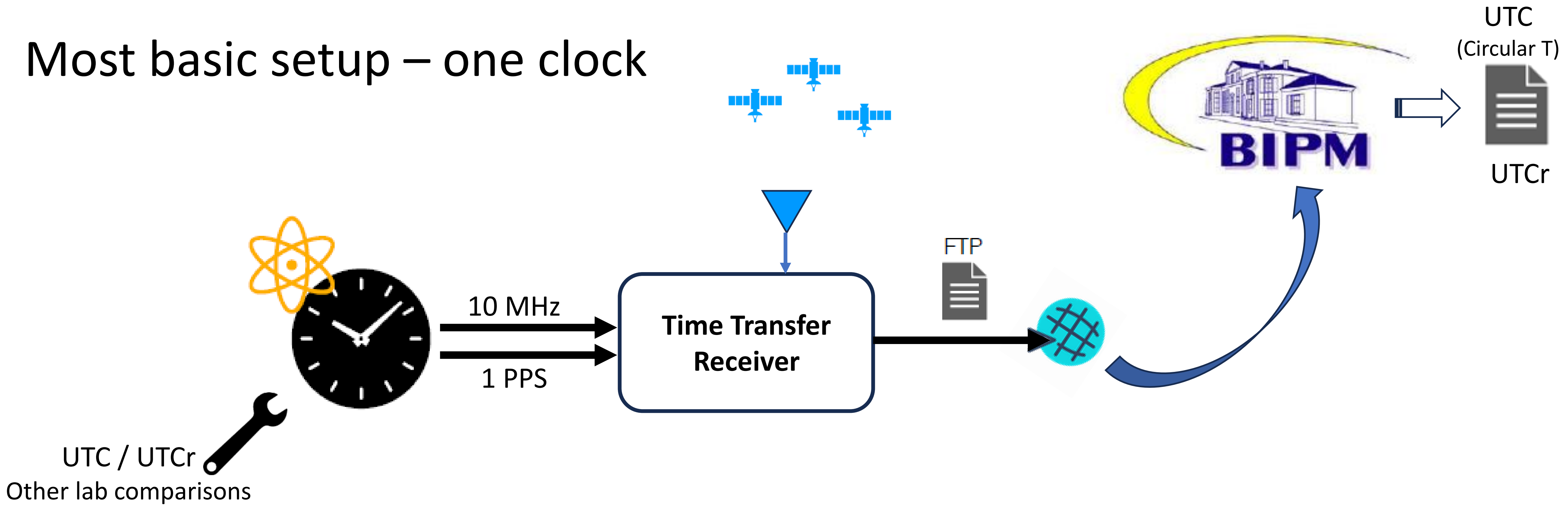
Diagrams of lab configurations

Most basic setup – one clock



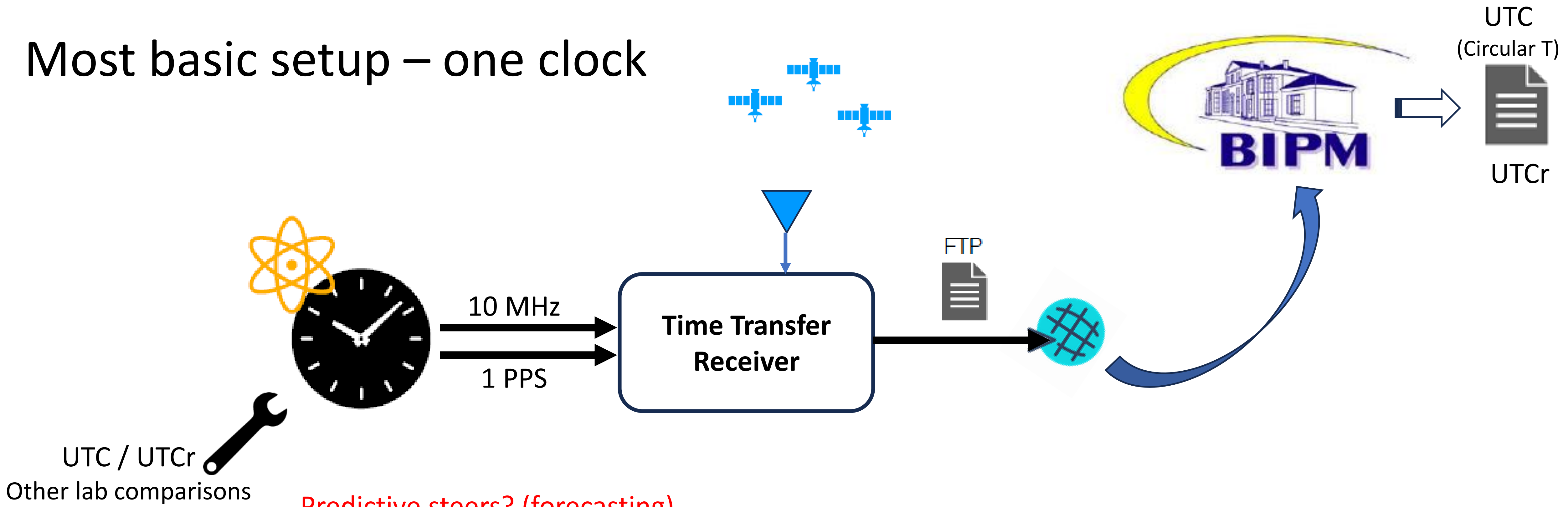
Diagrams of lab configurations

Most basic setup – one clock



Diagrams of lab configurations

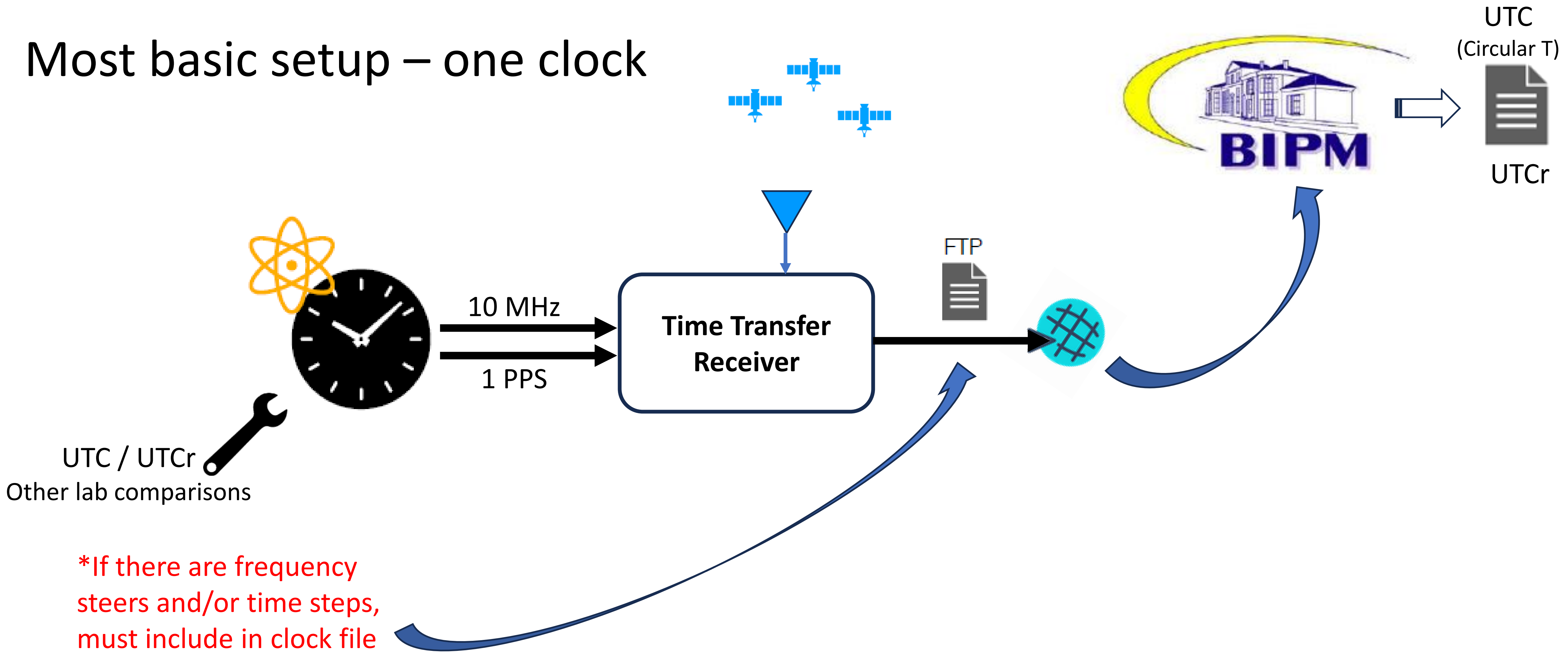
Most basic setup – one clock



Predictive steers? (forecasting)

Diagrams of lab configurations

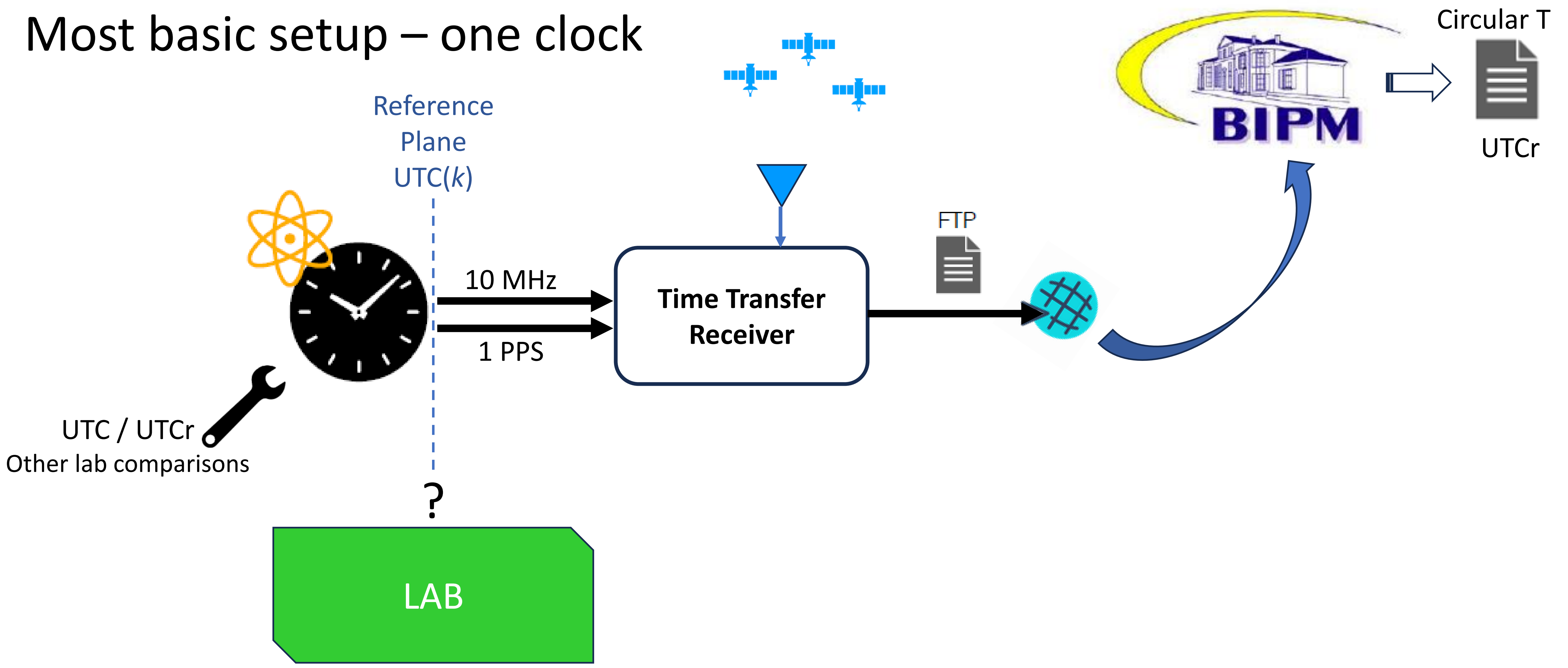
Most basic setup – one clock



*If there are frequency steers and/or time steps, must include in clock file

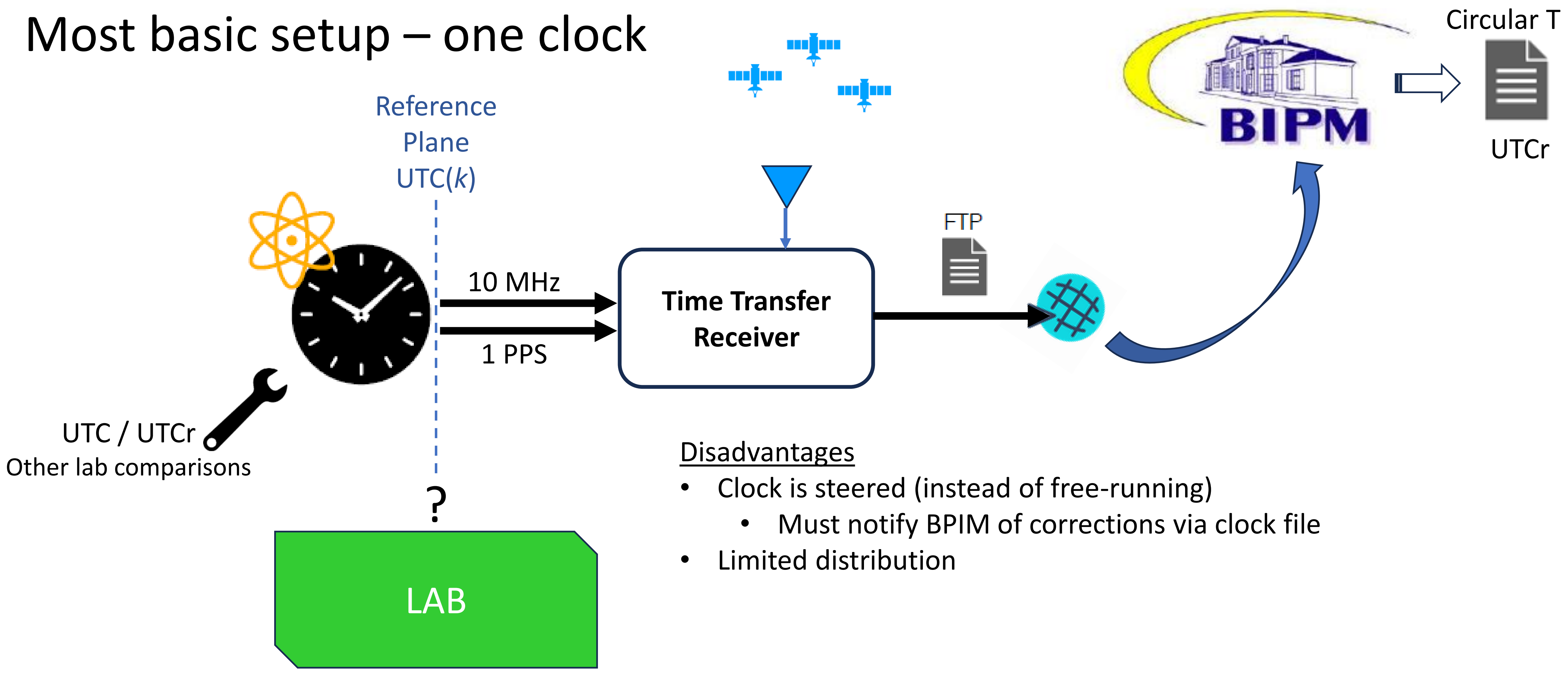
Diagrams of lab configurations

Most basic setup – one clock



Diagrams of lab configurations

Most basic setup – one clock

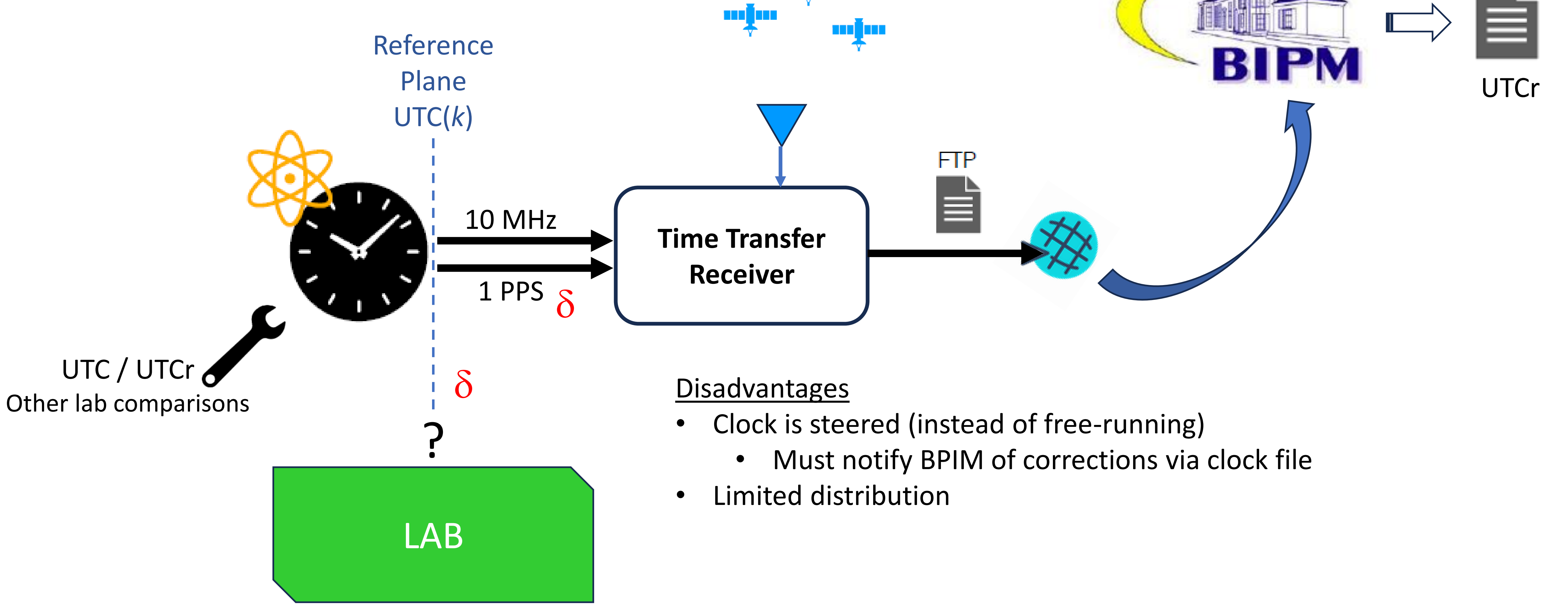


Disadvantages

- Clock is steered (instead of free-running)
  - Must notify BPIM of corrections via clock file
- Limited distribution

Don’t forget delays

Most basic setup – one clock

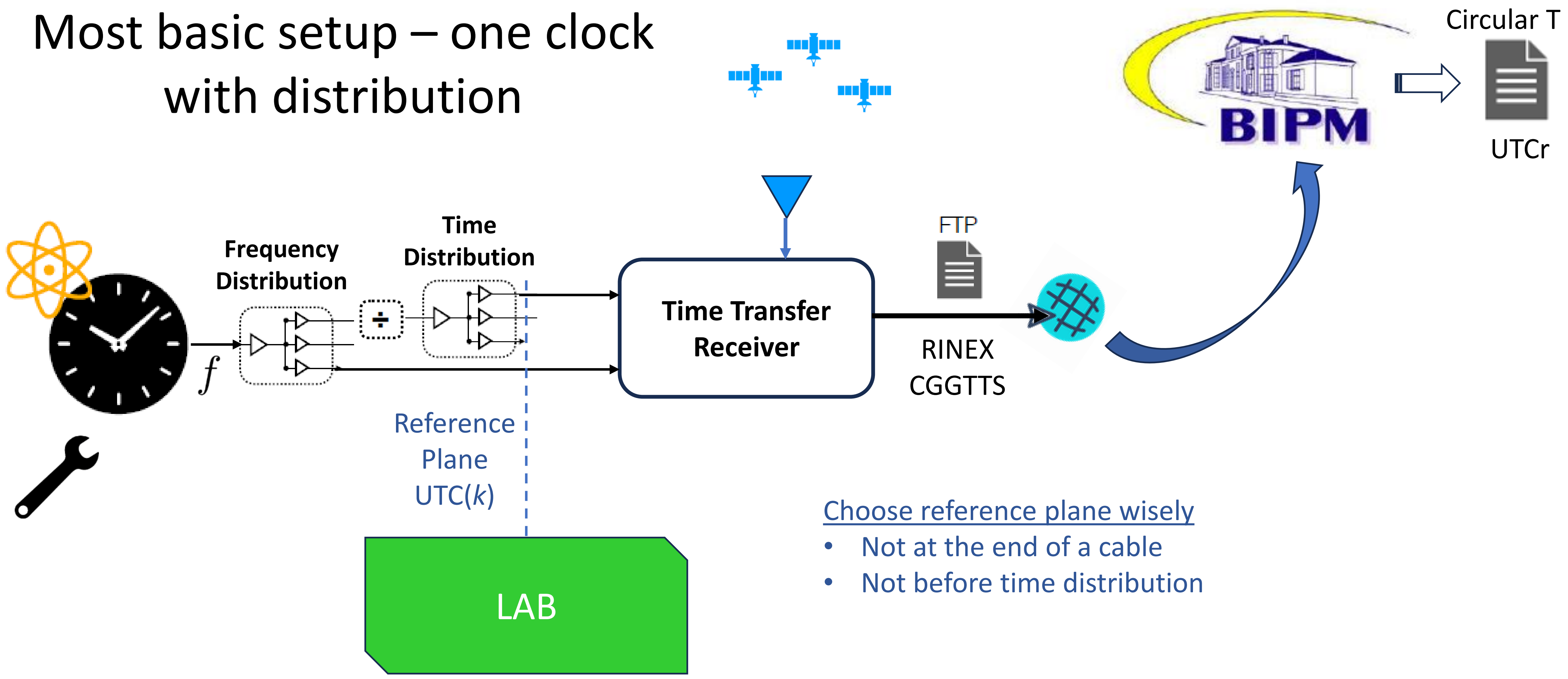


<u>Disadvantages</u>

- Clock is steered (instead of free-running)
  - Must notify BPIM of corrections via clock file
- Limited distribution

Diagrams of lab configurations

Most basic setup – one clock with distribution

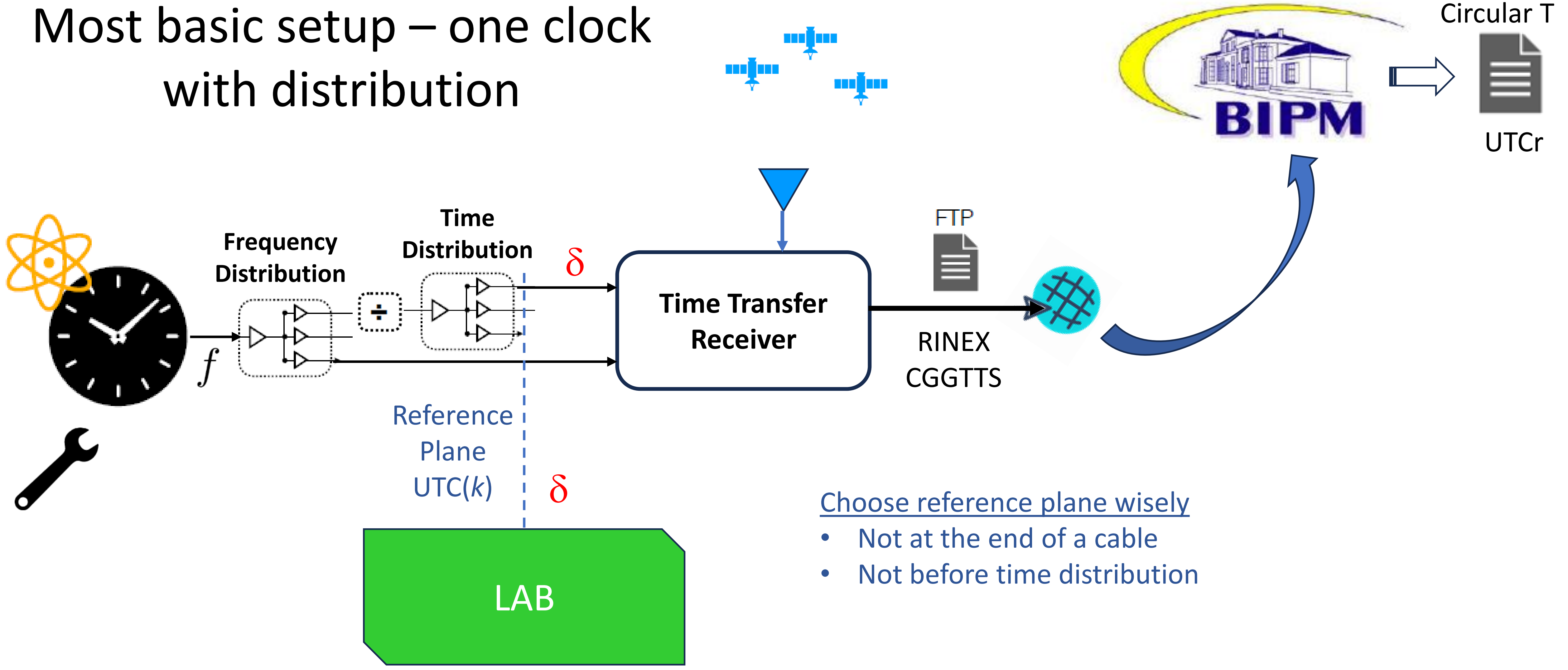


Choose reference plane wisely

- Not at the end of a cable
- Not before time distribution

Don’t forget delays

Most basic setup – one clock with distribution

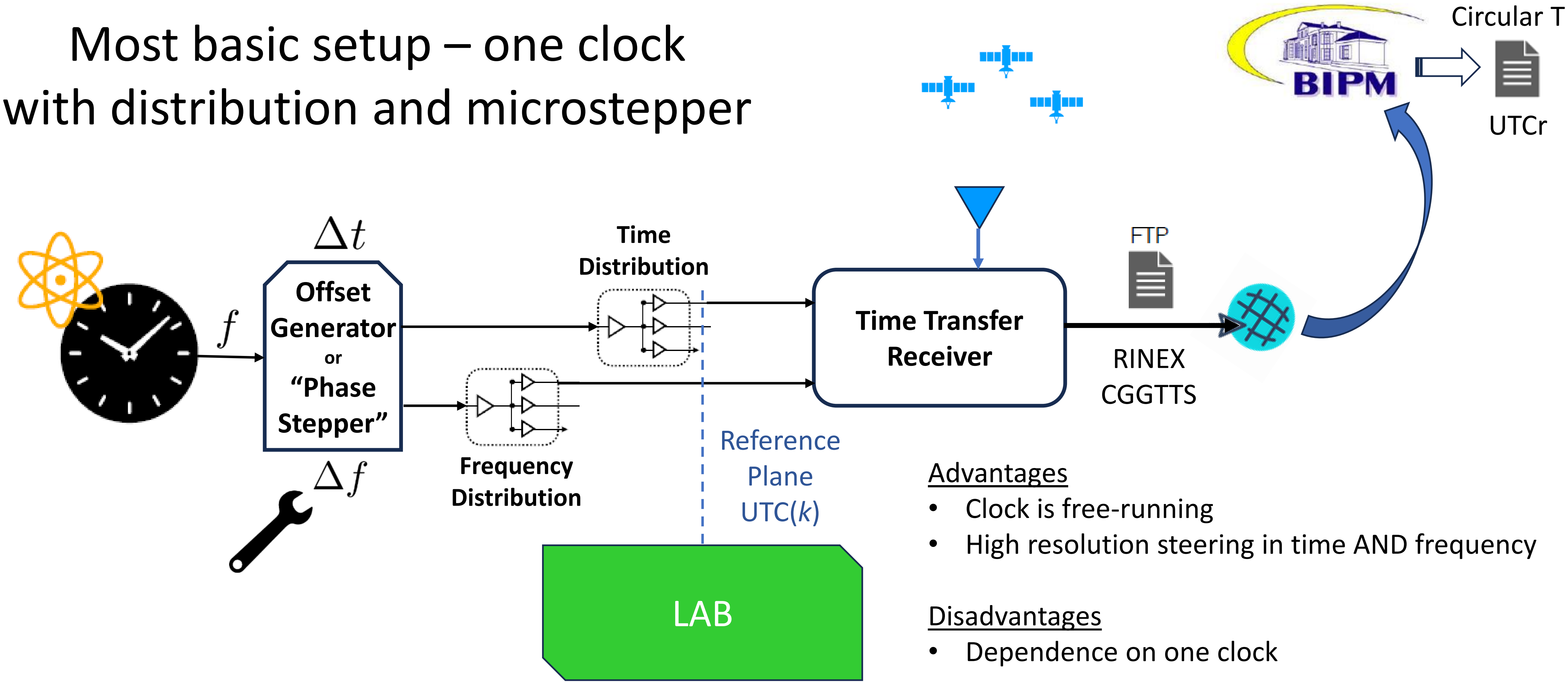


Choose reference plane wisely

- Not at the end of a cable
- Not before time distribution

Diagrams of lab configurations

Most basic setup – one clock
with distribution and microstepper

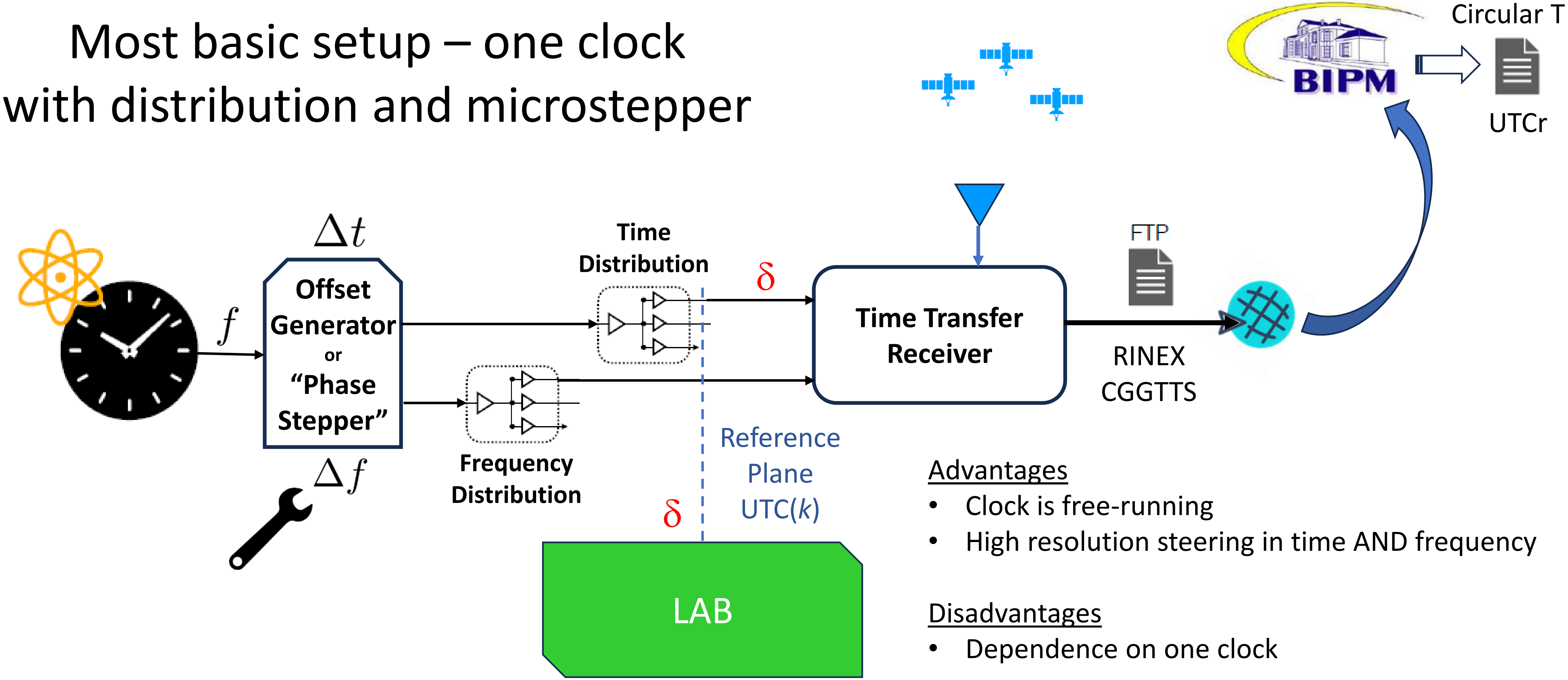


Advantages
- Clock is free-running
- High resolution steering in time AND frequency

Disadvantages
- Dependence on one clock

Don’t forget delays

Most basic setup – one clock
with distribution and microstepper

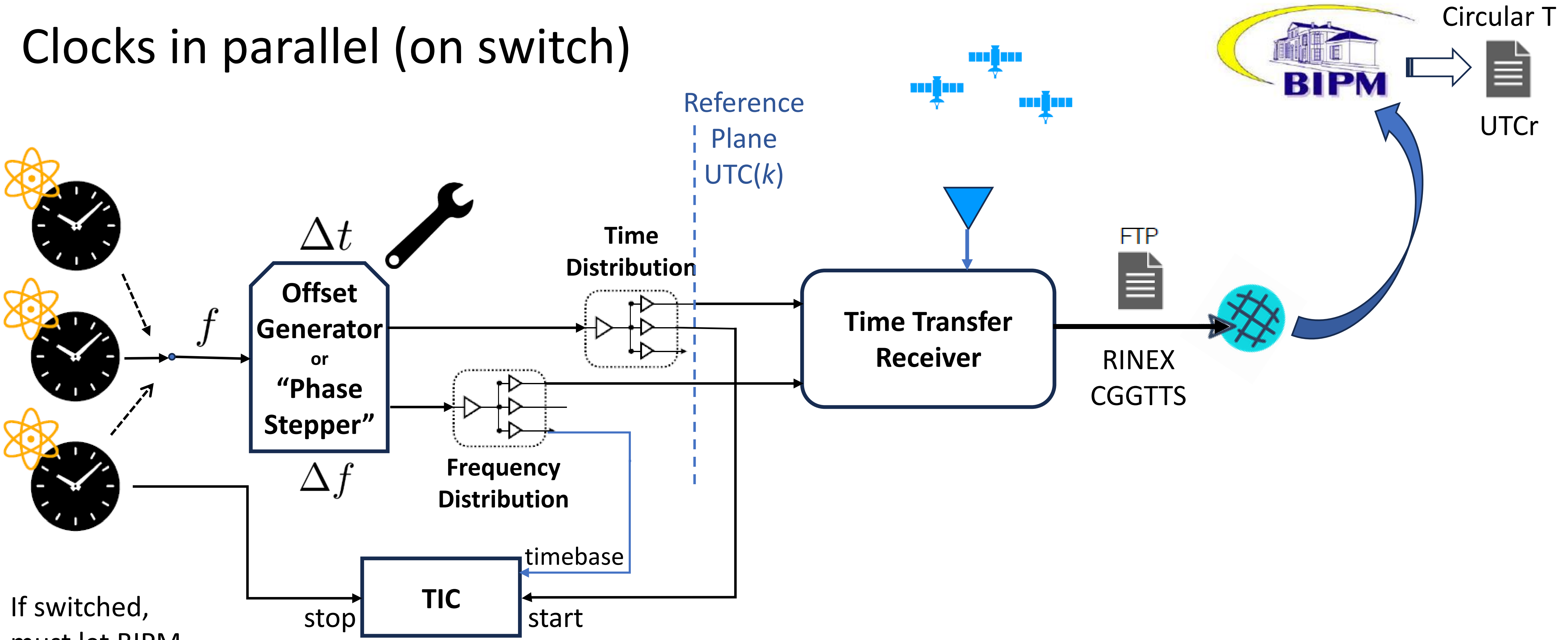


Advantages
- Clock is free-running
- High resolution steering in time AND frequency

Disadvantages
- Dependence on one clock

Diagrams of lab configurations

Clocks in parallel (on switch)

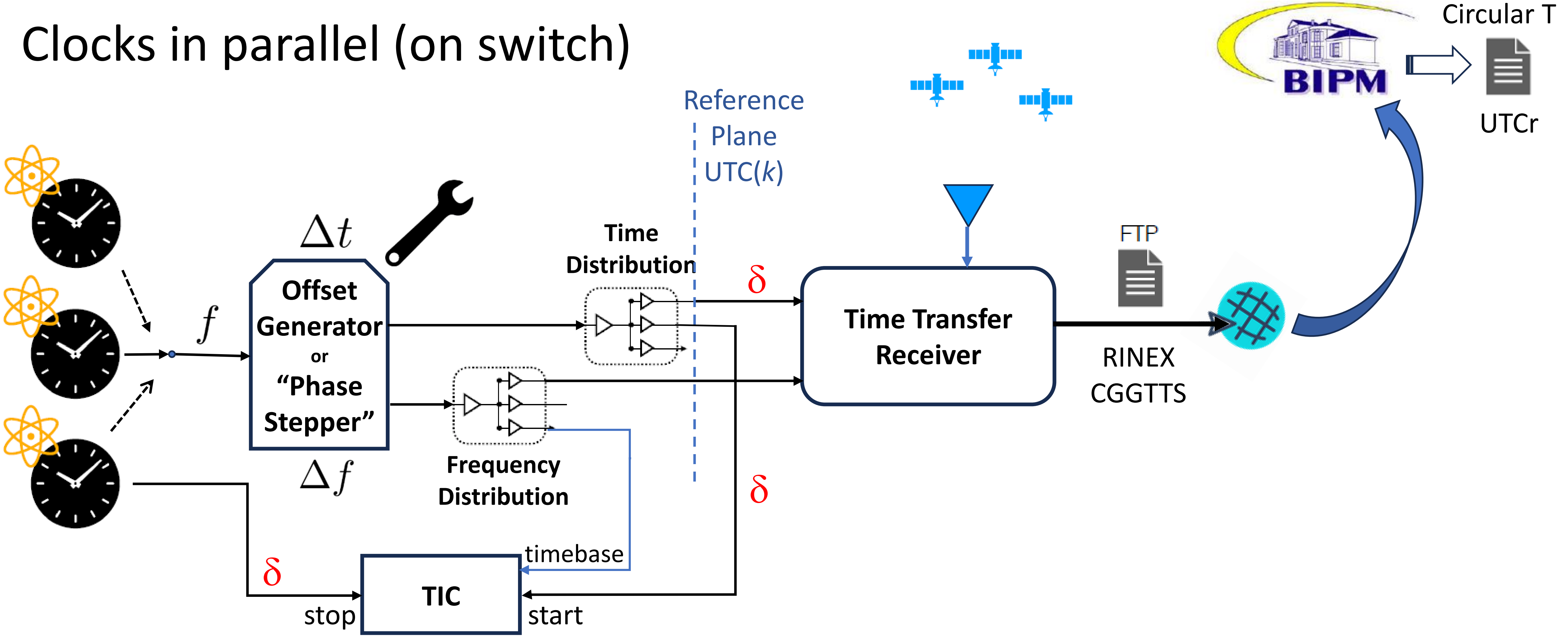


If switched, must let BIPM know.

[Replicate for each clock – add to clock file]

Don’t forget delays

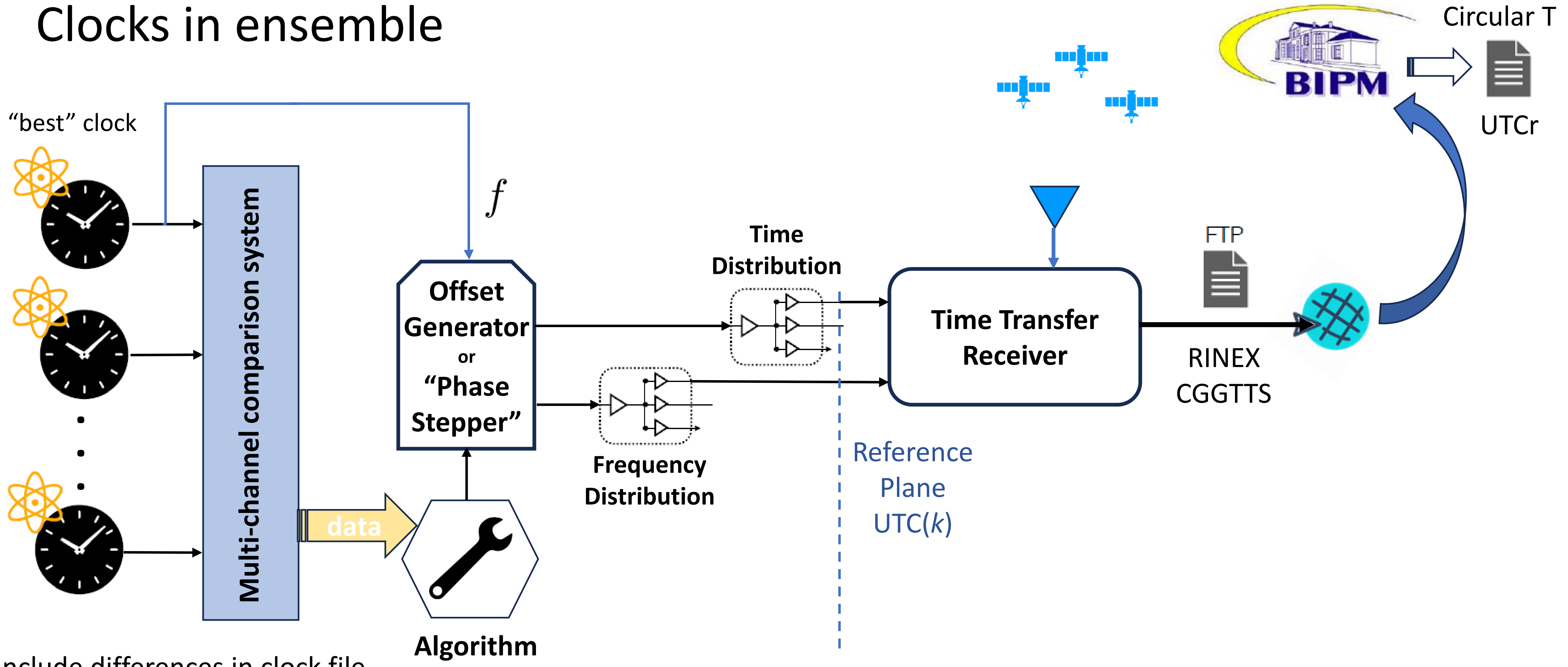
Clocks in parallel (on switch)



[Replicate for each clock – add to clock file]

Diagrams of lab configurations

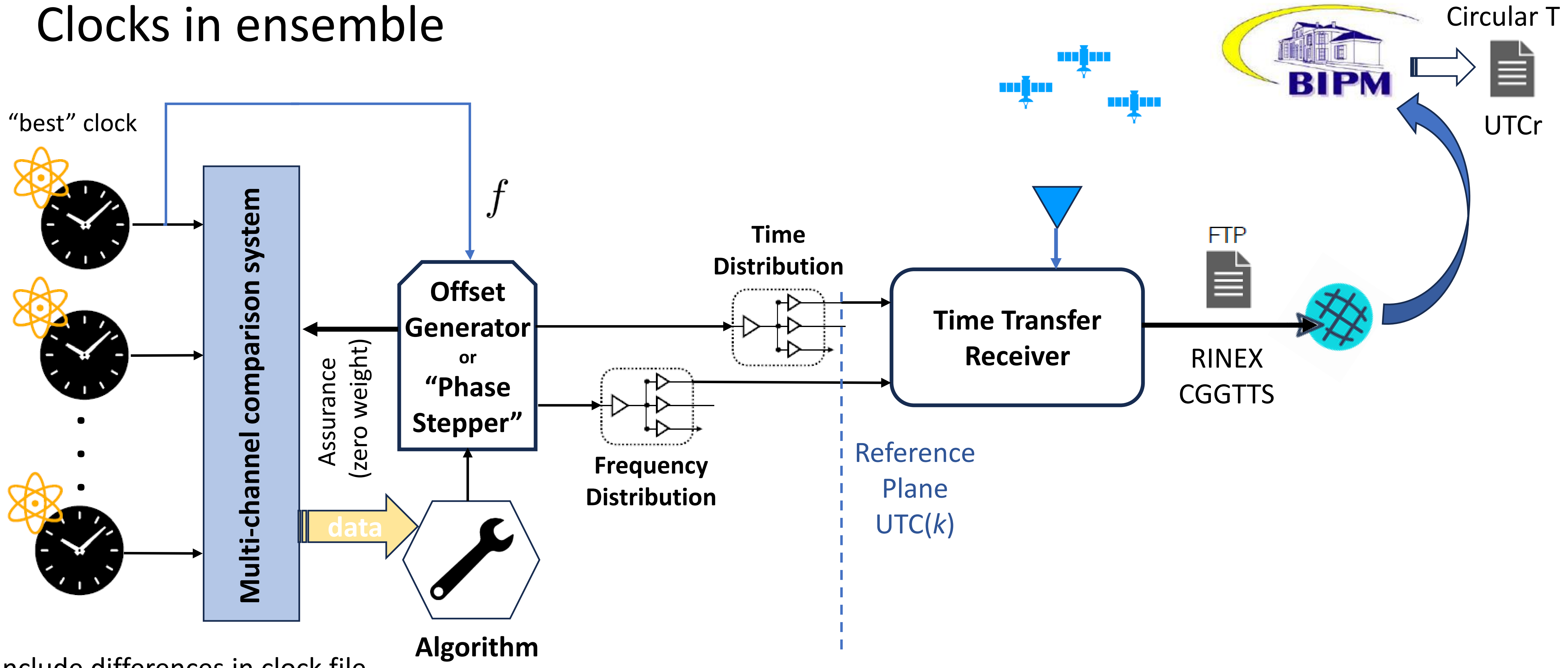
Clocks in ensemble



Include differences in clock file

Diagrams of lab configurations

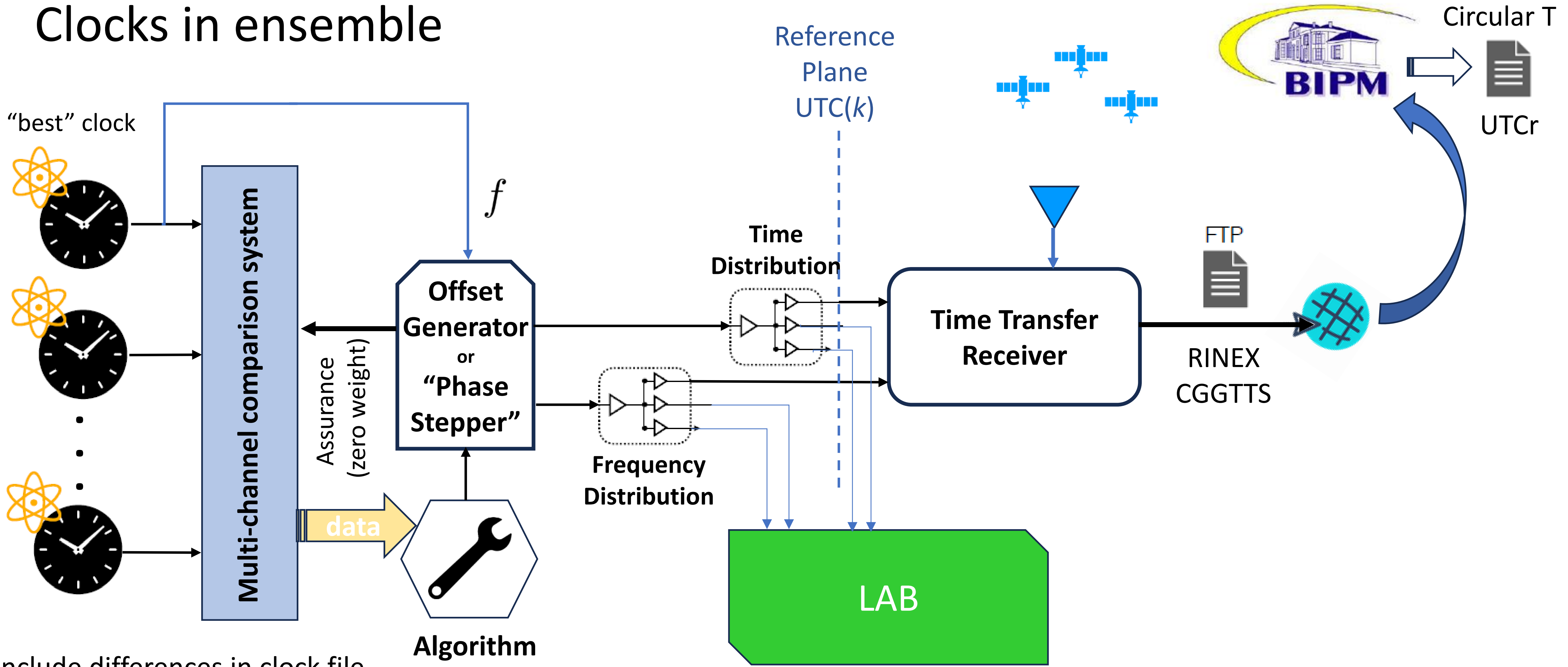
Clocks in ensemble



Include differences in clock file

Diagrams of lab configurations

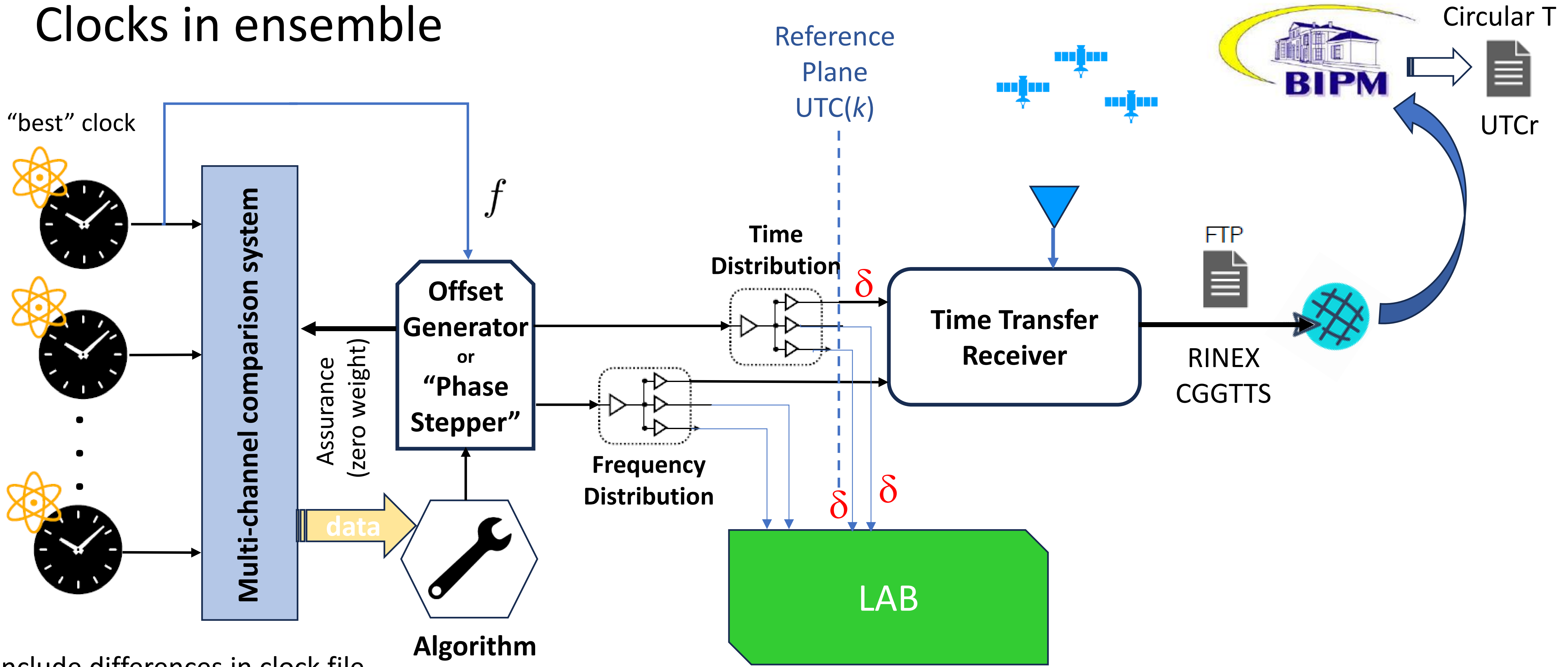
Clocks in ensemble



Include differences in clock file

Don’t forget delays

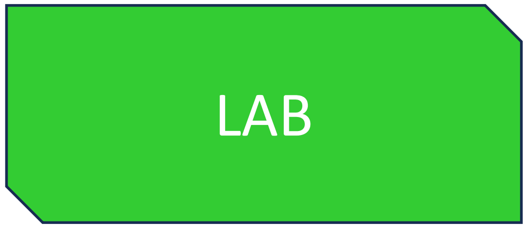
Clocks in ensemble



Include differences in clock file

Diagrams of lab configurations

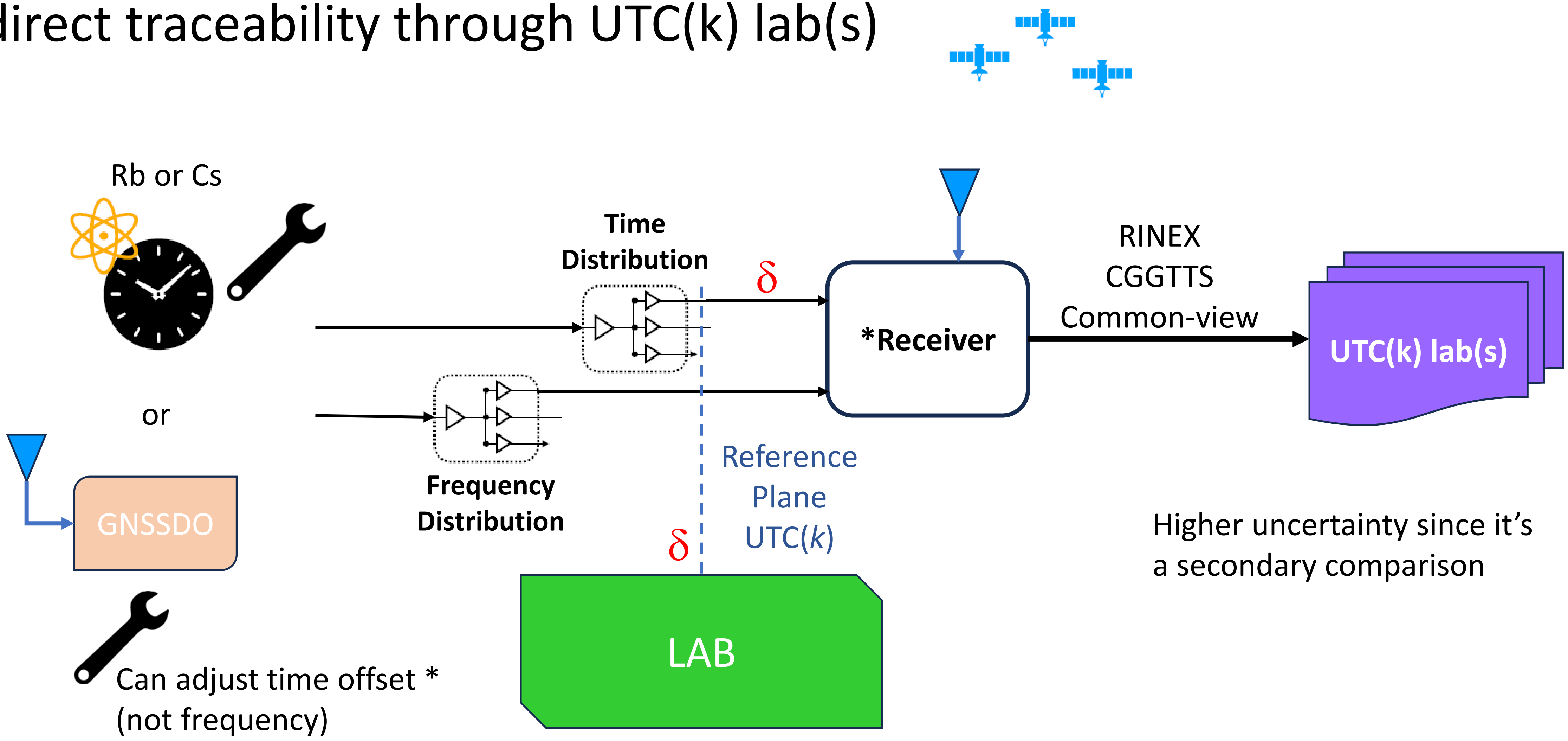
Using the UTC(*k*) signals – calibrations and time & frequency distribution



- Calibrations – timebases, stopwatches, GNSS, centrifuges, etc.
- Display clocks (s or 100s of ms)
- Telephone time service
- NTP service (ms)
- Web clock (s or hundreds of ms)
- Remote comparisons (ns e.g., common-view, two-way, fiber)
- Research

Diagrams of lab configurations

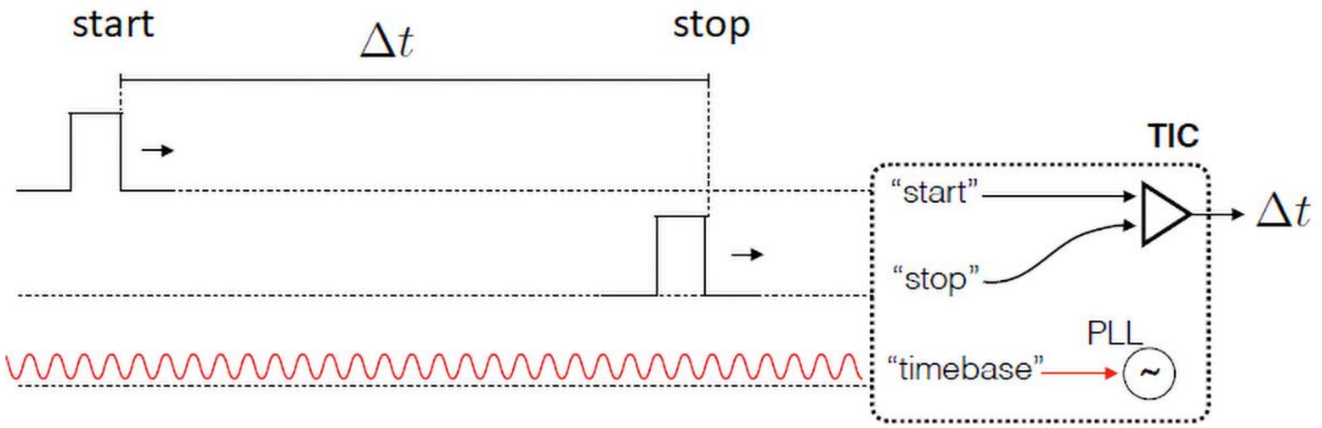
Indirect traceability through UTC(k) lab(s)



Higher uncertainty since it’s a secondary comparison

Equipment used in the lab

Time Interval Counter (TIC)



TIC locks an internal oscillator to the external timebase frequency and "counts" the number of cycles between the start pulse and the stop pulse, the result is a time duration ***start – stop = Δt.***

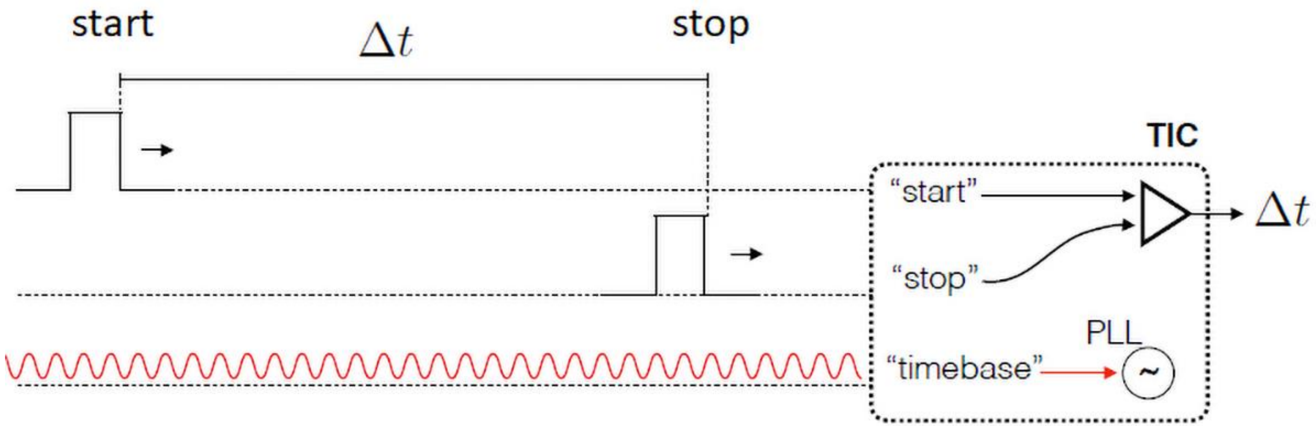
The signs can be confusing: when the stop pulse comes after the start pulse, it is "later" by *delta t* and we refer to the *delay* is a positive number, and we use the term "start – stop**"**. **The BIPM convention is to measure UTC(k) – clock.**
For instance, if you are measuring UTC(k) on the start channel and a free-running clock on the stop channel, and the TIC shows 6.2 ns, we know that the free-running clock is "later" by +6.2 ns.

So, ***start – stop = +6.2 ns*** or, in this case, ***UTC(k) – clock = +6.2 ns***, meaning the clock is late.

We can think that the PPS giving the START is the PPS denoting "noon". The same "noon" PPS of the clock is not yet arrived. It will arrive 6.2 ns later. When it is noon for UTC(k), it is not yet noon for the clock. Therefore the difference in time readings UTC(k) – clock, in the same instant, would be positive.

Equipment used in the lab

Time Interval Counter (TIC)



If the stop pulse is almost a complete second later, then you could consider it to be earlier than the start pulse by (***1 minus the delay)***.

Consider the previous example, where UTC(k) is on the start channel and a free-running clock on the stop channel, but the answer for ***start – stop = 0.9999999938 s.*** As the PPS of the clocks are usually closely synchronized to UTC(k) PPS, that indicates that the stop pulse came in 6.2 ns ***before*** the start pulse, so ***start – stop = -6.2 ns*** or ***UTC(k) – clock = -6.2 ns***.

Some TICs adjust this automatically to show a negative delay, so if start – stop is negative, then the clock on the stop channel is earlier. If not, you can see the small delay number if the sources of the start and stop channels are switched, but then you have to take into account that ***the sources of "start – stop" have been reversed***, and this may be difficult to keep track of.

If ***start – stop = 0.9999999938 s*** and you swap the inputs to get +6.2 ns, then you must consider that it is now ***clock – UTC(k) = +6.2 ns***, so ***UTC(k) – clock still equals -6.2 ns***.

Questions?

NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
U.S. DEPARTMENT OF COMMERCE

Time dissemination at NIST

A Few Time and Frequency Signals/Calibrations by NIST

NIST serves the private and public sectors through the continuous distribution of UTC(NIST).

Service	Best Case Uncertainty	Customer Cost
Two-way satellite T&F Transfer	2 ns	~$100k per year plus ground station
Time Measurement & Analysis Service	10 ns	$1300 to $1990 per month
Time Over Fiber	50 ns	>$5000/month, depending on route
Frequency Measurement and Analysis	2×10^{-13} at 1 day	TMAS ($1300) + FMAS add-on ($345/month)
WWVB	100us	Free
Internet Time Service (ITS)	10-50 ms	Free
www.time.gov	100 ms	Free

Common-view GPS (and other GNSS)

- SIM/TMAS systems use common-view GPS comparisons.

- UTC(NIST) is compared to the clocks on each satellite in view with a custom-built measurement system.
- Remote sites have the same system (calibrated at NIST), which compares customer clock to each satellite in view.
- The data files (10-minute averages) are uploaded to a web server.
  For each satellite ***in common-view*** (seen by both sites at the same time):

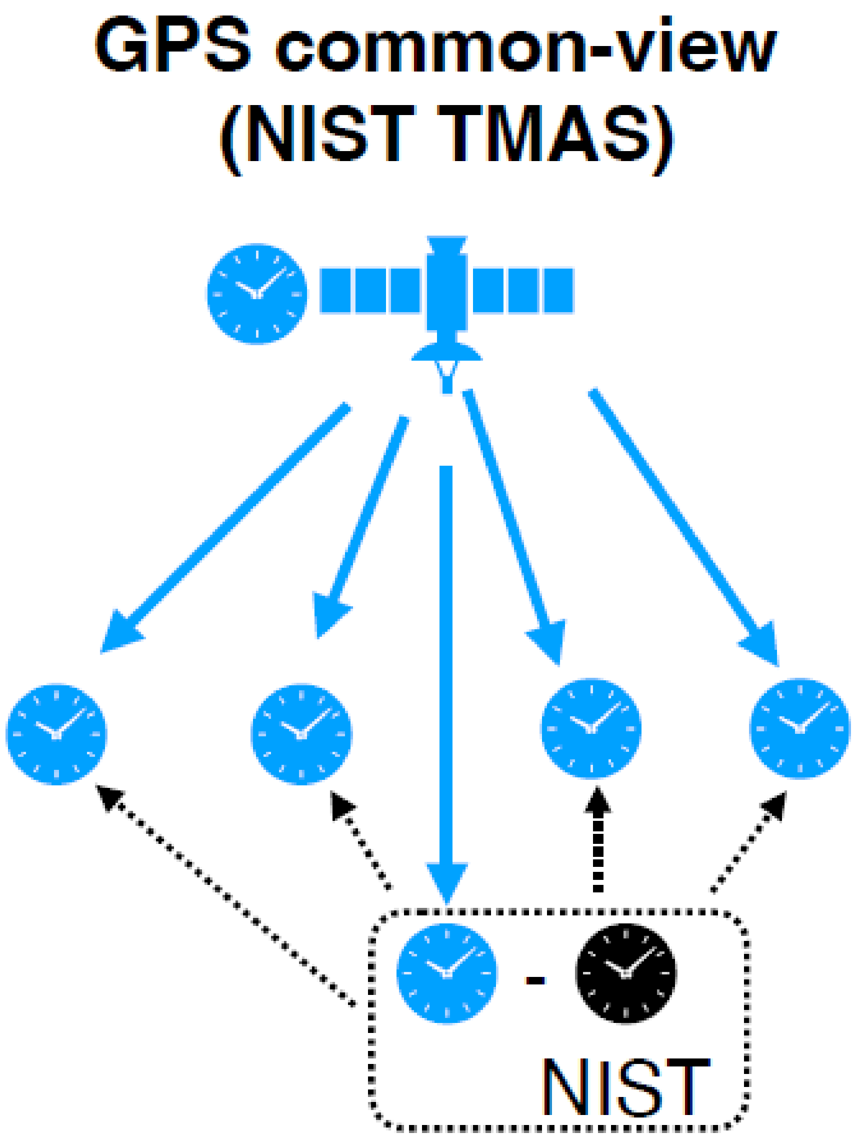
  (UTC(NIST) – clock on sat. x) – (Remote clock – clock on sat. x)

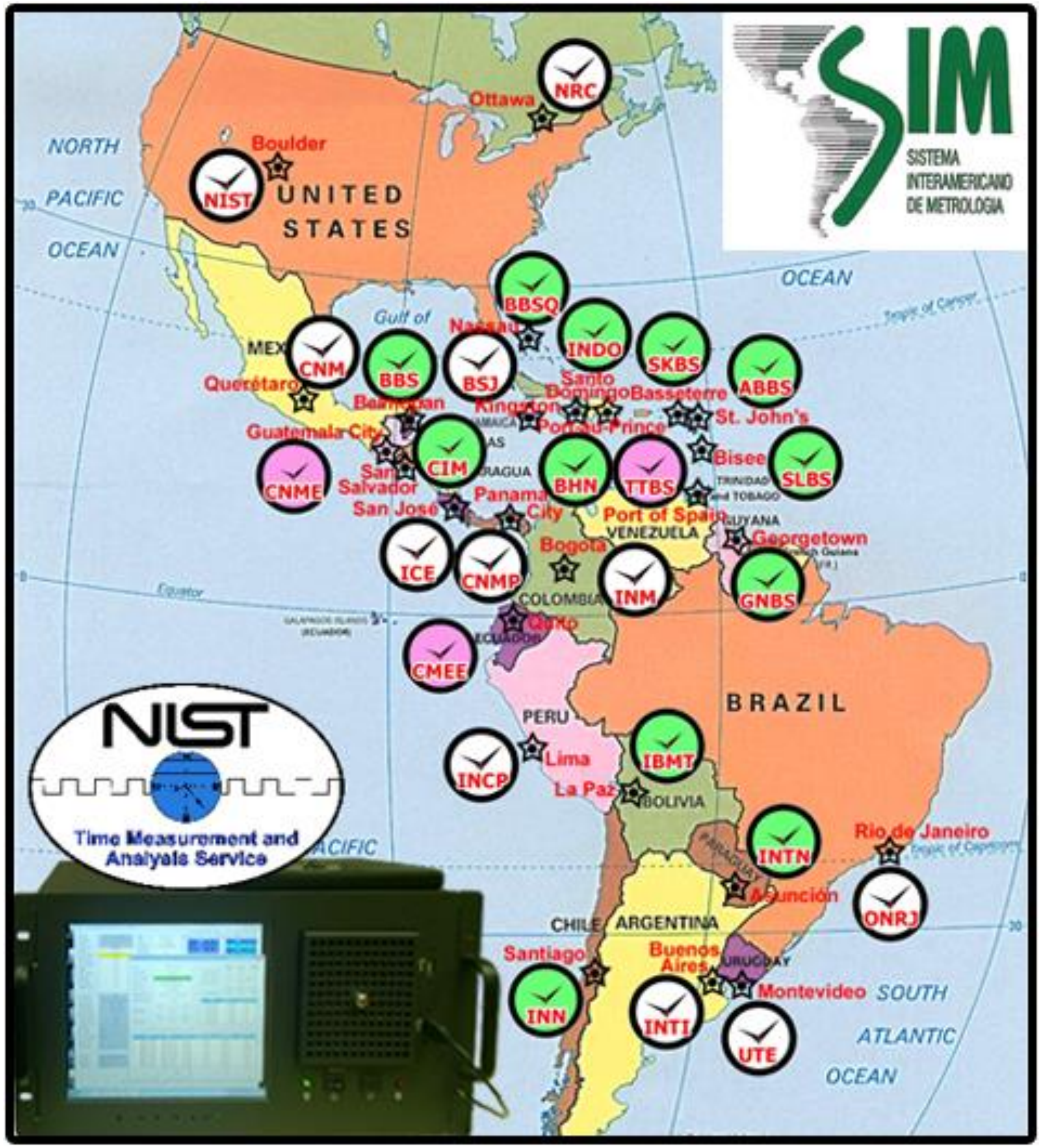
  = UTC(NIST) – Remote clock .

- Error terms include delay differences between the two sites caused by:

  - Ionospheric and tropospheric delays
  - Multipath signal reflections
  - Environmental conditions
  - Errors in the GPS antenna coordinates

- Known/measured quantities are entered as a correction after calibration.
- What is left is the uncertainty.





White clocks represent labs with cesium oscillator(s) or an ensemble time scale

Green clocks represent labs with Rb oscillators steered to SIMT

Purple clocks represent labs with GPSDOs or undisciplined Rb oscillators

TMAS Option Using Commercial Hardware

BlueSky GNSS Firewall

- Identifies and protects GNSS systems from spoofing/jamming.
- Uses the same receiver as our new system.
- They can replicate our file format (beta test already running).

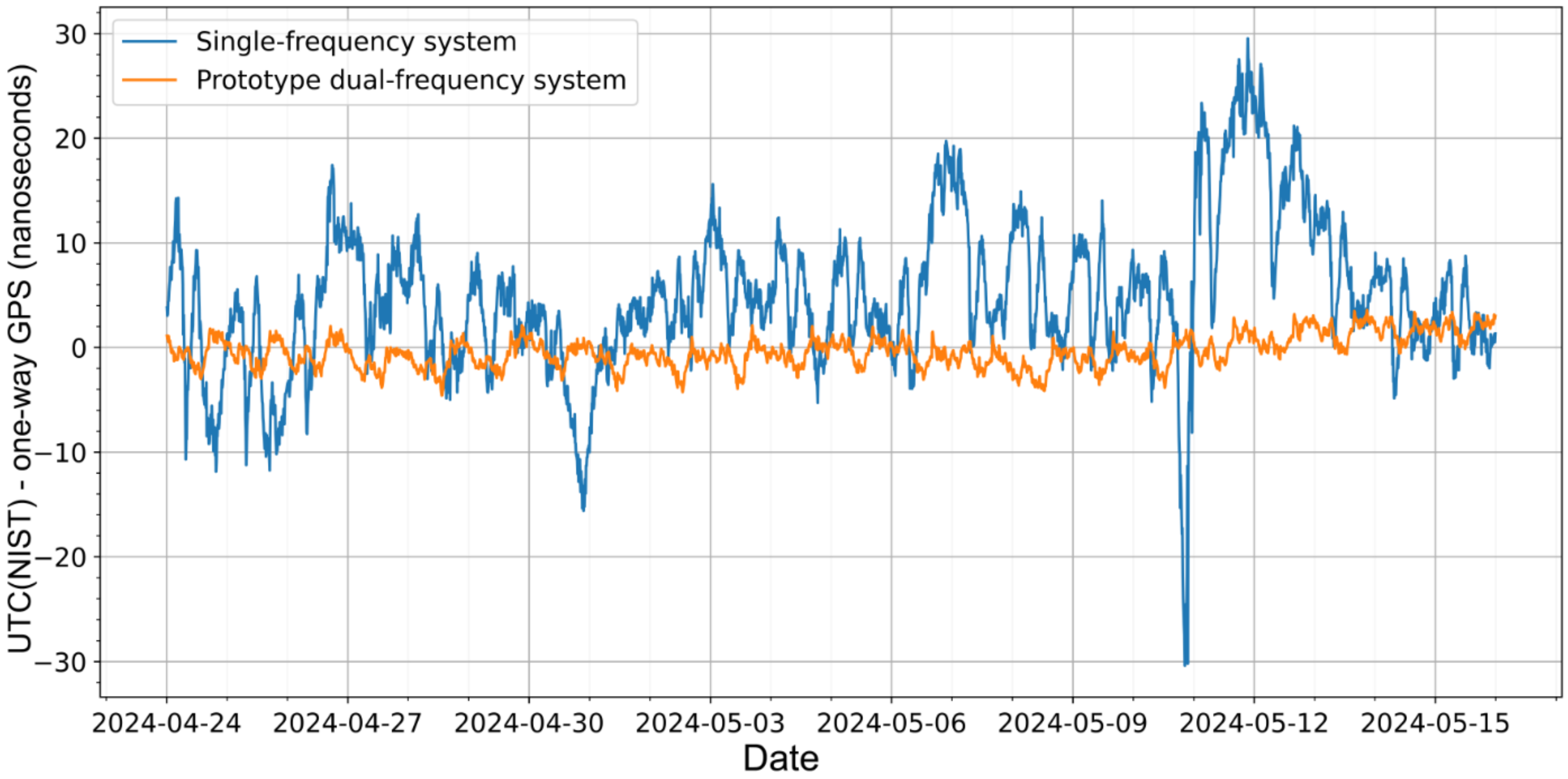
<u>Benefits</u>

- Existing product
- Existing potential customers
- We don’t have to build the hardware
- More scalable
- Adds some GNSS resilience
- Non-exclusive to this company

Improvements to TMAS

NIST

Extreme case of ionospheric effects



Single-frequency and dual-frequency one-way GPS data compared to UTC(NIST) before and during the solar storm on May 10, 2024.