Ad hoc fundamental physics experiments with SVLBI

with focus on probing the gravitational redshift

Norbert Bartel

York University, Toronto

Next Generation Space VLBI workshop

Astron/Jive 17 to 19 October 2022

OUTLINE

1. Previous ad hoc GR space experiments
2. Test of Einstein Equivalence Principle with RadioAstron
3. Ideas for Next Generation Space VLBI
4. Conclusions
5. Final thoughts

1. Previous ad hoc GR space experiments

Ad hoc: Shapiro delay conception

A. Goal: planetary astronomy

- Radar observations of Venus:

Victor and Stevens (USA)1961
Thomson et al. 1961 (GB)
Kotelnikov 1961 (USSR)

- Radar observations of Mercury:

Kotelnikov 1962 (USSR)

Fourth test of general relativity: Shapiro 1964

Classical tests of general relativity

1. Anomalous precession of perihelion of Mercury
2. Light deflection
3. Gravitational redshift
4. Shapiro delay

Millstone Radar, MA, USA

Ad hoc Cassini experiment

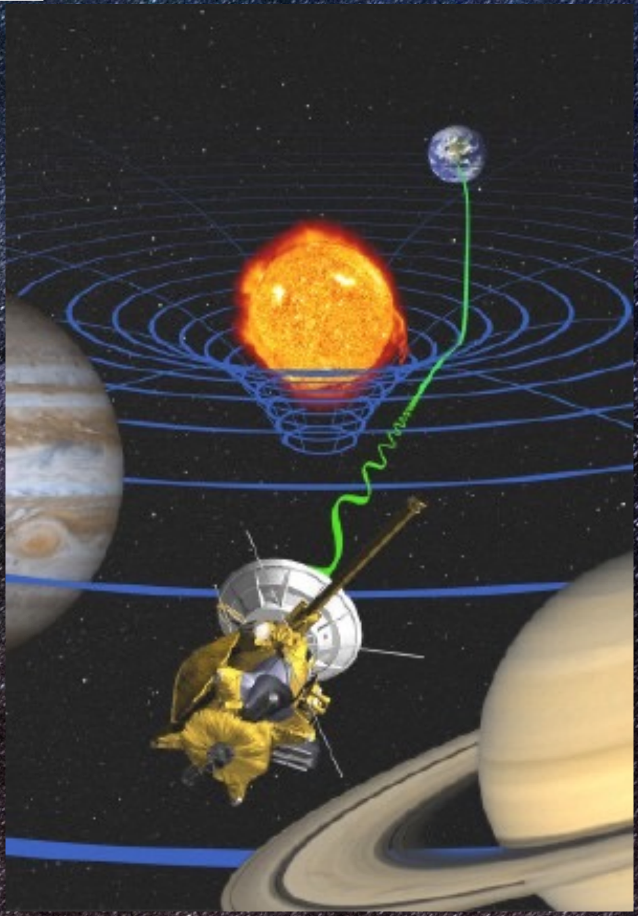
B. Goal: planetary astronomy

Cassini test of GR. Bertotti et al. 2003

Frequency shift of signal due to gravitational space-time distortion

Deviation from GR:

$\boldsymbol{\varepsilon = (2.1 \pm 2.3) \times 10^{-5}}$



Physics World

Frequency shift measured with rel. precision:$1\text{x}10^{-14}$

Ad hoc gravitational redshift experiment with Galileo

C. Goal: Building the European navigation system with Galileo satellites

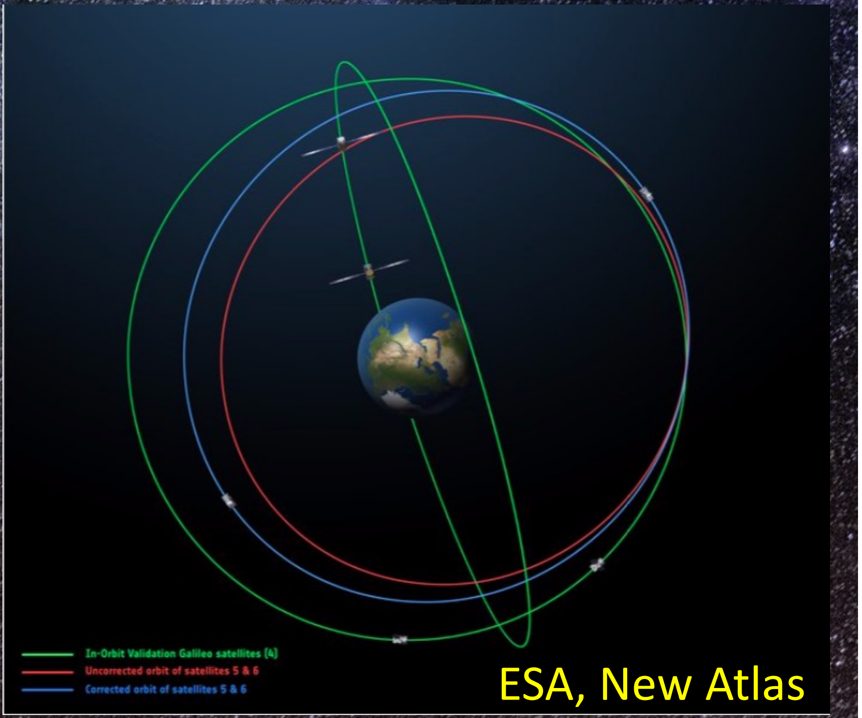
Problem: orbit of satellites 5, 6
was slightly elliptical

Gravitational redshift experiment
with Galileo satellites

Deviation from GR:

$\varepsilon=(0.19\pm2.48)\times10^{-5}$ (Delva et al. 2018)

$\varepsilon=(1.9\pm1.6)\ to\ (4.5\pm3.1)\times10^{-5}$ (Hermann et al. 2018)



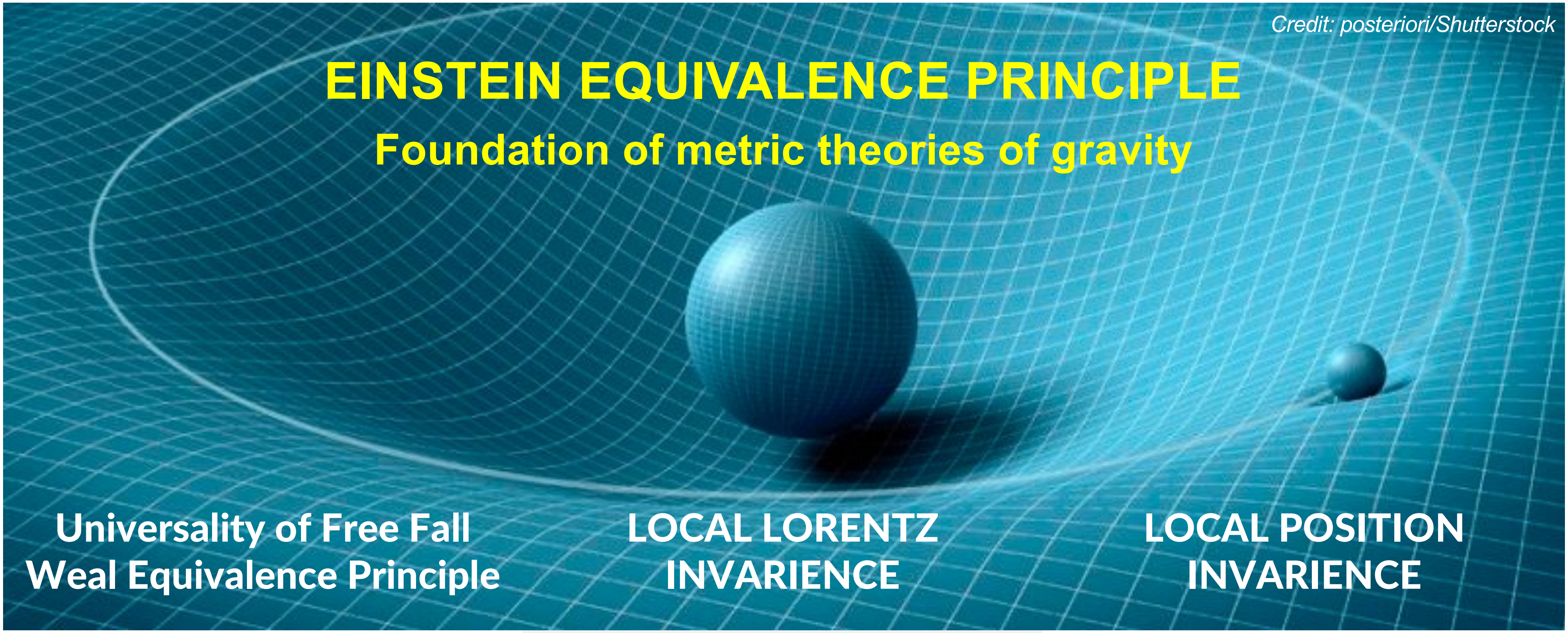
ESA, New Atlas

2. Test of Einstein Equivalence Principle with RadioAstron

by probing the gravitational redshift

N. Nunes[1], N. Bartel[1], M. Bietenholz[1], A. Belonenko[2],
G. Cimò[3], D. Dirkx[4], A. Filetkin[2], L. Gurvits[3,4], A. Gusev[2], D. Litvinov, G. Manucharyan[2]
G. Molera Calves[5], S. Popov[2], V. Rudenko[2], M. Zakhvatkin[6]

[1] York University, Toronto, Canada
[2] Sternberg Astronomical Institute, Moscow State University, Moscow, Russia
[3] JIVE, Netherlands
[4] Delft University, Delft, Netherlands
[5] University of Tasmania, Hobart, Australia
[6] Keldysh Institute of Applied Mathematics, Moscow, Russia



Credit: posteriori/Shutterstock

EINSTEIN EQUIVALENCE PRINCIPLE

Foundation of metric theories of gravity

Universality of Free Fall
Weal Equivalence Principle

Neutral objects fall in a gravitational field at the same rate regardless of their internal structure

$$10^{-15}$$

LOCAL LORENTZ INVARIENCE

The laws of physics are independent of the velocity of the frame of reference in which the laws are expressed

$$10^{-8}$$

LOCAL POSITION INVARIENCE

The outcome of any non-gravitational experiment is independent of where and when it is performed

$$\sim 2.5\times 10^{-5}$$

Gravitational redshift

GRAVITATIONAL REDSHIFT

Local Position Invariance → Gravitational Redshift

Relative or fractional frequency Shift

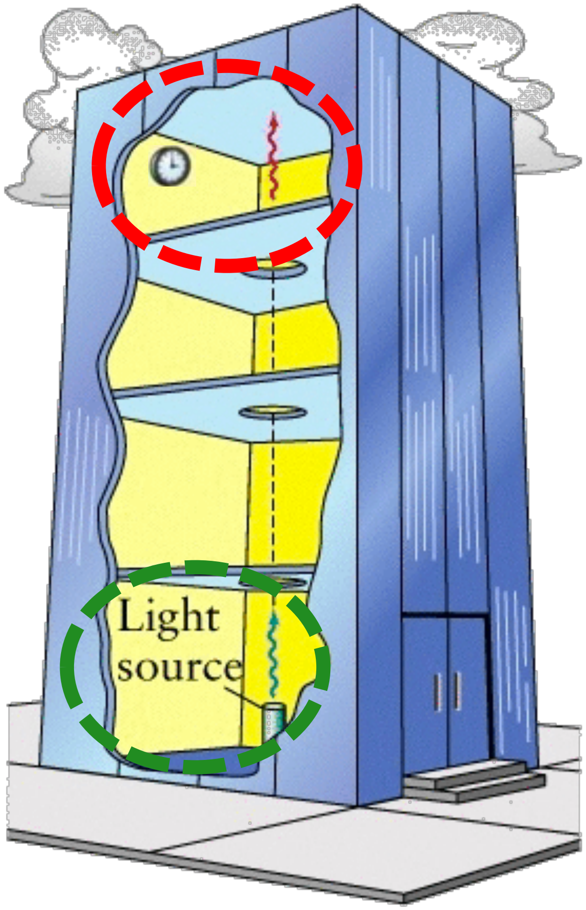
Difference in gravitational potential between clock locations

$$y \equiv \frac{\Delta f}{f} = (1 + \varepsilon)\frac{\Delta U}{c^2}$$

Violation parameter

Unification theories lead to $\varepsilon \neq 0$
Also to consider: dark matter, dark energy

Pound - Rebka 1959



Credit: Figure 21-7, Universe, 10th Edition
© 2014 W.H. Freeman and Co

RADIOASTRON

- Russian-led international space-VLBI mission
- Onboard “space” H-maser (SHM)
- Perigees as low as 7,000 km
- Apogees up to **370,000** km
- Eccentricity of 0.6 to 0.96
- Uplink frequency of 7.2GHz
- Downlink at 8.4GHz and 15GHz
- Tracking stations in Pushchino, Russia and Green Bank, USA

$$Goal: \delta\varepsilon \sim 2\times10^{-5}$$

GROUND (TRACKING) STATIONS

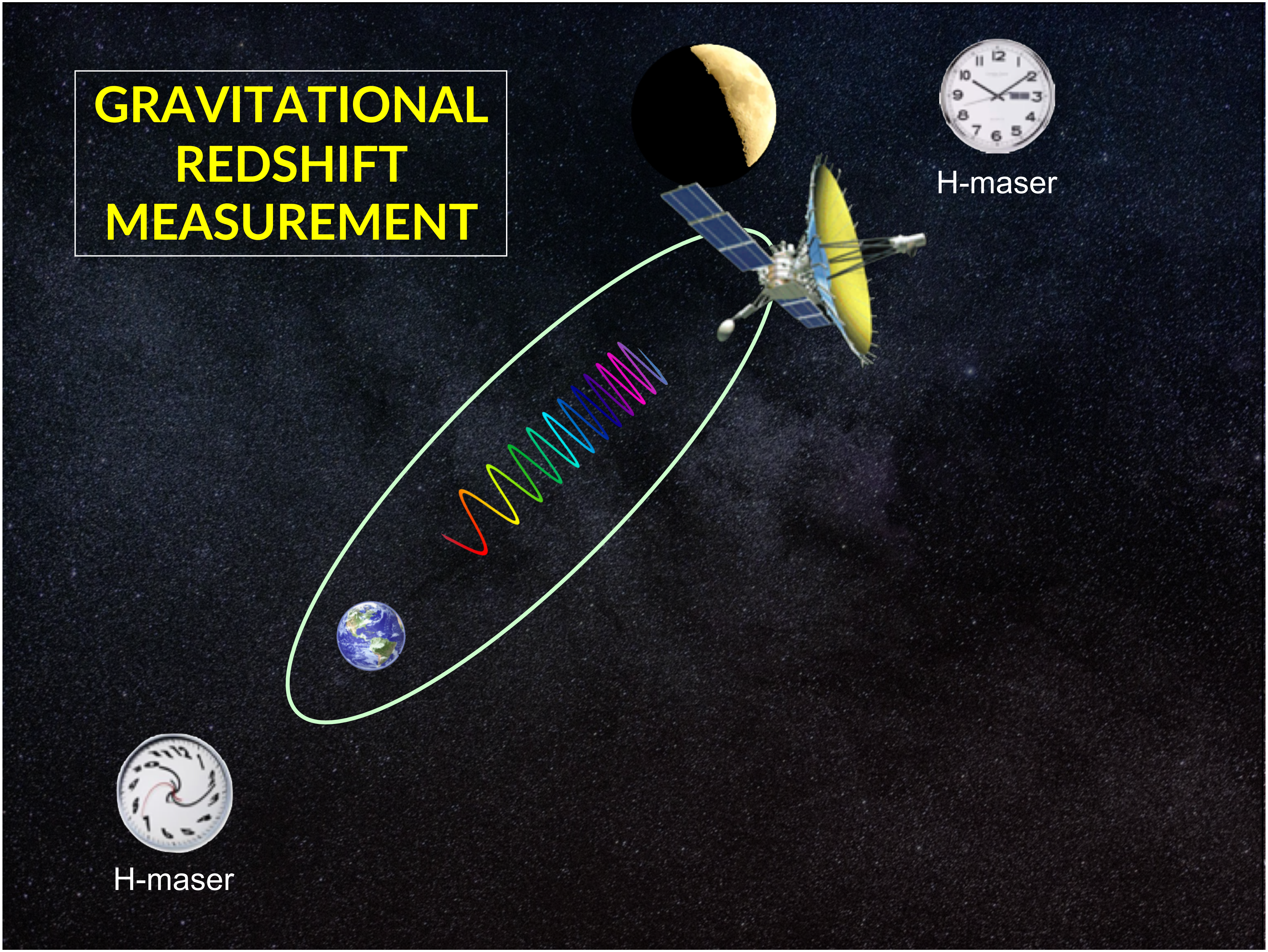
Credit: Astro Space Center

Credit: NRAO/AUI/NSF

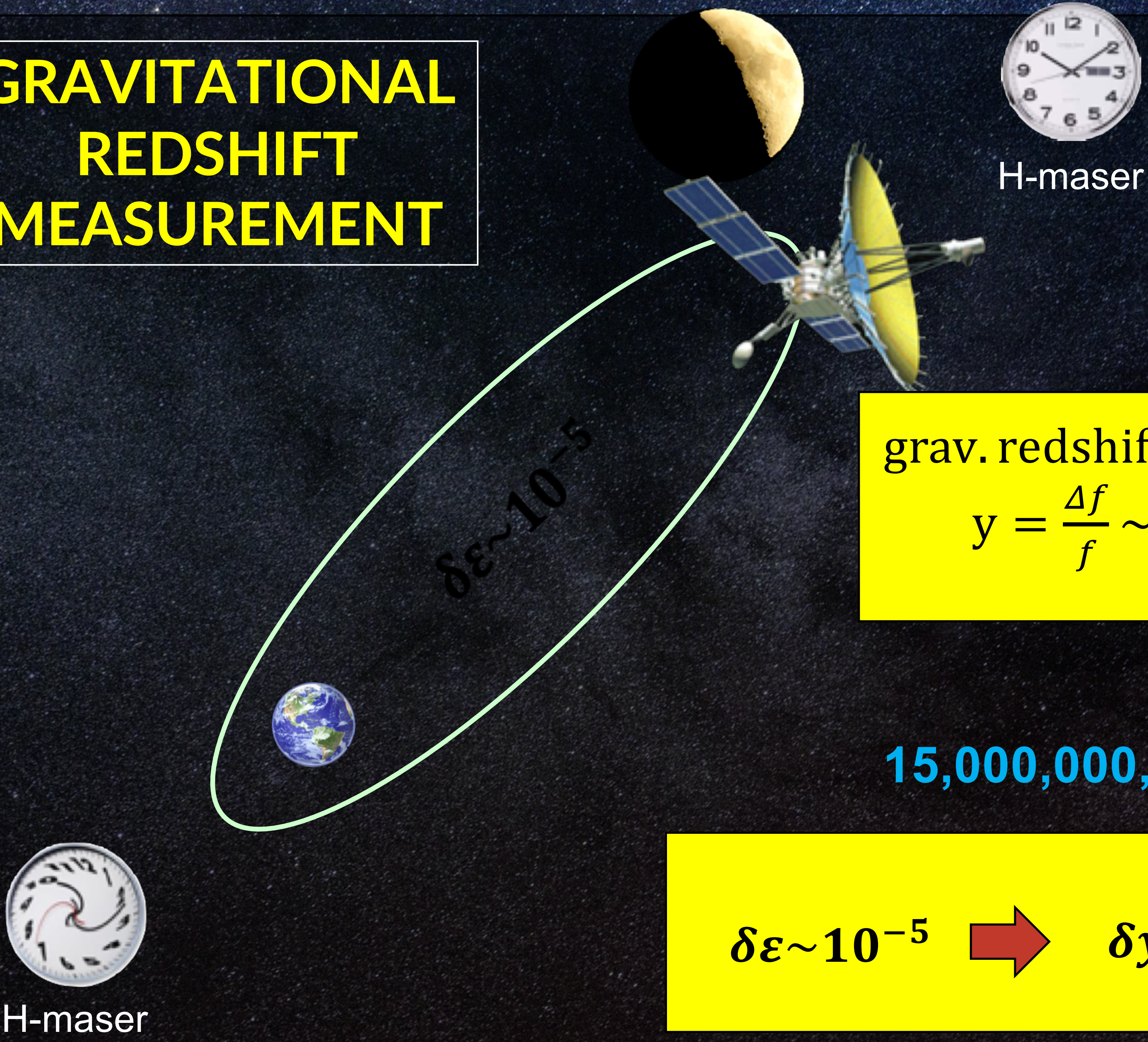
Pushchino, Russia

Green Bank, USA

GRAVITATIONAL REDSHIFT MEASUREMENT



GRAVITATIONAL REDSHIFT MEASUREMENT



grav. redshift variation

$$y = \frac{\Delta f}{f} \sim \mathbf{10^{-10}}$$

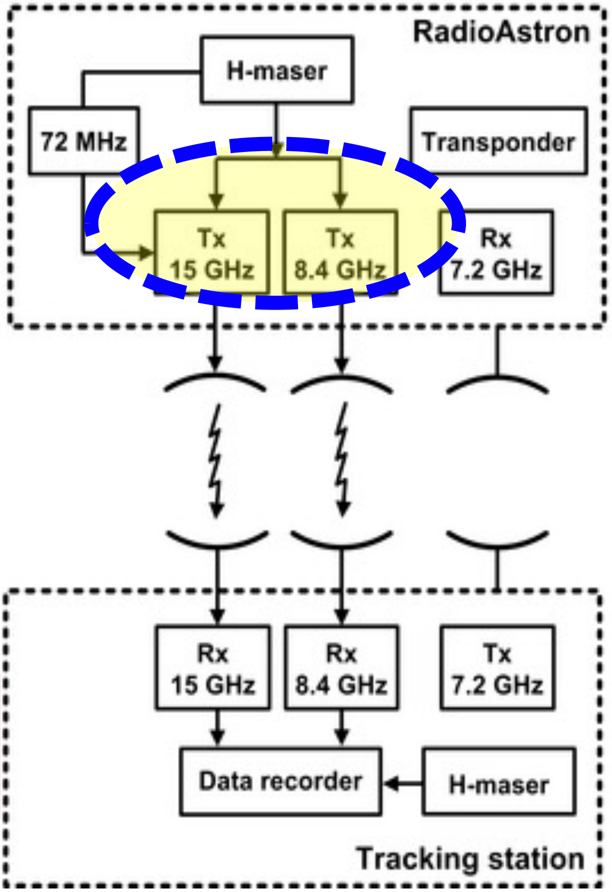
15,000,000,000 Hz

$$\boldsymbol{\delta\varepsilon \sim 10^{-5}} \Rightarrow \boldsymbol{\delta y \sim 10^{-15}}$$

2a. DYNAMICAL MODEL

RADIOASTRON COMMUNICATION MODE

1-way mode



Spacecraft

Ground station

Doppler tracking device

Downlink signals synchronized to onboard H-maser

1-WAY FREQUENCY SHIFT MODEL

$$y_{1w} = \boxed{-\frac{\dot{D}}{c}}$$

Non-Relativistic Doppler Shift

Gravitational
Redshift

$$+\boxed{\frac{\Delta U}{c^2}} - \boxed{\frac{\left|\vec{v}_e - \vec{v}_s\right|^2}{2c^2} + \frac{\vec{D} \cdot \vec{a}_s}{c^2}} + \boxed{\Delta h}$$

Second-Order Doppler Shift

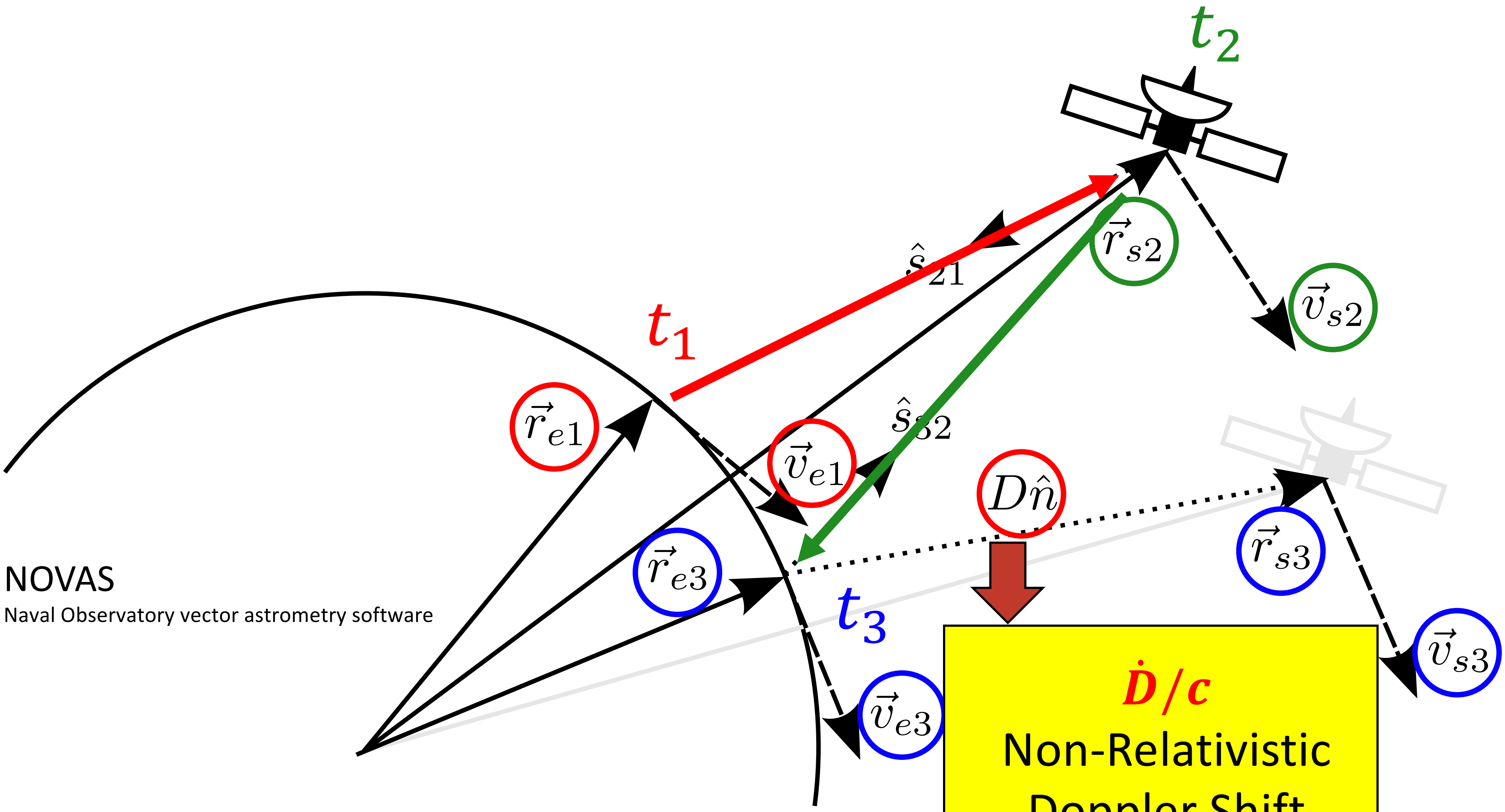
Frequency Bias

$$+\boxed{y_{trop}} + \boxed{y_{ion}} + \boxed{y_{pcm}}$$

Troposphere **Ionosphere** **Phase center motion (Antenna effect)**

$$+ O\left(\frac{v}{c}\right)^3$$ and other 3rd order effects

STATE VECTORS & DOPPLER SHIFT



NOVAS

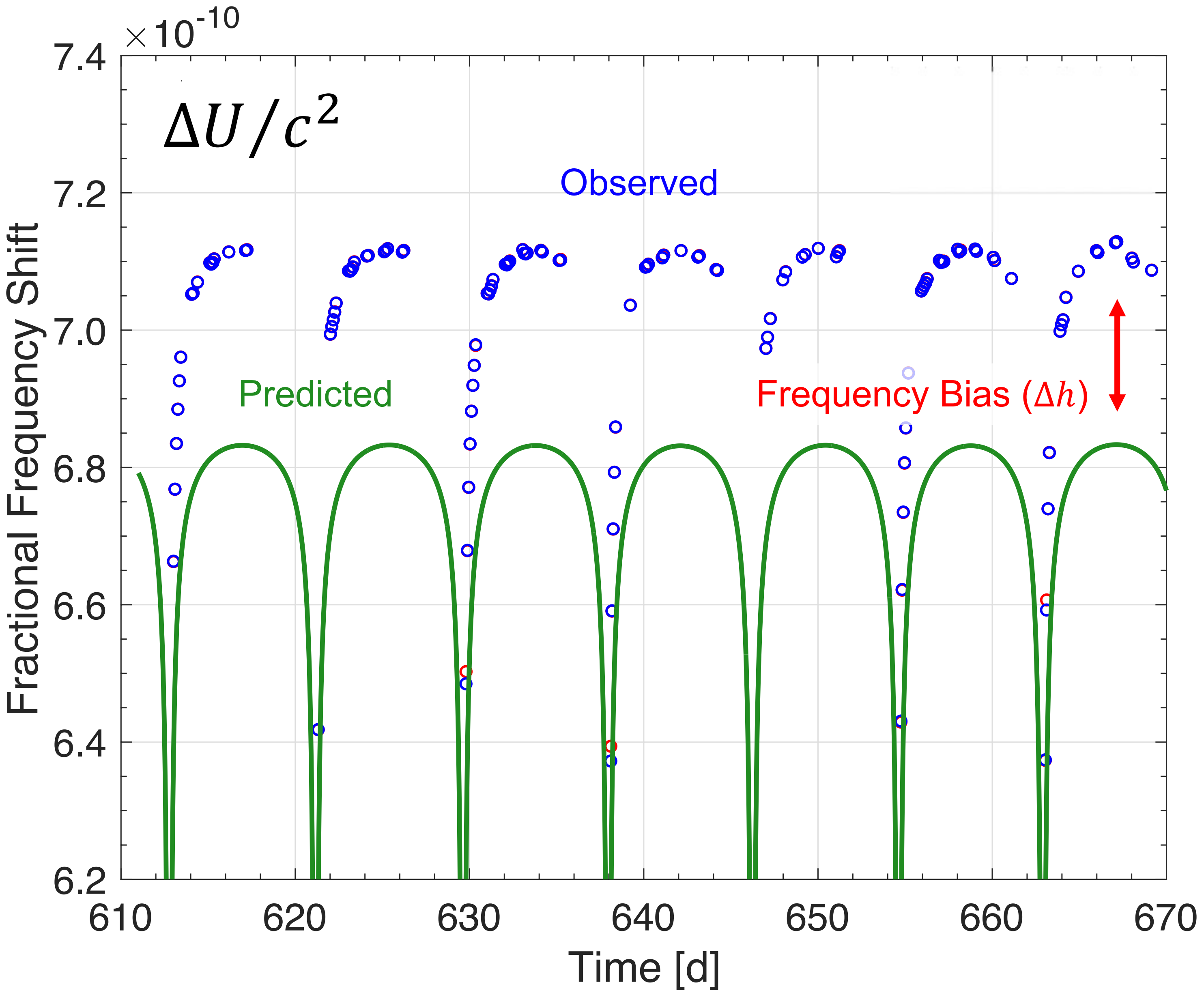
Naval Observatory vector astrometry software

$\dot{D}/c$

Non-Relativistic Doppler Shift

Model uses state vectors at t_3 (observation time)

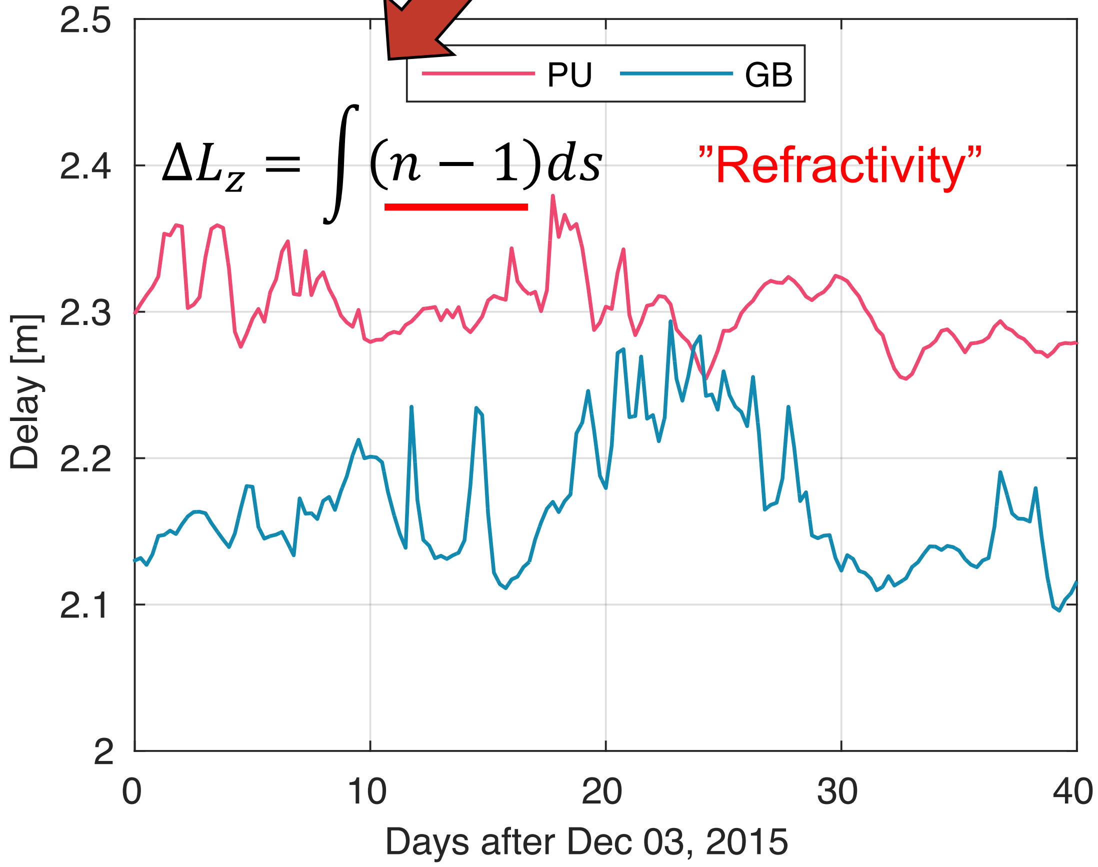
FREQUENCY BIAS, Δh



TROPOSPHERIC REFRACTION

$$\Delta L = \int_G ds$$

Geometric Path



$$\Delta L_z = \int \underline{(n-1)}ds$$

"Refractivity"

Varies with:

- Temperature / Pressure (∴ Latitude, Season)
- Weather (~10%)
- Elevation

$$\boxed{y_{trop} = -\frac{1}{c}\frac{d\Delta L}{dt}}$$

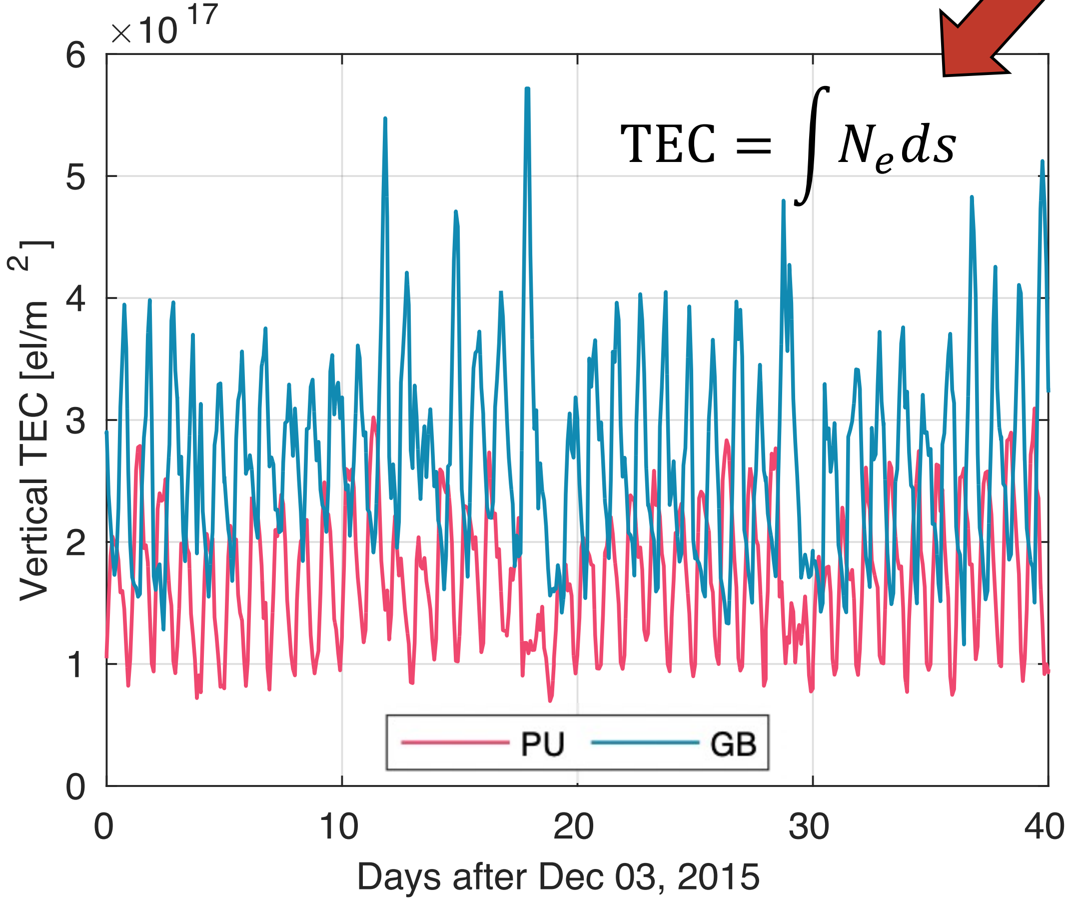
IONOSPHERIC REFRACTION

Ionospheric Delay

$$\Delta L = \int_P \overline{\left(1 - \frac{40.308}{\bigcirc\!\!\!\!f^2} \,\bigcirc\!\!\!\!\!N_e\right)} ds - \int_G ds$$

Refracted Path

Geometric Path

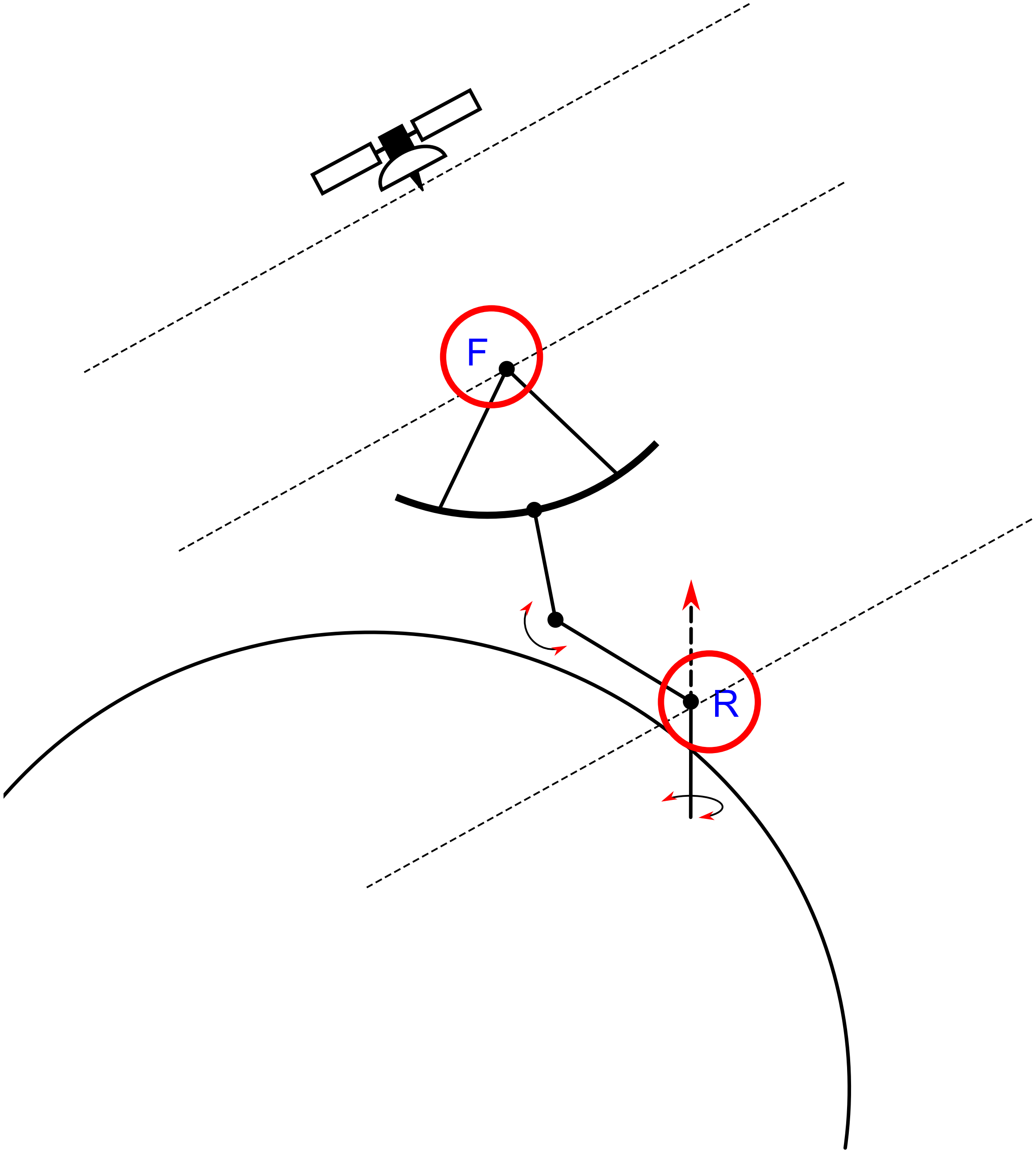


Varies with:

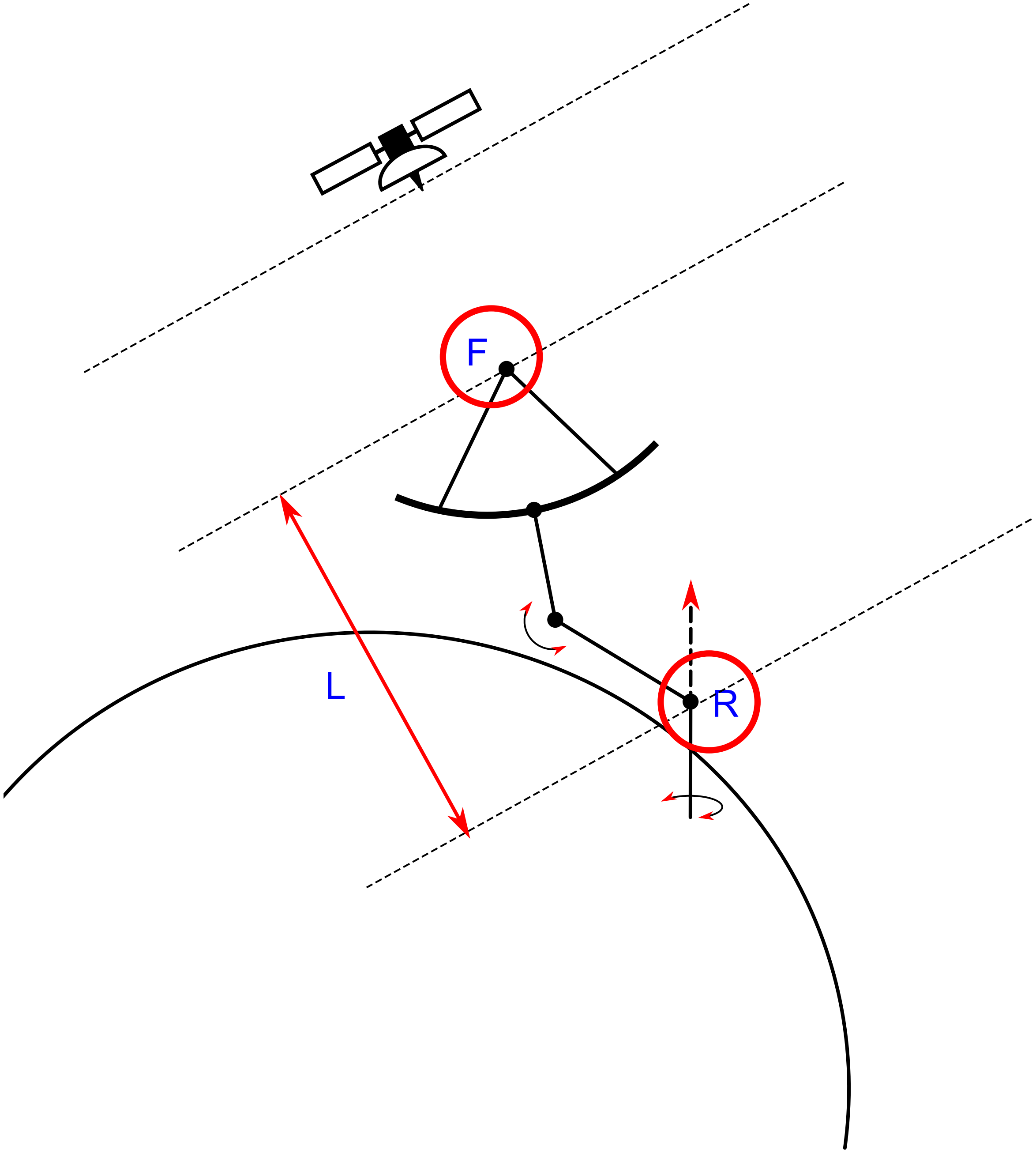
- Time-of-Day
- Solar Illumination Angle (∴ Latitude, Season)
- Elevation

$$\boxed{y_{ion} = -\frac{1}{c}\frac{d\Delta L}{dt}}$$

PHASE-CENTRE MOTION (PCM)

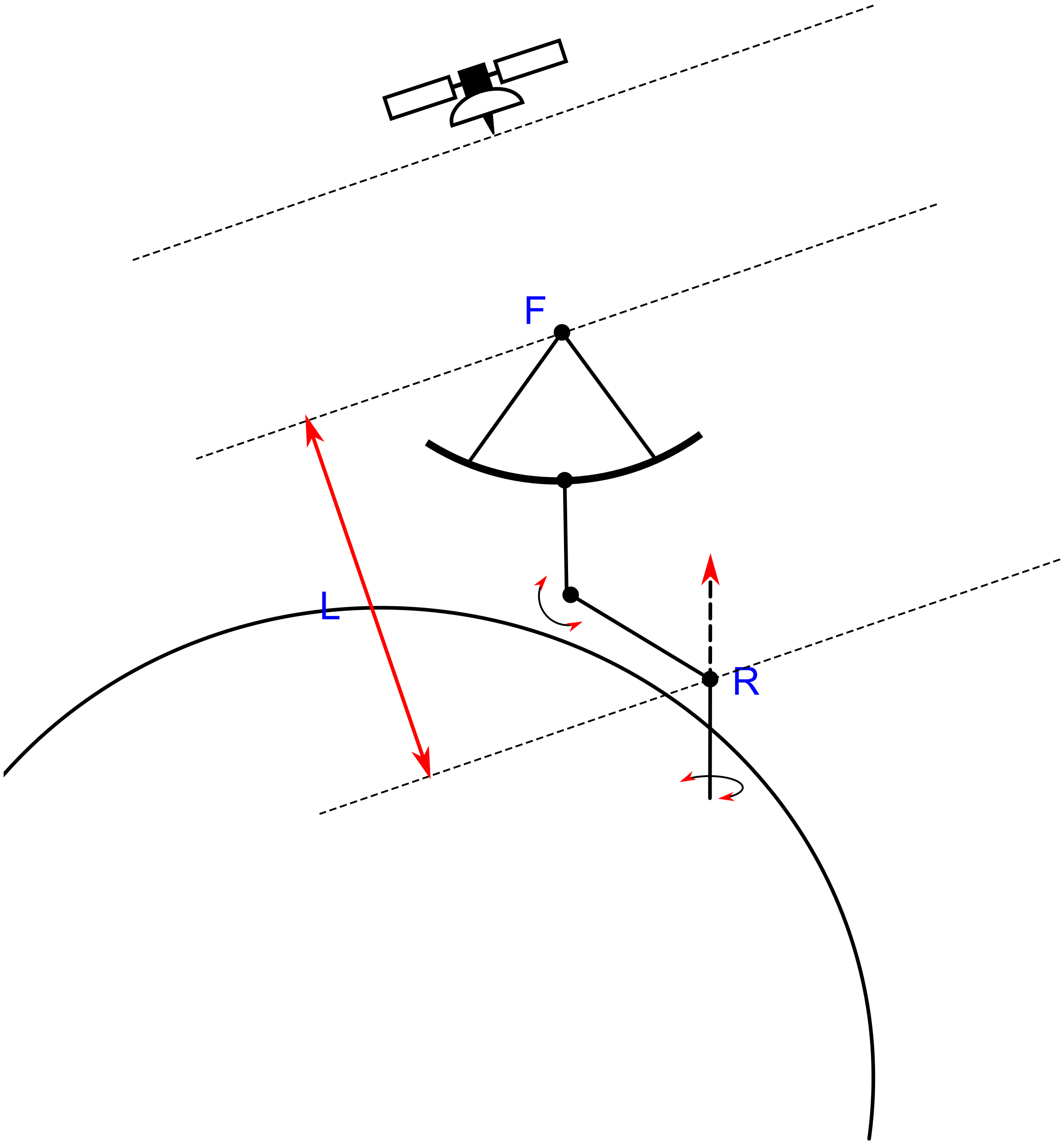


PHASE-CENTRE MOTION (PCM)



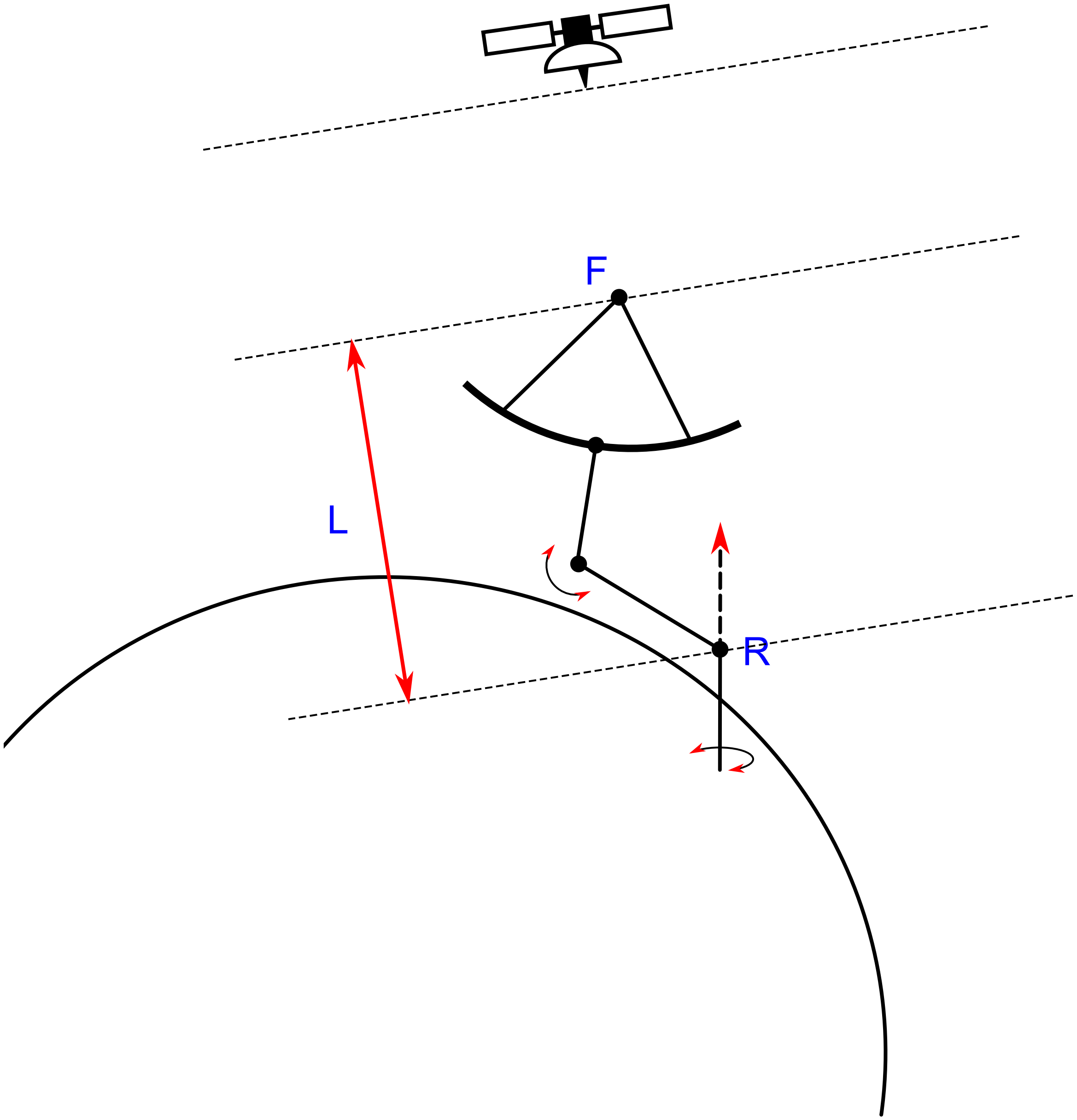
L = distance travelled by wavefront between **F** (focal point) and **R** (reference point)

PHASE-CENTRE MOTION (PCM)



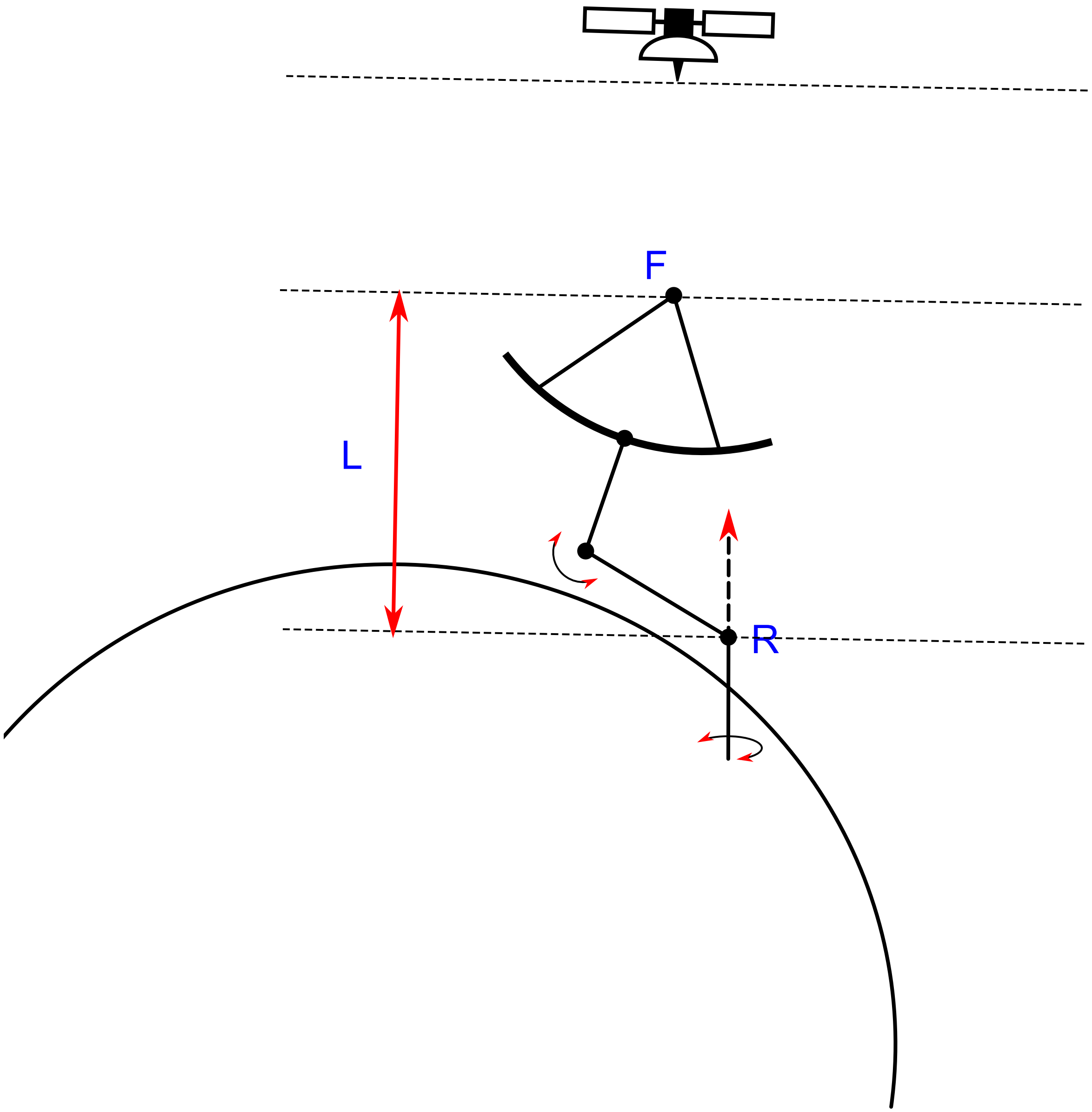
L = distance travelled by wavefront between **F** (focal point) and **R** (reference point)

PHASE-CENTRE MOTION (PCM)



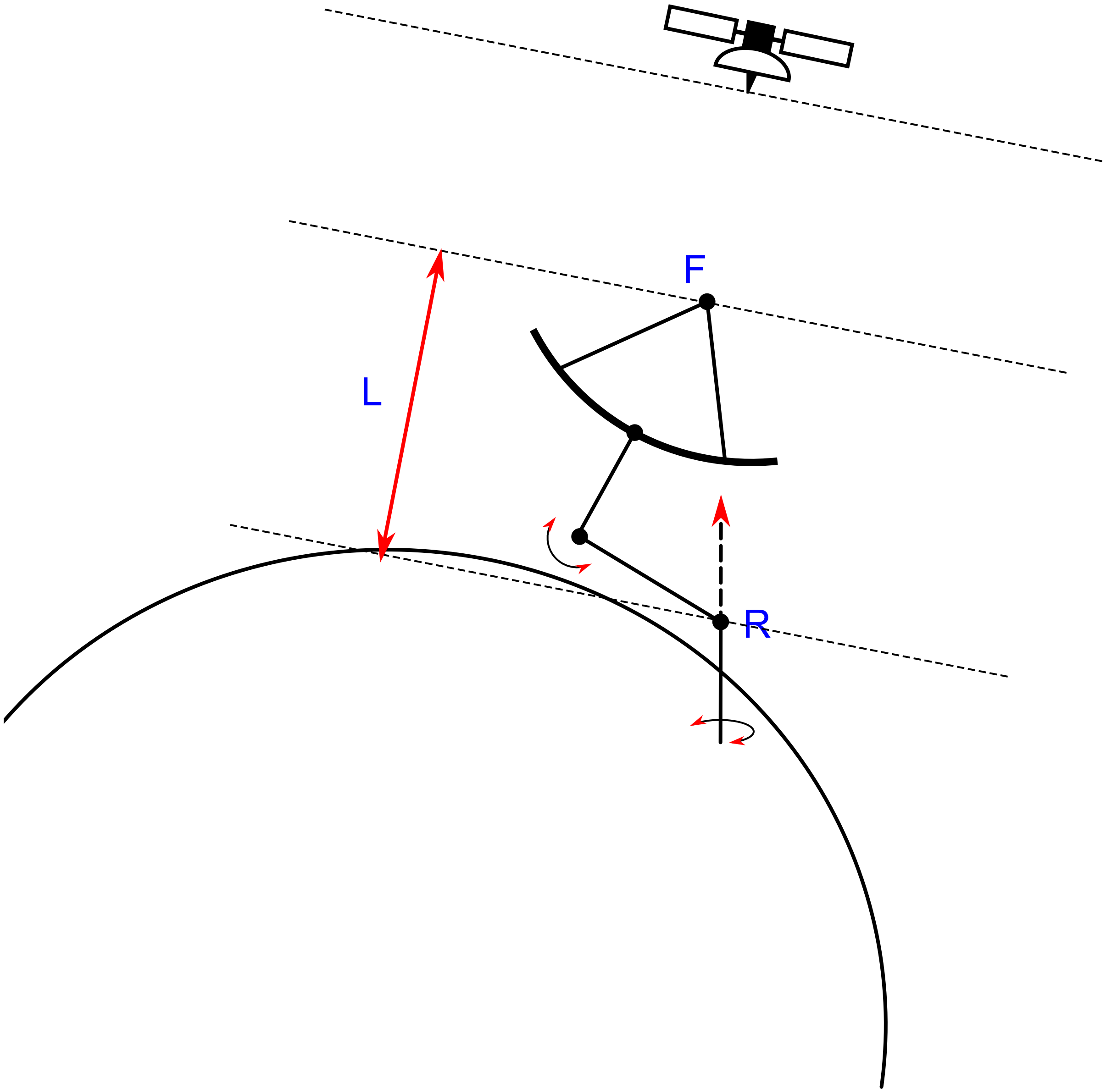
L = distance travelled by wavefront between **F** (focal point) and **R** (reference point)

PHASE-CENTRE MOTION (PCM)



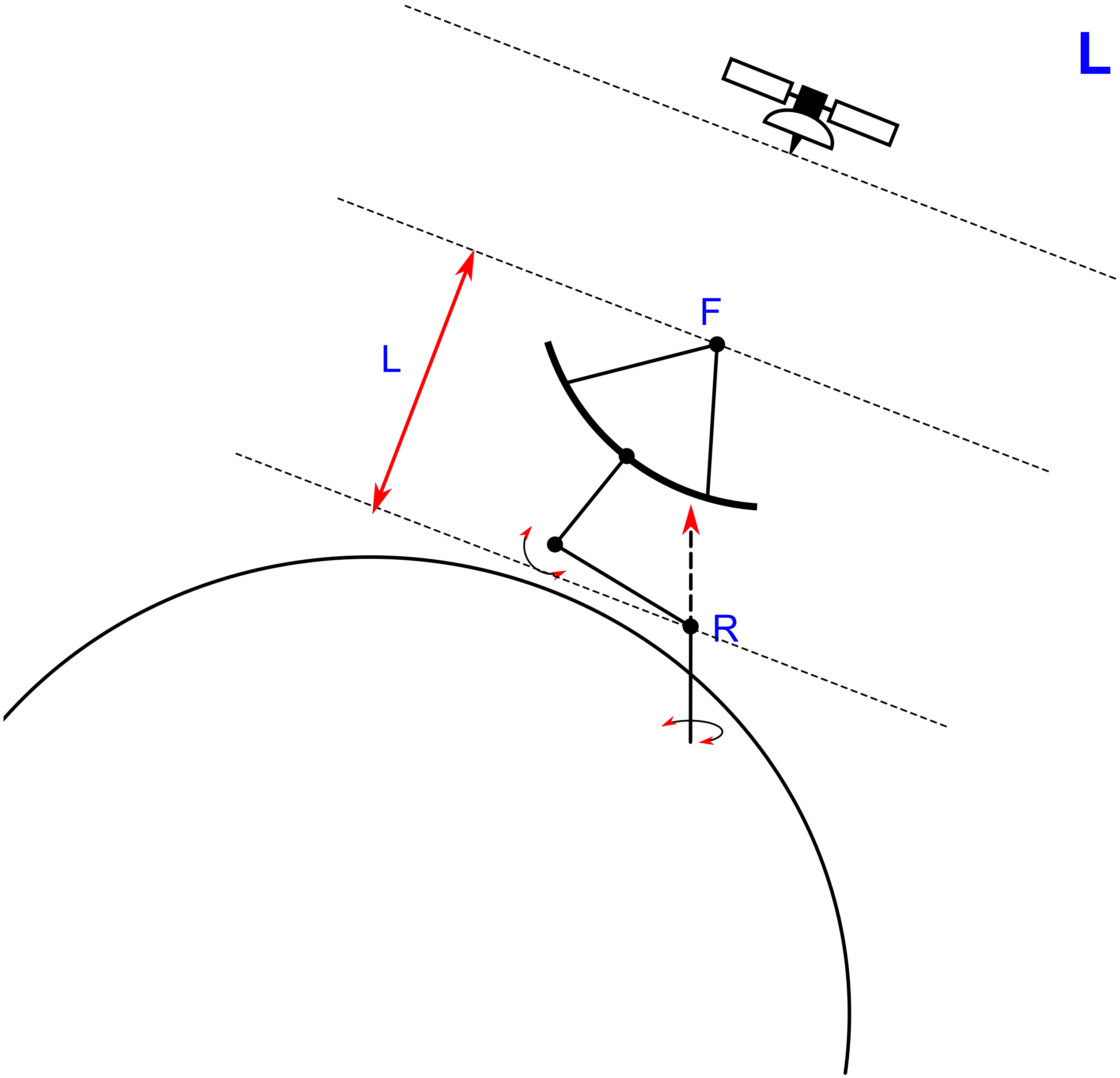
L = distance travelled by wavefront between **F** (focal point) and **R** (reference point)

PHASE-CENTRE MOTION (PCM)



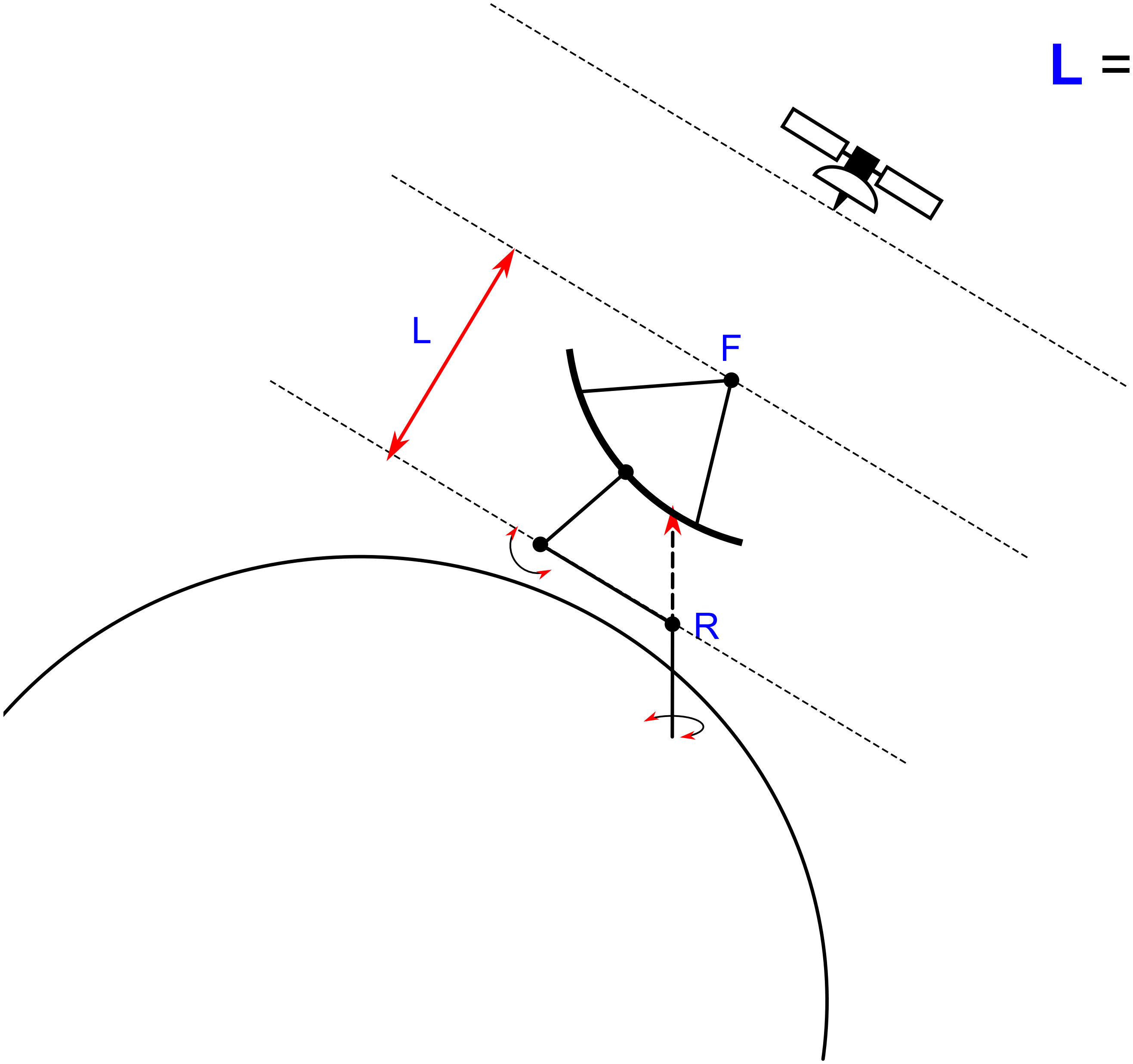
L = distance travelled by wavefront between **F** (focal point) and **R** (reference point)

PHASE-CENTRE MOTION (PCM)



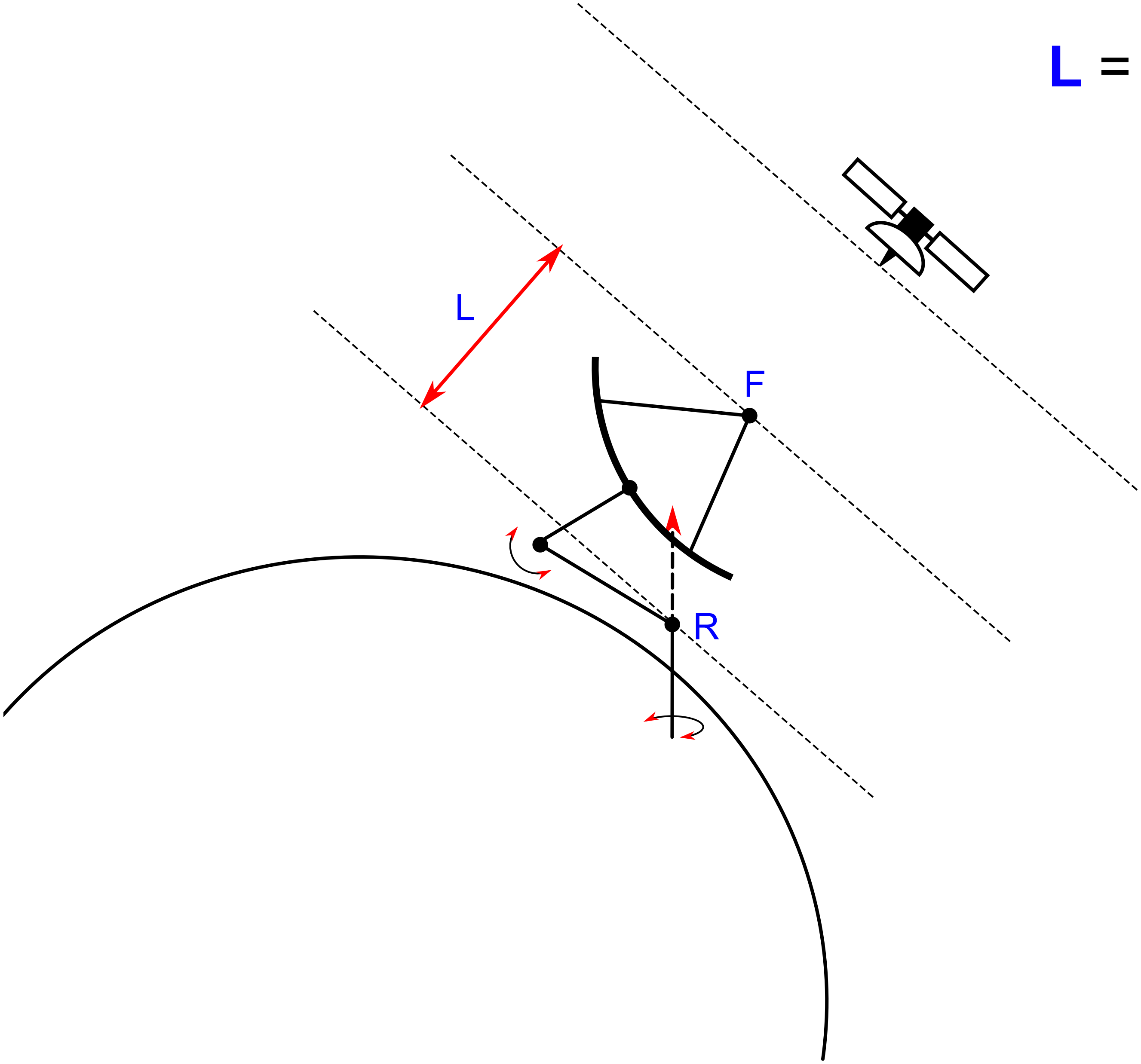
L = distance travelled by wavefront between **F** (focal point) and **R** (reference point)

PHASE-CENTRE MOTION (PCM)



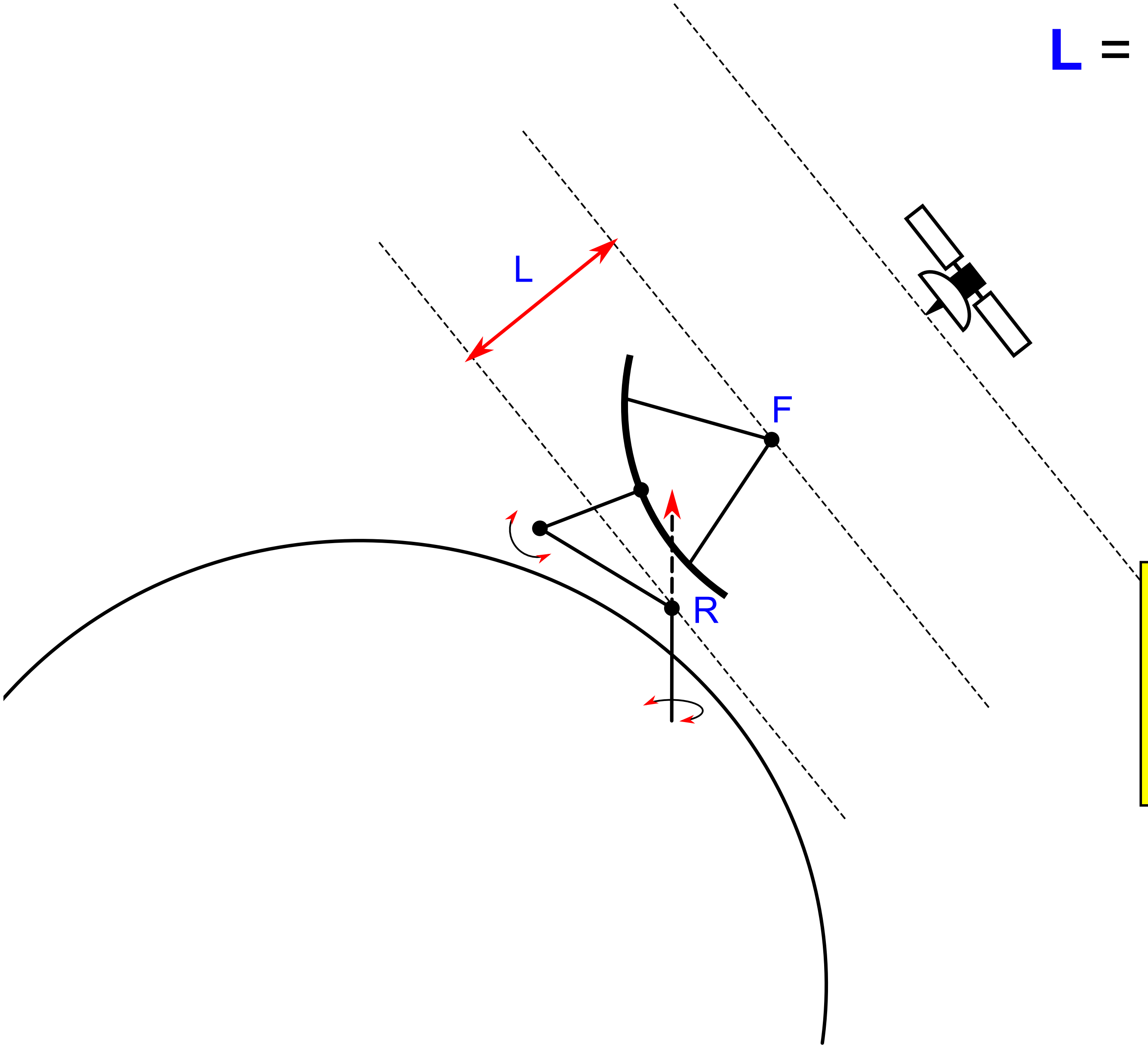
L = distance travelled by wavefront between **F** (focal point) and **R** (reference point)

PHASE-CENTRE MOTION (PCM)



L = distance travelled by wavefront between **F** (focal point) and **R** (reference point)

PHASE-CENTRE MOTION (PCM)

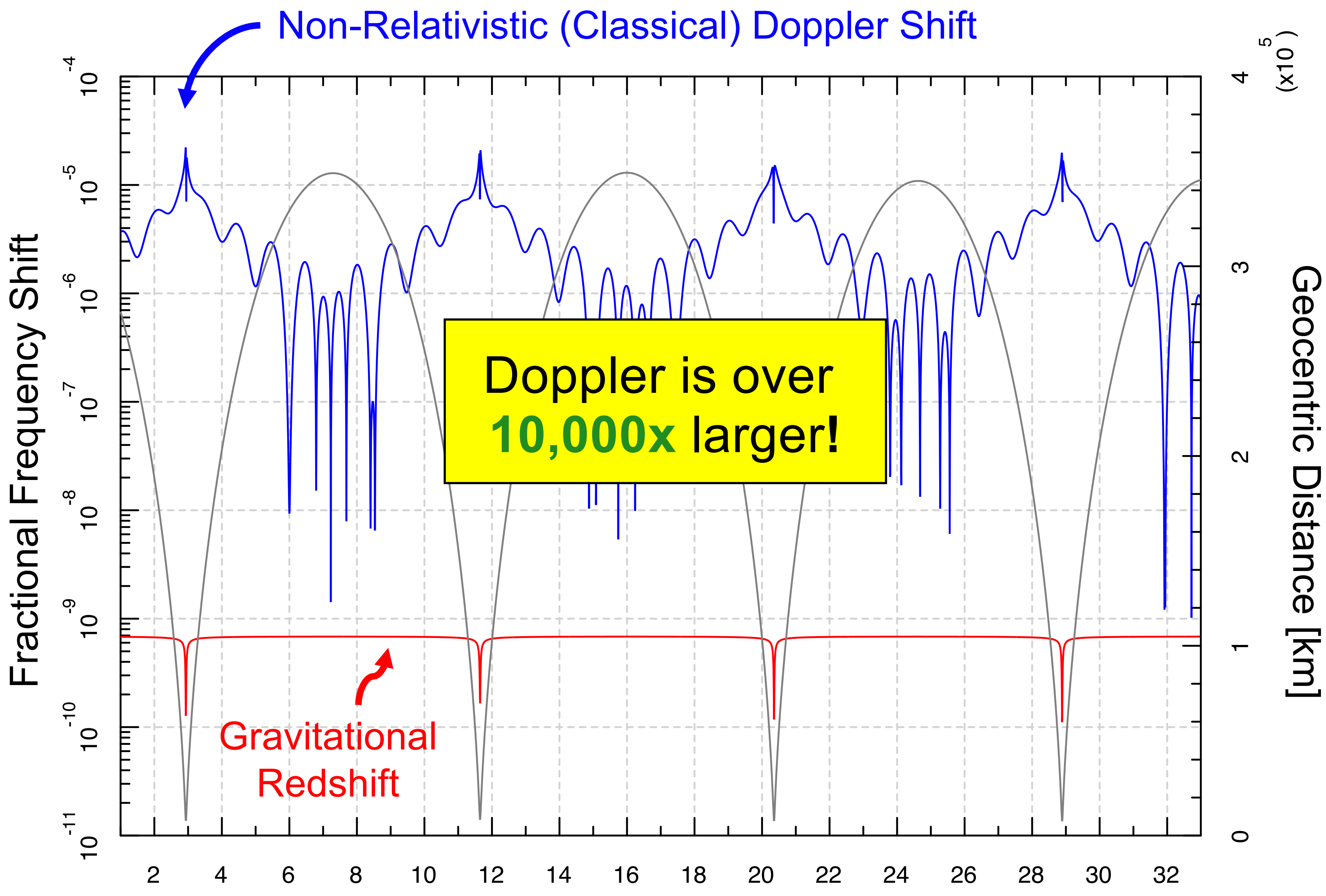


L = distance travelled by wavefront between **F** (focal point) and **R** (reference point)

$$y_{pcm} = -\frac{1}{c}\frac{dL}{dt}$$

Litvinov et al. 2021

DOWNLINK FREQUENCY SHIFT



Doppler is over **10,000x** larger!

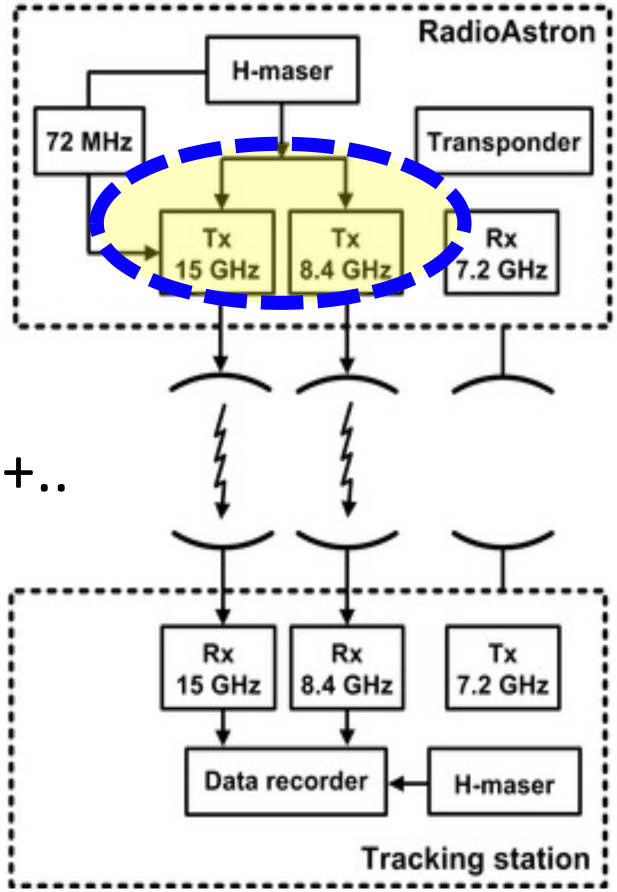
January 2014

$\Delta\epsilon = \pm 0.030_{syst}$ Nunes et al. 2020

2b. Doppler compensation

RADIOASTRON COMMUNICATION MODES

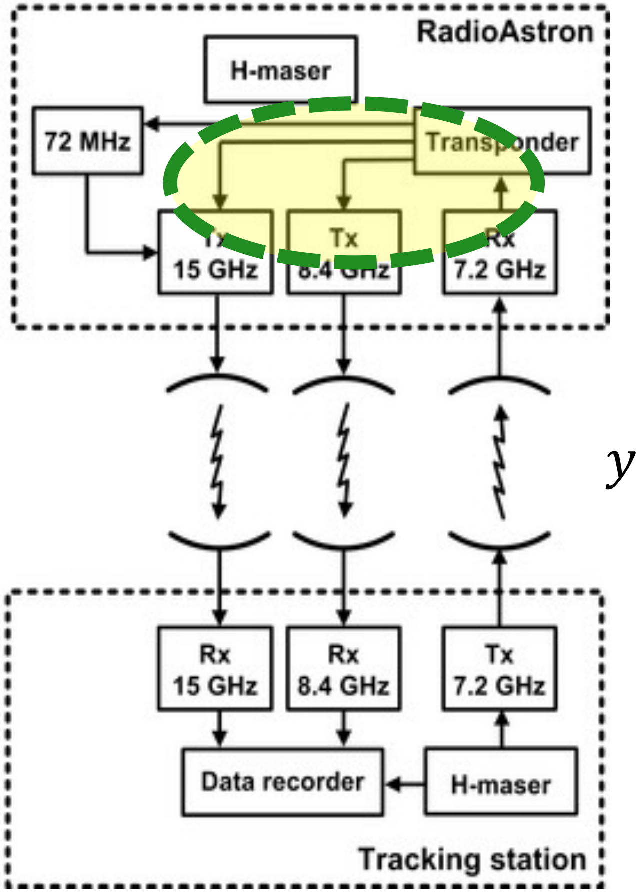
1-way mode



$$y_{1w} = -\frac{\dot{D}}{c} + \frac{\Delta U}{c^2} + ..$$

Downlink signals synchronized to onboard H-maser

2-way mode



$$y_{2w} = -2\frac{\dot{D}}{c} + ..$$

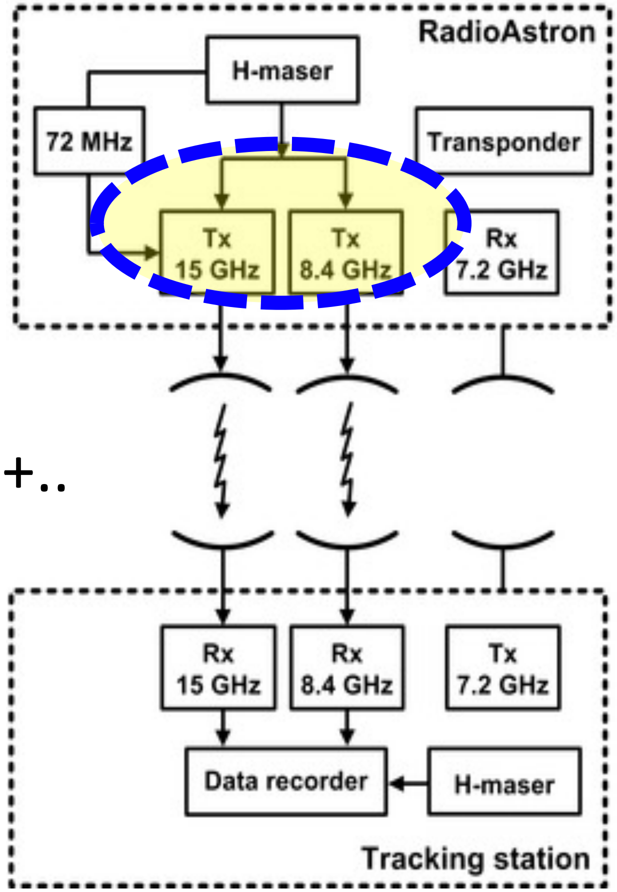
Biriukov et al., 2014

Downlink signals phase-coherently generated by uplink signal

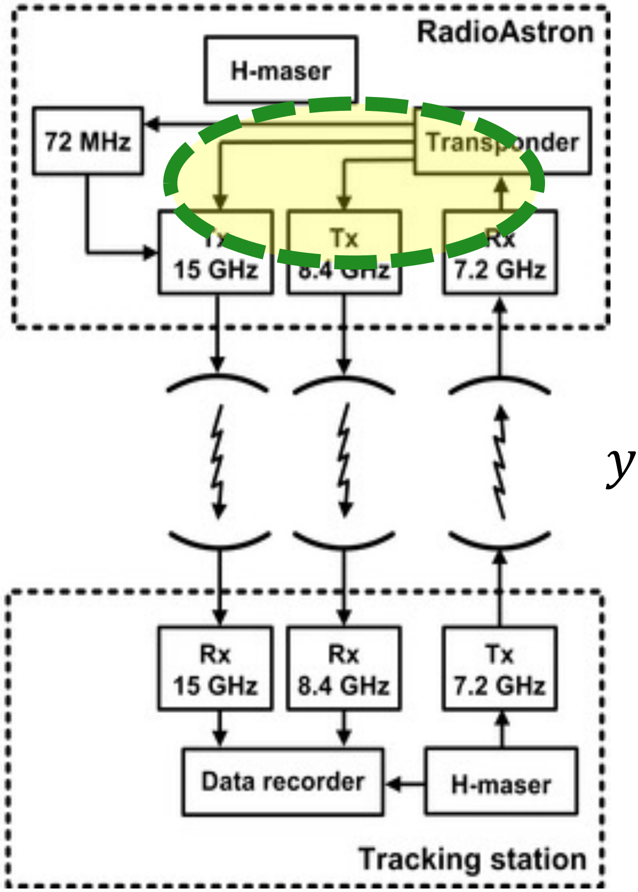
RADIOASTRON COMMUNICATION MODES

$$y_{1w} = -\frac{\dot{D}}{c} + \frac{\Delta U}{c^2} + ..$$

1-way mode



2-way mode



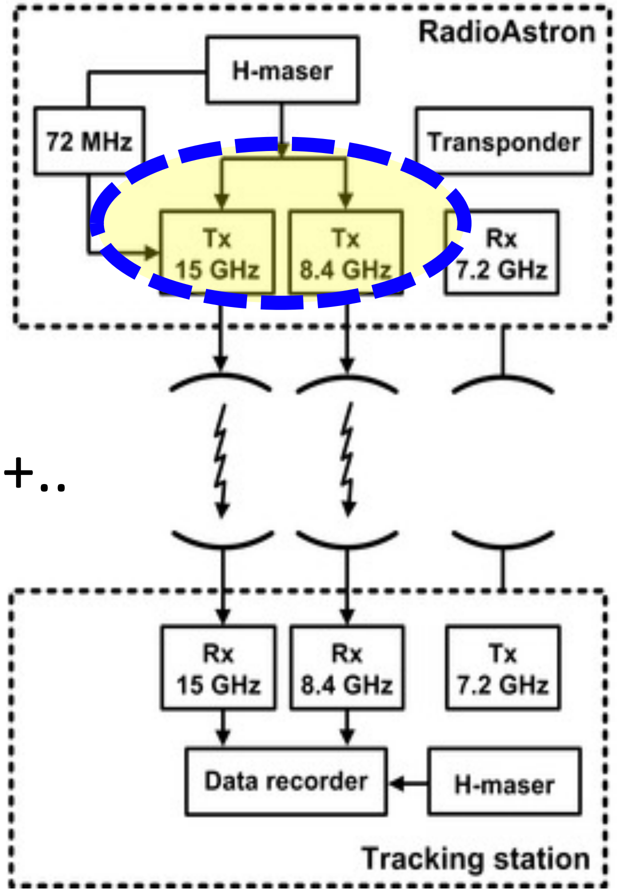
$$y_{2w} = -2\frac{\dot{D}}{c} + ..$$

Biriukov et al., 2014

$$y_{1w} - \frac{1}{2} y_{2w} = -\frac{\dot{D}}{c} + \frac{\dot{D}}{c} + \frac{\Delta U}{c^2} + ..$$

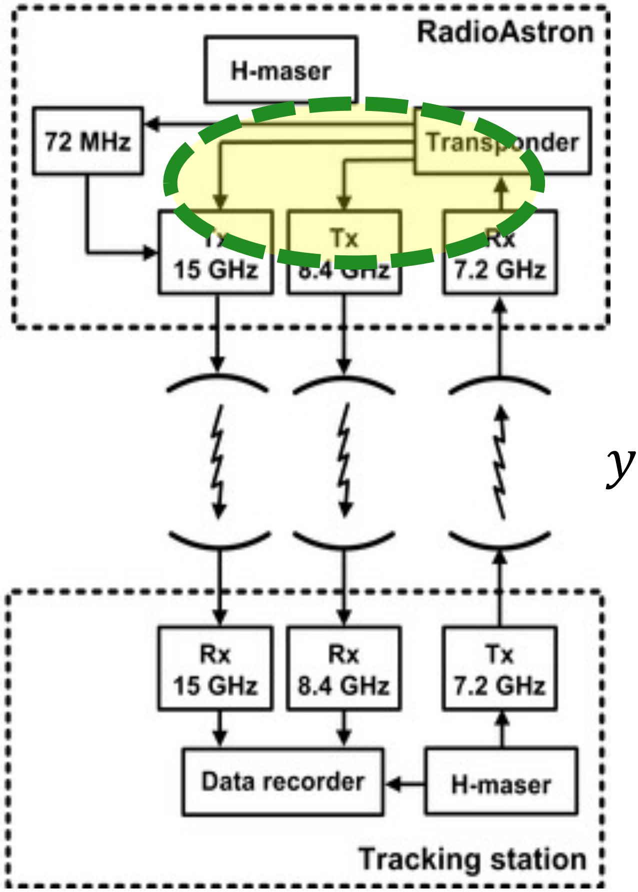
RADIOASTRON COMMUNICATION MODES

1-way mode



$$y_{1w} = -\frac{\dot{D}}{c} + \frac{\Delta U}{c^2} + ..$$

2-way mode

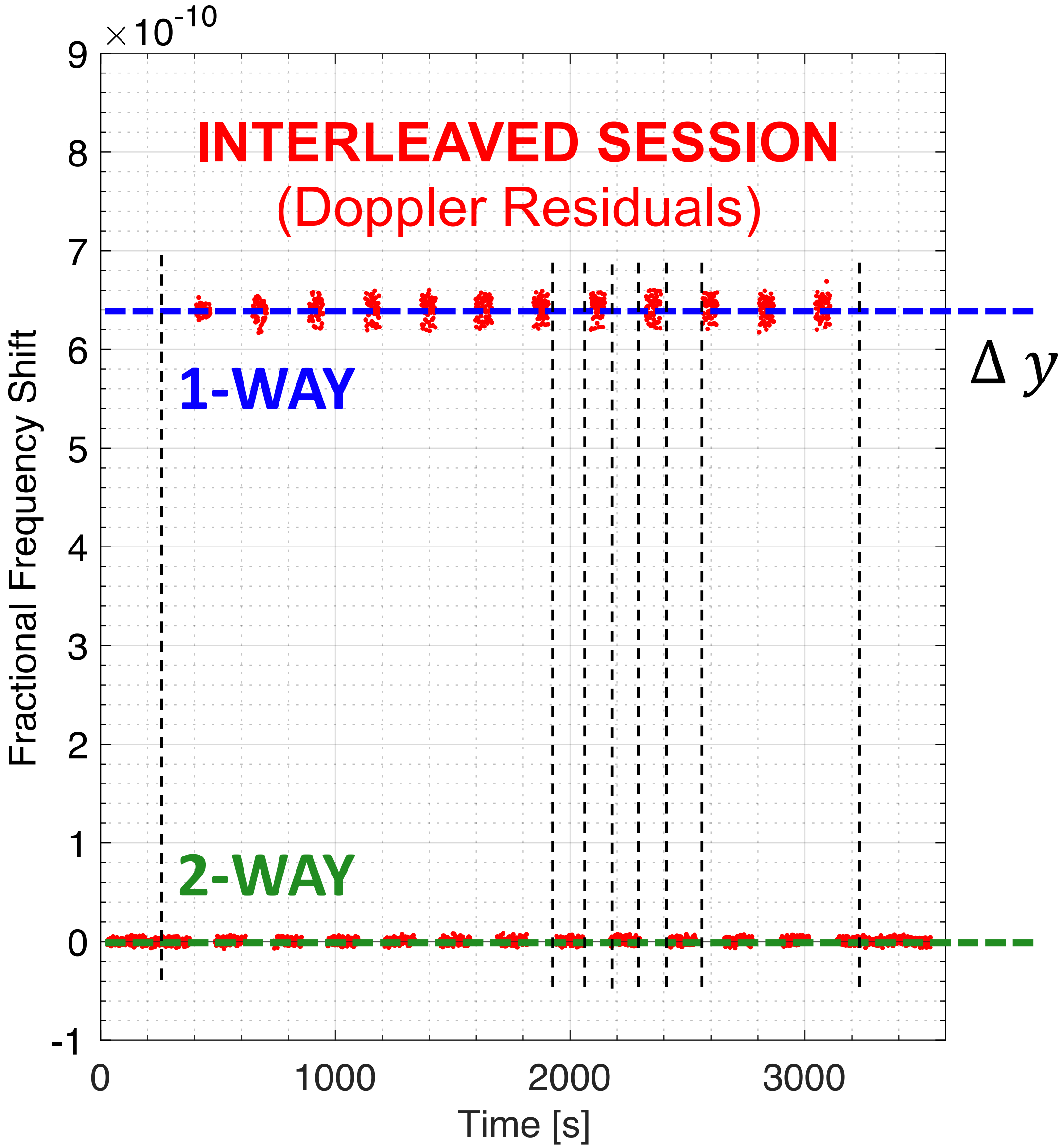


$$y_{2w} = -2\frac{\dot{D}}{c} + ..$$

Biriukov et al., 2014

$$\boxed{y_{1w} - \frac{1}{2} y_{2w} = \cancel{-\frac{\dot{D}}{c} + \frac{\dot{D}}{c}} + \frac{\Delta U}{c^2} + ..}$$

DOPPLER COMPENSATION SCHEME



$$\Delta y = y_{1w} - \frac{1}{2} y_{2w}$$

$$= \frac{\Delta U}{c^2}$$

Gravitational Redshift is **LEADING** effect!

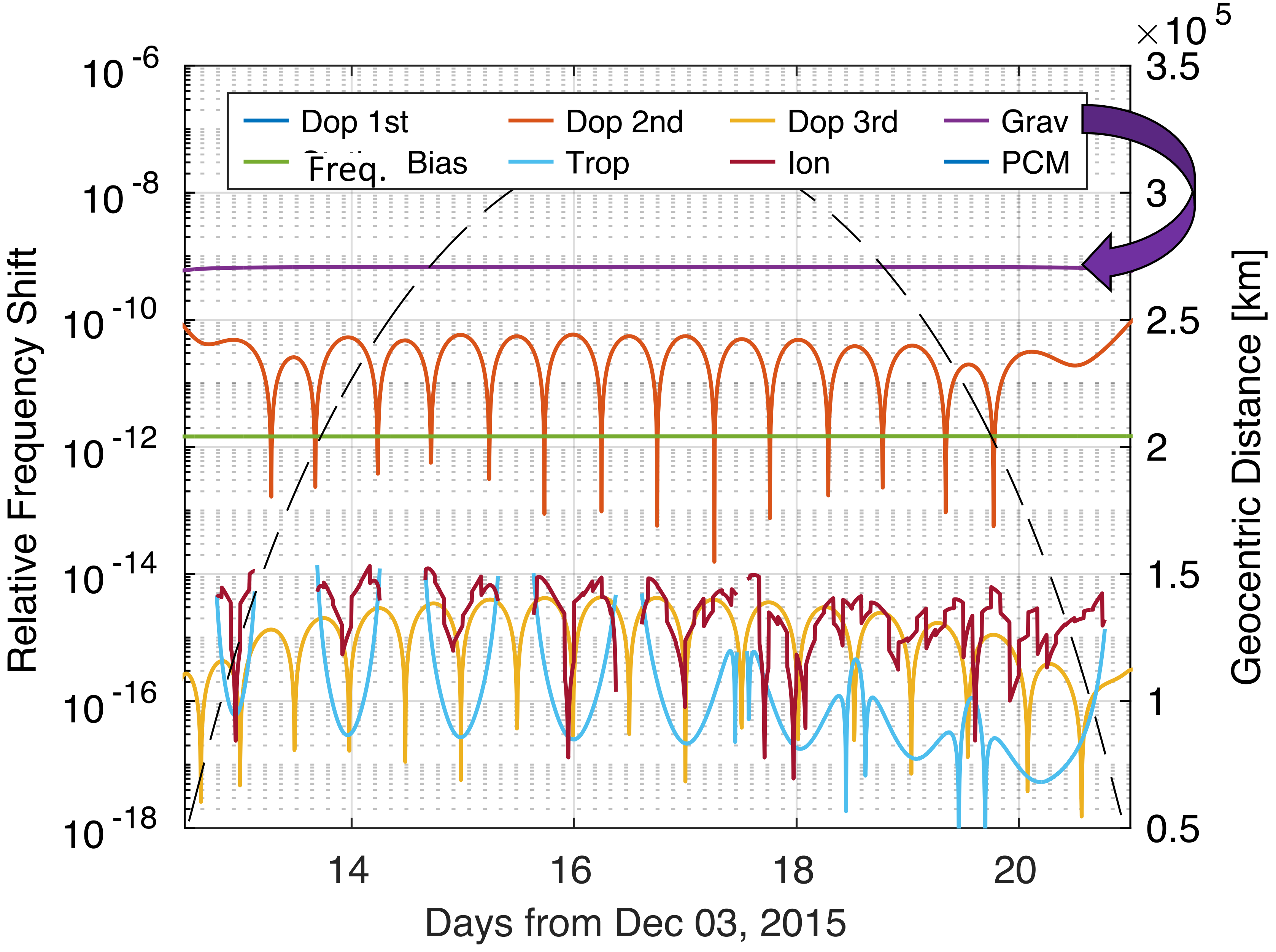
$$+\Delta y_{dop} + \Delta y_{pcm} + \Delta y_{atm}$$

$$+\Delta h$$

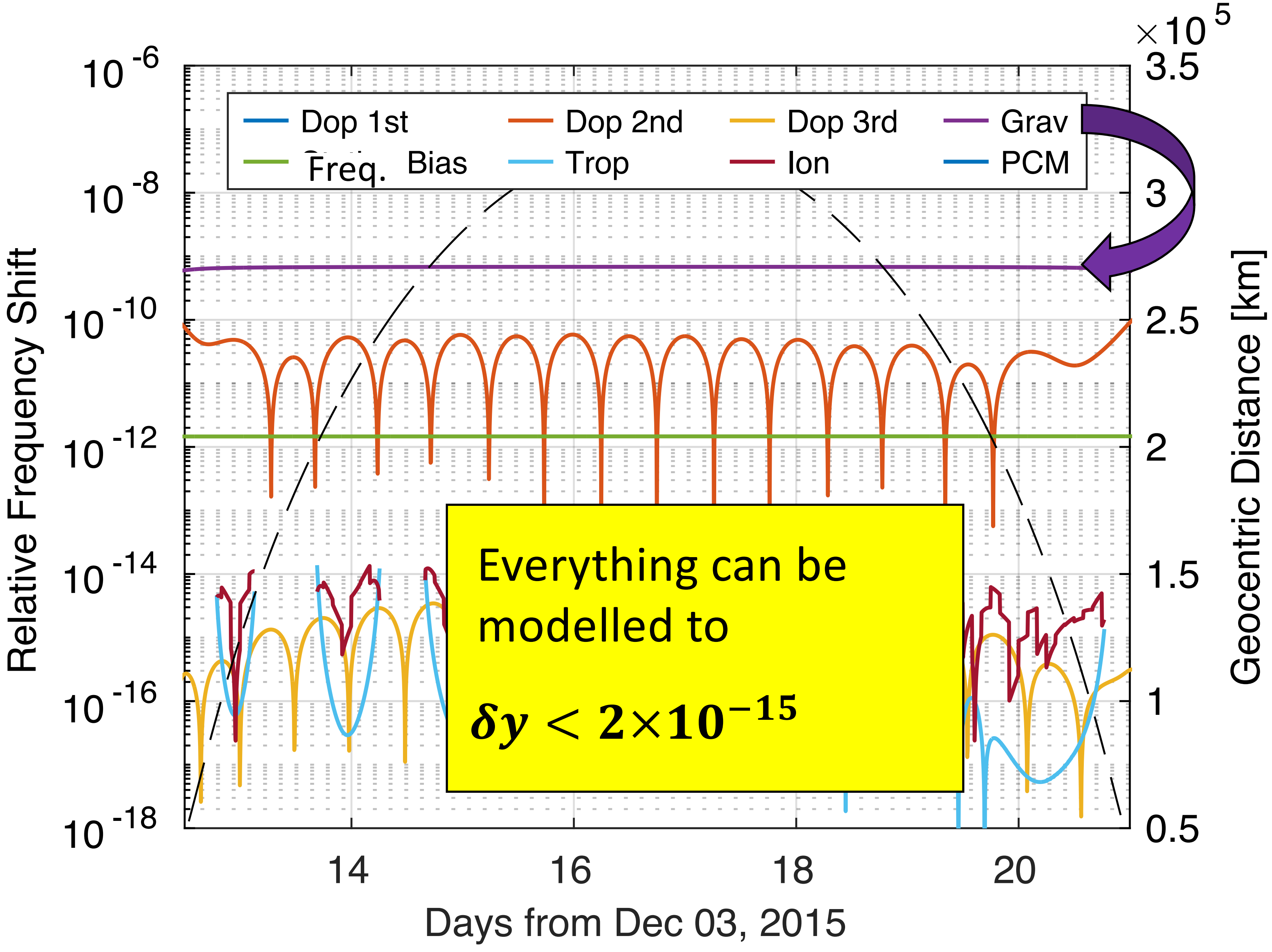
Other effects reduced

Most significant remaining systematic is Frequency Bias

DOPPLER COMPENSATED SHIFT MODEL



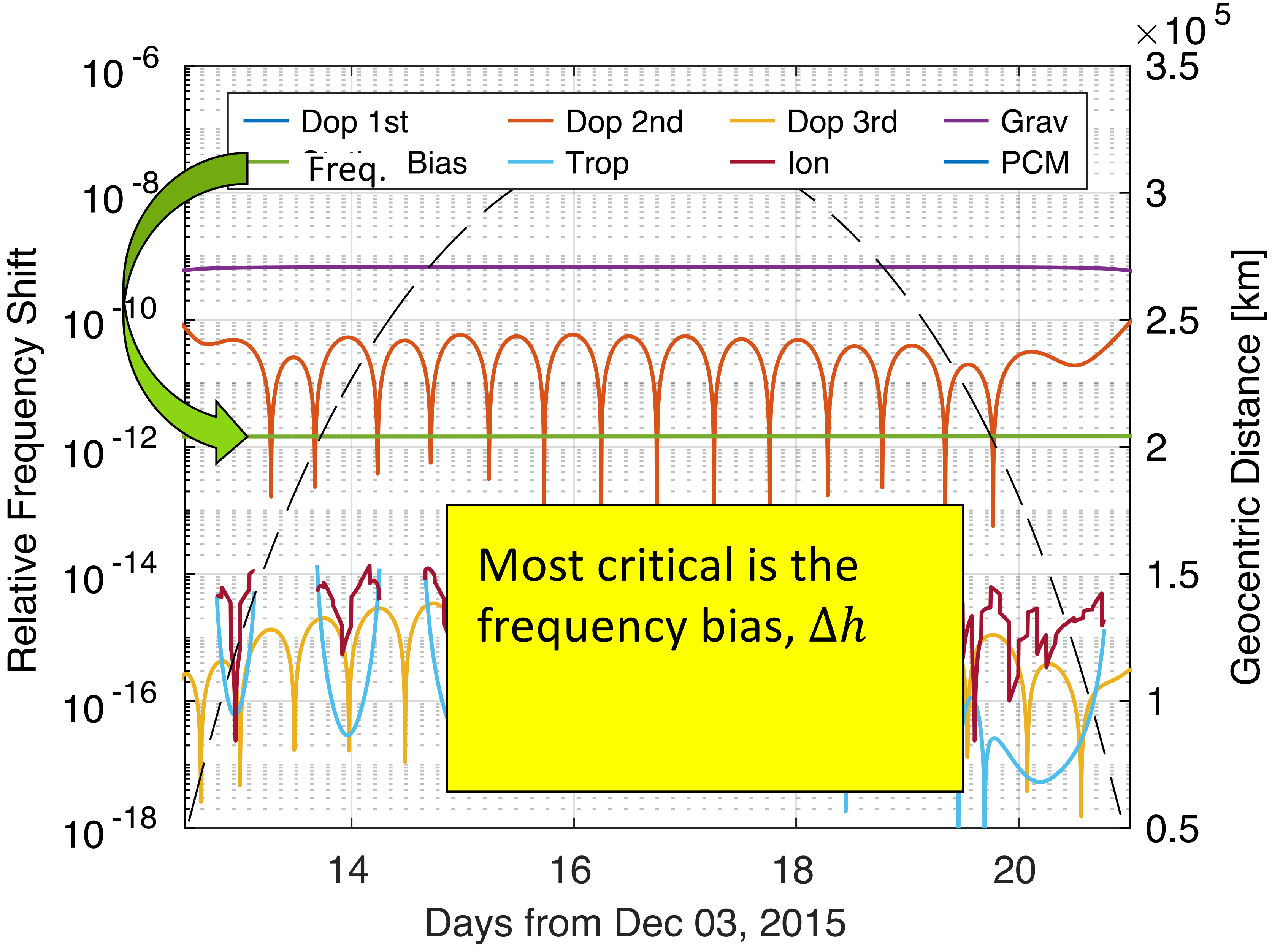
DOPPLER COMPENSATED SHIFT MODEL



Everything can be modelled to

$\delta y < 2\times10^{-15}$

DOPPLER COMPENSATED SHIFT MODEL

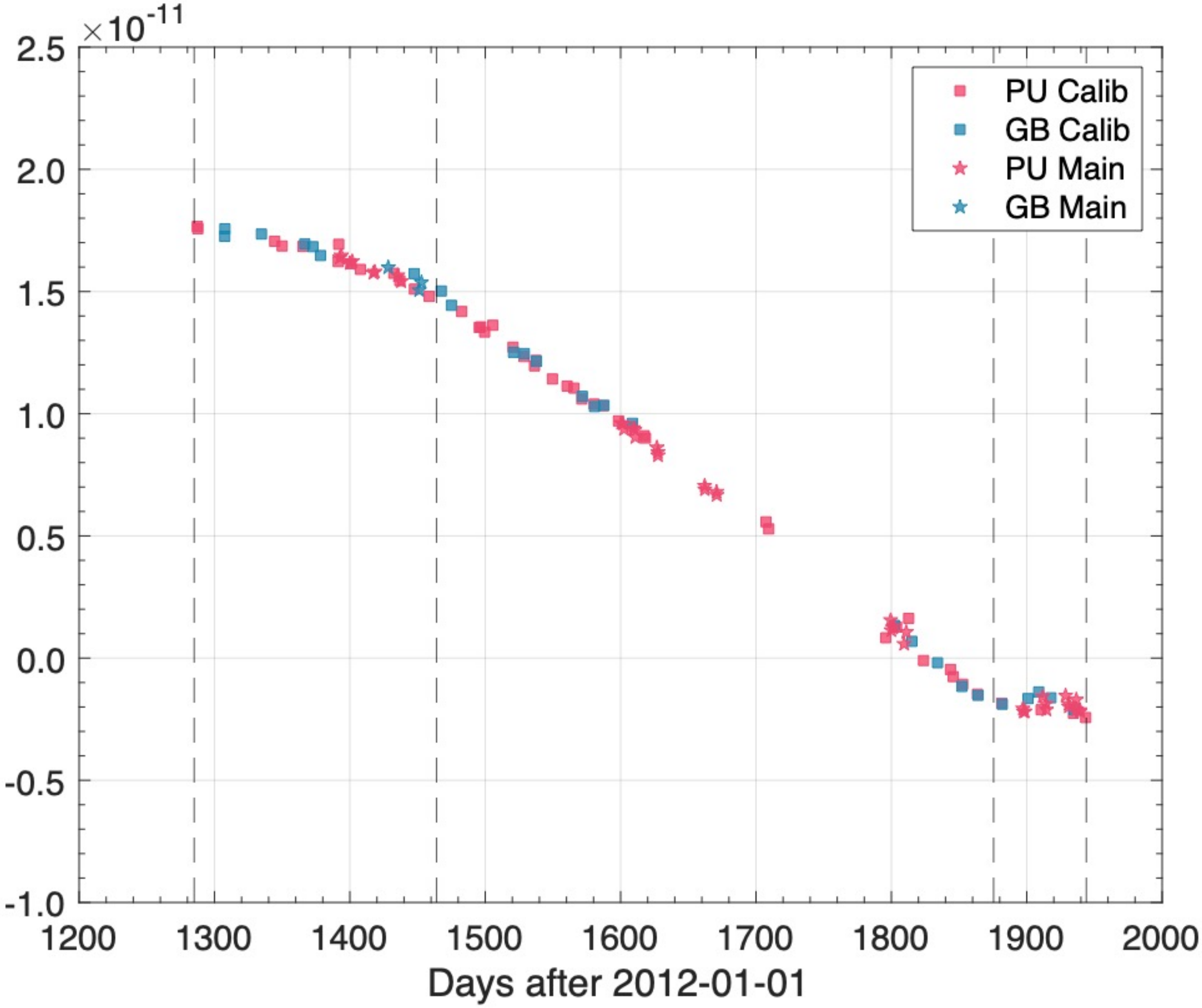


Most critical is the frequency bias, Δh

Frequency bias as a function of time

3 Intervals

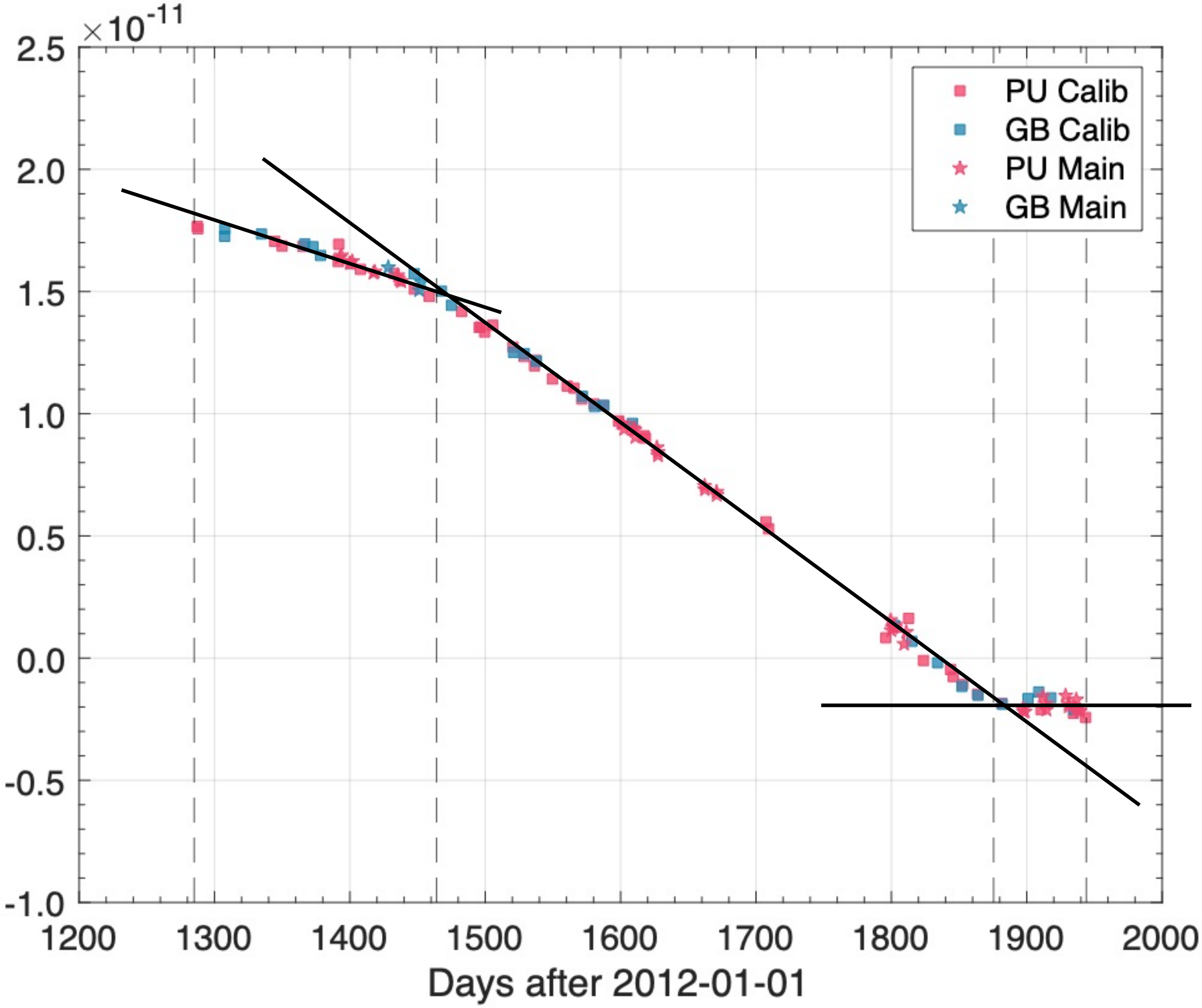
Δh



Frequency bias as a function of time

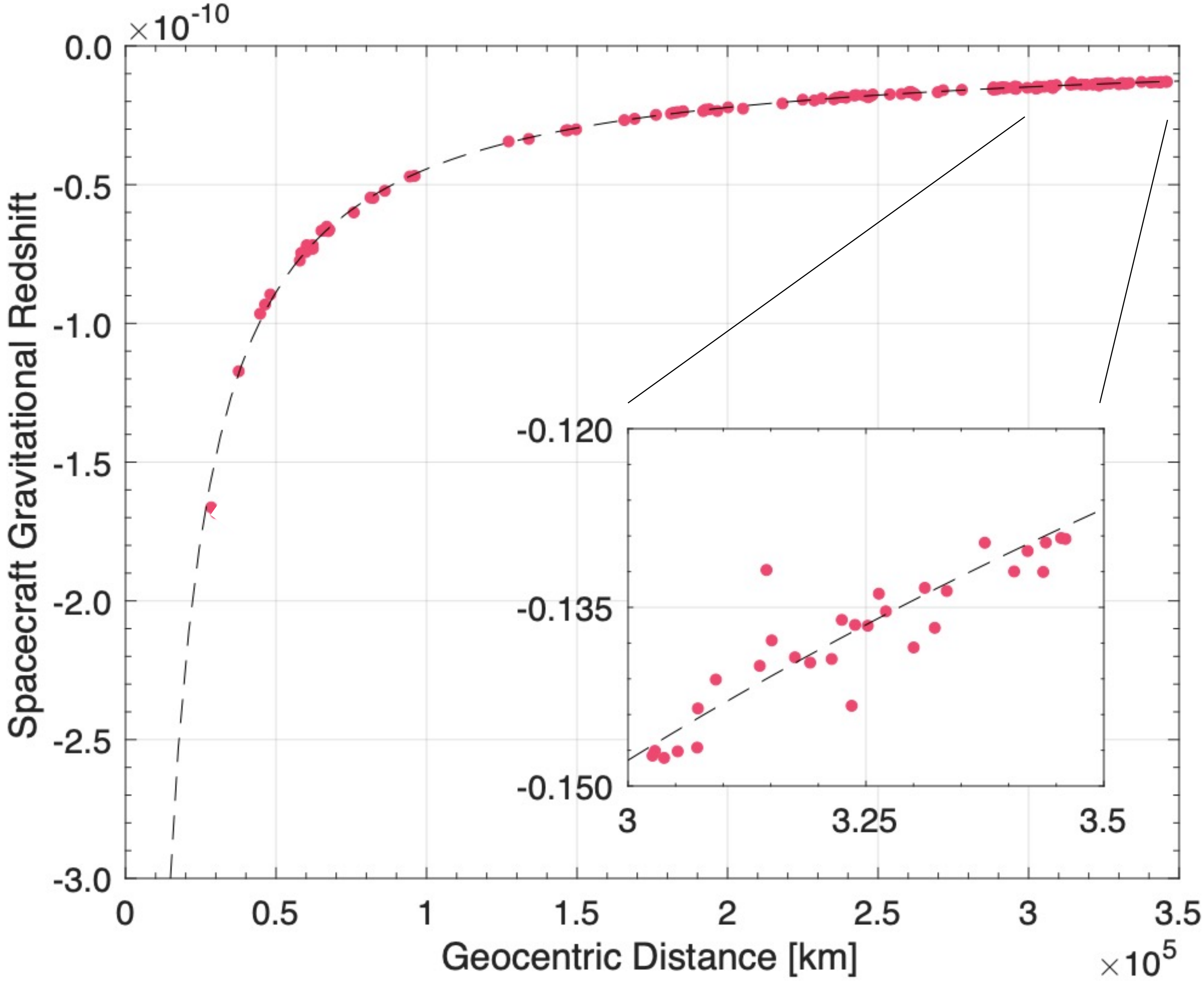
3 Intervals

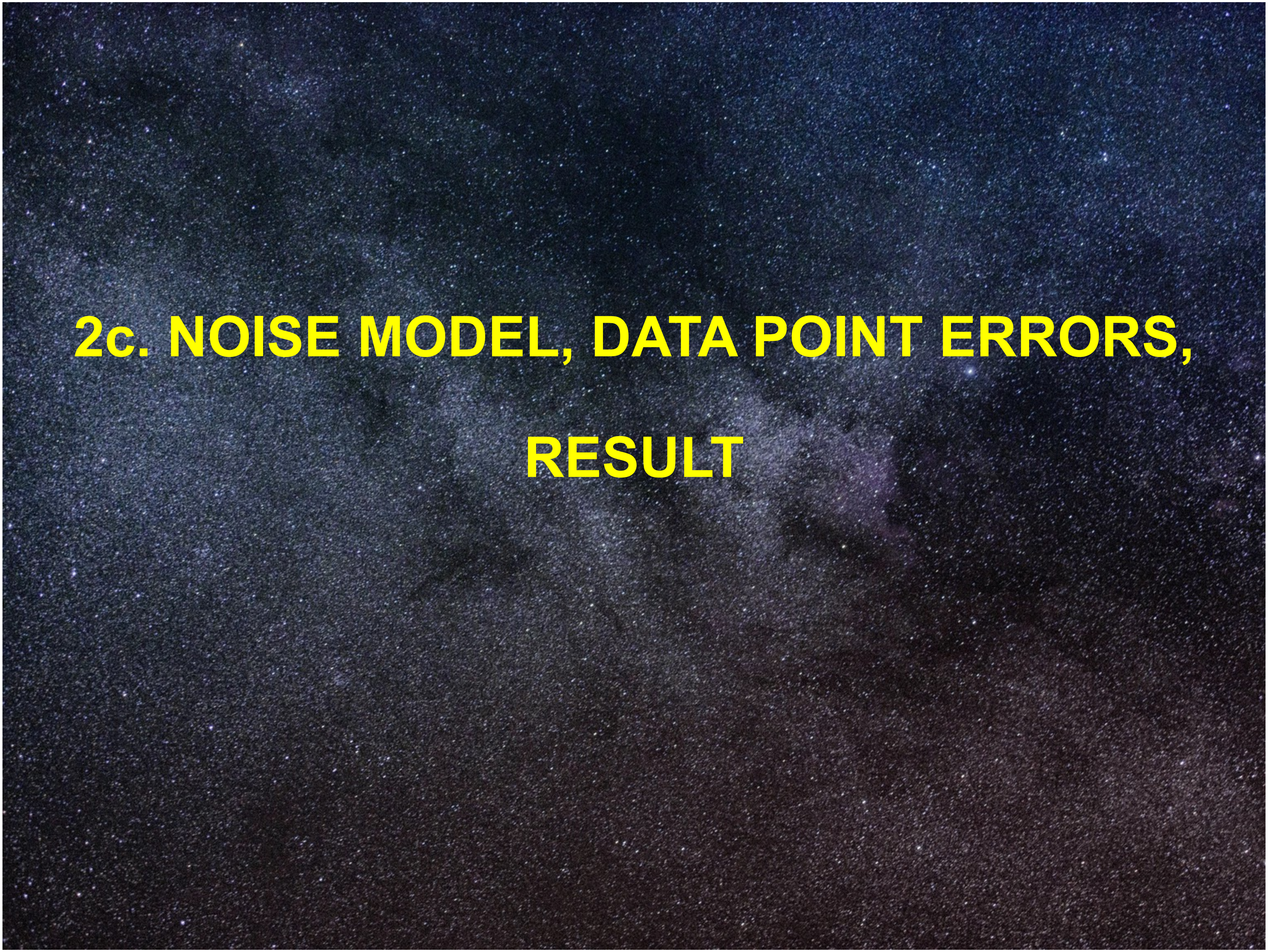
Δh



Gravitational redshift of spacecraft relative to observer at infinity from 30,000 to 350,000 km

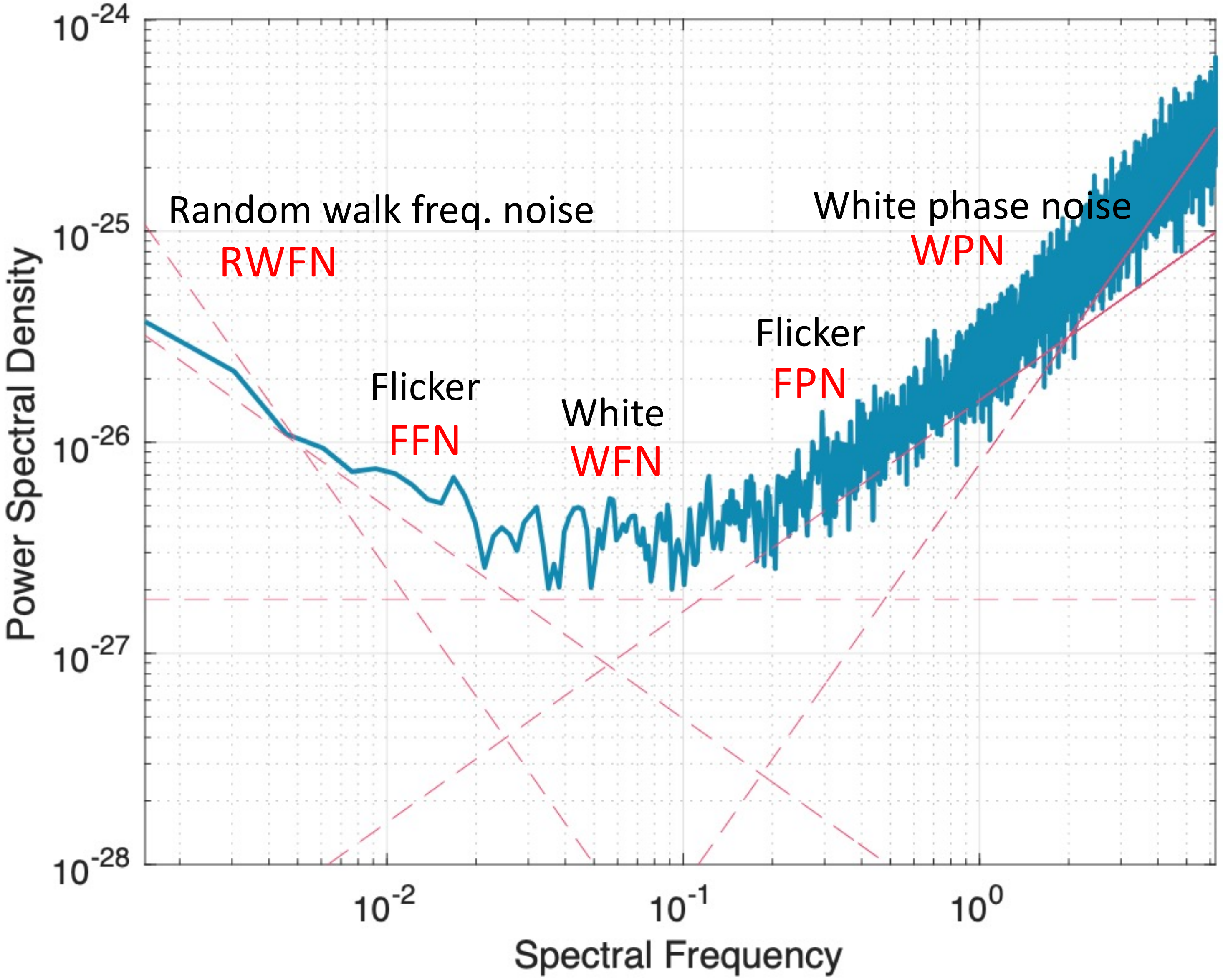
Unique test from Earth to the Moon





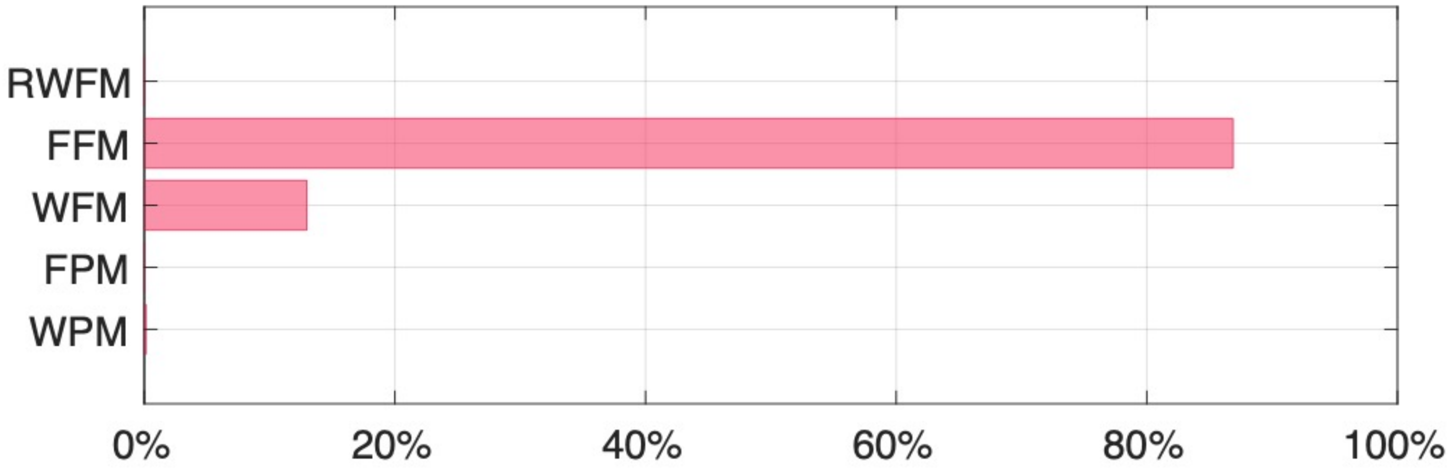
2c. NOISE MODEL, DATA POINT ERRORS, RESULT

Simulated spectrum of five noise types

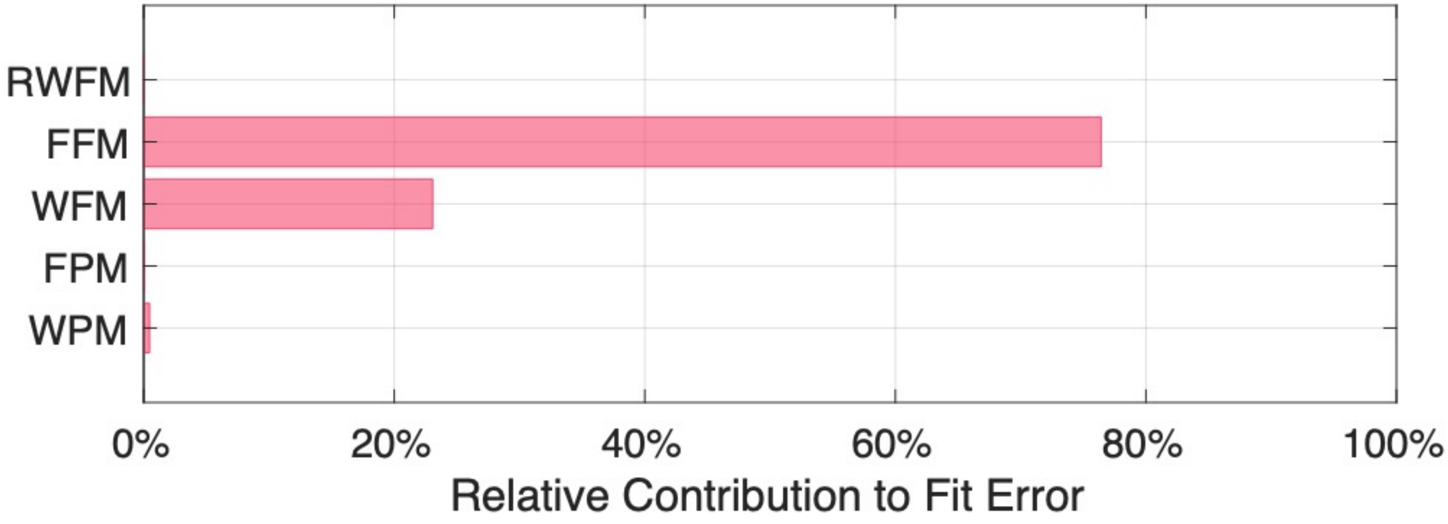


Relative contribution to fit error

Pushchino

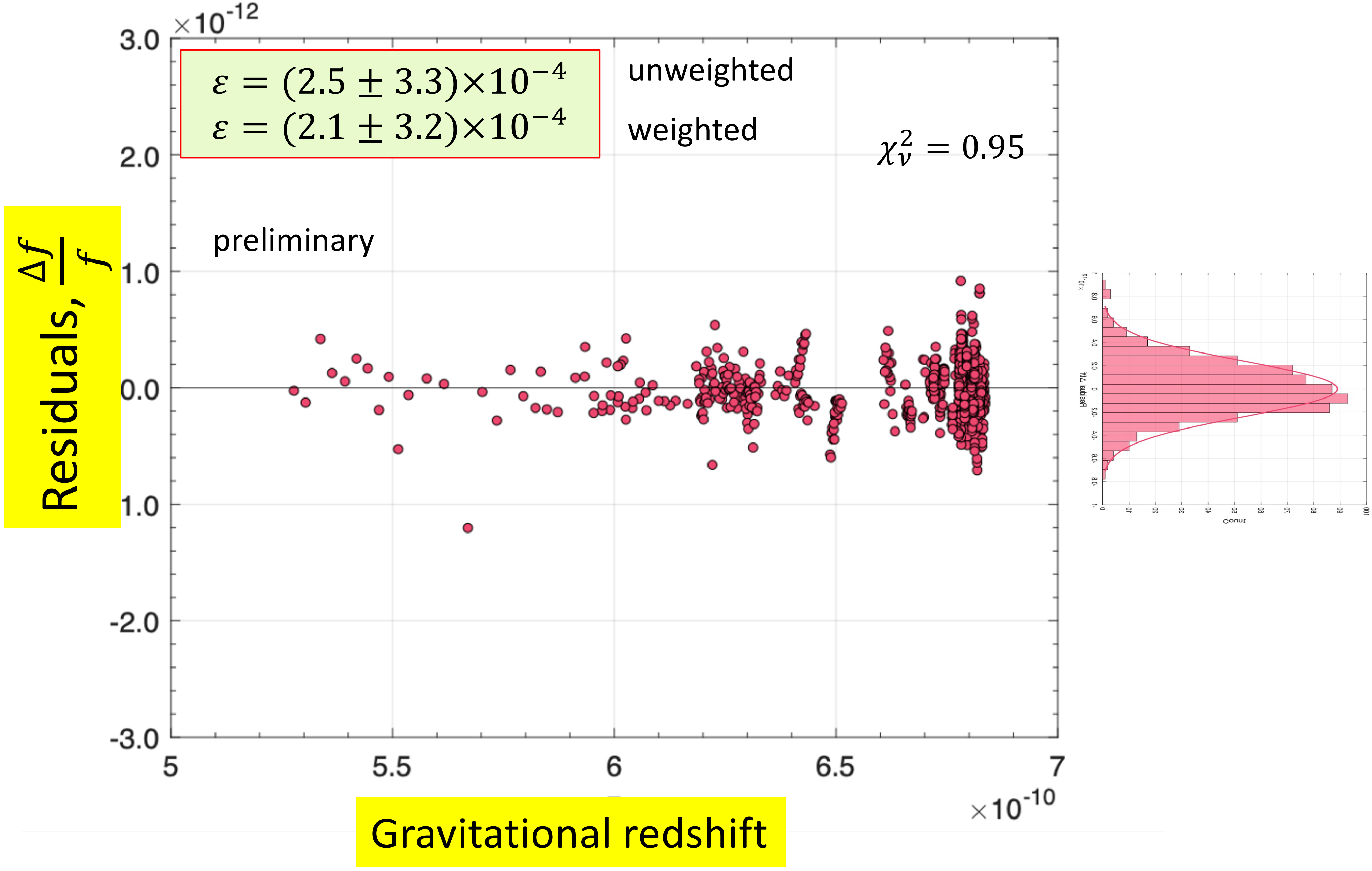


Green Bank



Flicker frequency noise dominates for example integration time

Result and residuals of global fit



$\varepsilon = (2.5 \pm 3.3){\times}10^{-4}$ unweighted

$\varepsilon = (2.1 \pm 3.2){\times}10^{-4}$ weighted

$\chi_\nu^2 = 0.95$

preliminary

2d. FUTURE PROSPECTS

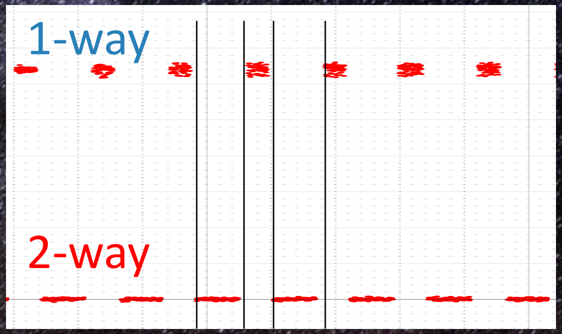
Analysis of VLBI data
recorded in dedicated sessions
by VLBI network

➡ $\Delta\epsilon \sim 2 \cdot 10^{-5}$?

Unsurpassed accuracy in 3+1 classical tests of GR
AND
from here to the Moon

3. Ideas for next generation space VLBI

1. Gravitational redshift measurements as piggy back on routine space VLBI observations
2. Recordings continuously over years at tracking stations
3. Simultaneous operation in 1 way and 2 way modes for Doppler compensation
4. Highly elliptical orbits
5. Synchronization of clocks



→ $\Delta\epsilon \sim 10^{-7}$? (1 yr continuous measurements)

3. Ideas for next generation space VLBI

1. Gravitational redshift measurements as piggy back on routine space VLBI observations
2. Recordings continuously over years at tracking stations
3. Simultaneous operation in 1 way and 2 way modes for Doppler compensation
4. Highly elliptical orbits
5. Synchronization of clocks

$\Delta\epsilon \sim 10^{-7}$?(1 yr continuous measurements)

4. CONCLUSIONS

a) Ad hoc experiments have given remarkable results in the past without much effort

b) Ad hoc RadioAstron gravity experiment with Doppler tracking device $\varepsilon = (\,2.1 \pm 3.2)\times 10^{-4}$

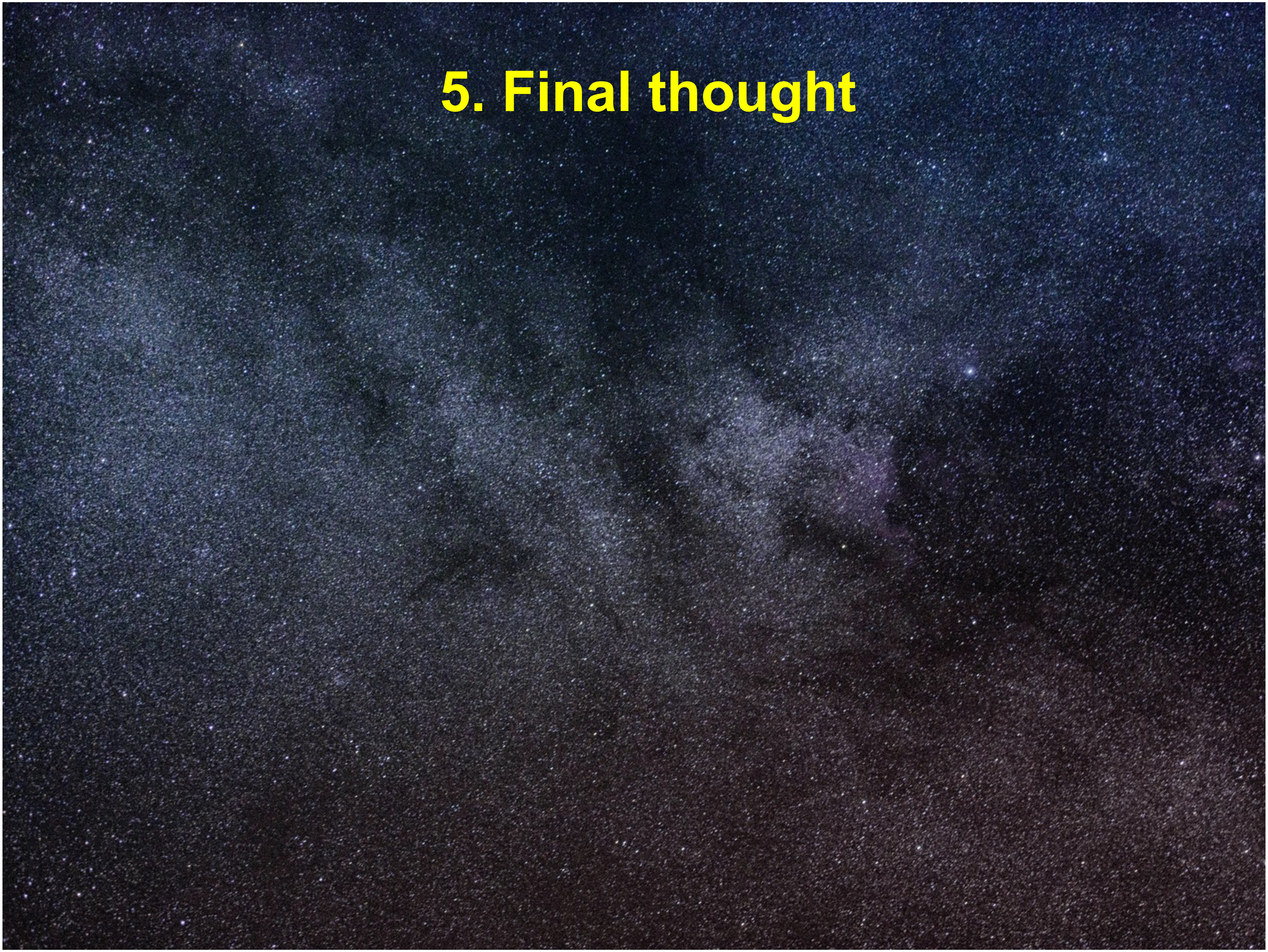
---- consistent with GR

(preliminary)

c) Goal with VLBI data: unsurpassed $\delta\varepsilon \sim 2\times 10^{-5}$

d) Unique probing of grav. redshift from 26,000 to 370,000 km

5. Final thought



5. Final thought

Big Science Can Be Too Big

By BENEDICT CAREY

Modern science is largely a team sport, and over the past few decades the makeup of those teams has shifted, from small groups of collaborators to ever larger consortiums. Answering big questions often requires scientists and institutions to pool resources and data.

But that shift has prompted scientists to examine the relative merits of small groups versus large ones.

Now, investigators have found that the smaller the research team working on a problem, the more likely it was to generate innovative solutions. Large consortiums are still important drivers of progress, but they are best suited to confirming or consolidating novel findings, rather than generating them.

The results could have wide-ranging implications for individual investigators, the academic centers that employ them and the government agencies that provide so much of the financing.

In the study, investigators mined selections from three vast databases: the Web of Science, using more than 42 million articles published since 1950; the United States Patent and Trademark Office, with five million patents granted since 1978; and GitHub, with 16 million software projects posted since 2011.

The researchers found a clear pattern: smaller groups were more likely to produce novel findings than larger ones. Those novel contributions usually took a year or so to catch on, after which larger research teams did the work of consolidating the ideas and solidifying the evidence.

"You might ask what is large, and what is small," said James A. Evans, a sociologist at the University of Chicago who led the study. "The answer is that this relationship holds no matter where you cut the number: between one person and two, between 10 and 20, between 25 and 26."

It also holds within every field in science, whether physics, psychology, computer science, mathematics, or zoology, he added: "You see it within field, within topics. And two-thirds of the effect we found is within the individual. That means that if I'm writing a paper, and I partner with one other person, or two, the result is less disruptive with each person I add."

Psychologists have found that people working in larger groups tend to generate fewer ideas than when they work in smaller groups, or when working alone, and become less receptive to ideas from outside. Why that would be isn't entirely clear, but it runs counter to intuition, said Suparna Rajaram, a professor of psychology at Stony Brook University near New York City.

"We find that the product of three individuals working separately is greater than if those three people collaborate as a group," Dr. Rajaram said. "When brainstorming, people produce fewer ideas when working in groups than when working alone."

There are upsides to working in groups, Dr. Rajaram said. Over time, group members learn a lot from each other, and incorporate that knowledge. "But overall, this new study provides findings on a large scale that are consistent with the underlying principles of our work," she said.

The study suggests that a new kind of funding approach may be needed, one that takes more risk and spends the time and money to support promising individuals and small groups, Dr. Evans said.

"Think of it like venture capitalists do," he said. "They expect a 5 percent success rate, and they try to minimize the correlation between the business they fund. They have a portfolio, one that gives them a higher risk-tolerance level, and also higher payoffs."

BRENDAN BANNON FOR THE NEW YORK TIMES

Large groups are best suited to confirming findings rather than generating them, researchers found.

> The smaller the group, the more novel the ideas.

2019

2-3 March NEW YORK TIMES International weekly

Study:
42 Mill. Articles
5 Mill. Patents
16 Mill software projects

5. Final thought

Large groups are still important drivers of progress, but they are best suited to confirming novel findings rather than generating them.

The smaller the group, the more novel the ideas

Big Science Can Be Too Big

By BENEDICT CAREY

Large groups are best suited to confirming findings rather than generating them, researchers found.

Modern science is largely a team sport, and over the past few decades the makeup of those teams has shifted, from small groups of collaborators to ever larger consortiums. Answering big questions often requires scientists and institutions to pool resources and data.

But that shift has prompted scientists to examine the relative merits of small groups versus large ones.

Now, investigators have found that the smaller the research team working on a problem, the more likely it was to generate innovative solutions. Large consortiums are still important drivers of progress, but they are best suited to confirming or consolidating novel findings, rather than generating them.

The results could have wide-ranging implications for individual investigators, the academic centers that employ them and the government agencies that provide so much of the financing.

In the study, investigators mined selections from three vast databases: the Web of Science, using more than 42 million articles published since 1950; the United States Patent and Trademark Office, with five million patents granted since 1978; and GitHub, with 16 million software projects posted since 2011.

The researchers found a clear pattern: smaller groups were more likely to produce novel findings than larger ones. Those novel contributions usually took a year or so to catch on, after which larger research teams did the work of consolidating the ideas and solidifying the evidence.

"You might ask what is large, and what is small," said James A. Evans, a sociologist at the University of Chicago who led the study. "The answer is that this relationship holds no matter where you cut the number: between one person and two, between 10 and 20, between 25 and 28."

It also holds within every field in science, whether physics, psychology, computer science, mathematics, or zoology, he added: "You see it within field, within topics. And two-thirds of the effect we found is within the individual. That means that if I'm writing a paper, and I partner with one other person, or two, the result is less disruptive with each person I add."

The smaller the group, the more novel the ideas.

Psychologists have found that people working in larger groups tend to generate fewer ideas than when they work in smaller groups, or when working alone, and become less receptive to ideas from outside. Why that would be isn't entirely clear, but it runs counter to intuition, said Suparna Rajaram, a professor of psychology at Stony Brook University near New York City.

"We find that the product of three individuals working separately is greater than if those three people collaborate as a group," Dr. Rajaram said. "When brainstorming, people produce fewer ideas when working in groups than when working alone."

There are upsides to working in groups, Dr. Rajaram said. Over time, group members learn a lot from each other, and incorporate that knowledge. "But overall, this new study provides findings on a large scale that are consistent with the underlying principles of our work," she said.

The study suggests that a new kind of funding approach may be needed, one that takes more risk and spends the time and money to support promising individuals and small groups, Dr. Evans said.

"Think of it like venture capitalists do," he said. "They expect a 5 percent success rate, and they try to minimize the correlation between the business they fund. They have a portfolio, one that gives them a higher risk-tolerance level, and also higher payoffs."

2019
2-3 March NEW YORK TIMES International weekly

5. Final thought

Ad hoc experiments: important to consider

Big Science Can Be Too Big

By BENEDICT CAREY

Modern science is largely a team sport, and over the past few decades the makeup of those teams has shifted, from small groups of collaborators to ever larger consortiums. Answering big questions often requires scientists and institutions to pool resources and data.

But that shift has prompted scientists to examine the relative merits of small groups versus large ones.

Now, investigators have found that the smaller the research team working on a problem, the more likely it was to generate innovative solutions. Large consortiums are still important drivers of progress, but they are best suited to confirming or consolidating novel findings, rather than generating them.

The results could have wide-ranging implications for individual investigators, the academic centers that employ them and the government agencies that provide so much of the financing.

In the study, investigators mined selections from three vast databases: the Web of Science, using more than 42 million articles published since 1950; the United States Patent and Trademark Office, with five million patents granted since 1978; and GitHub, with 16 million software projects posted since 2011.

The researchers found a clear pattern: smaller groups were more likely to produce novel findings than larger ones. Those novel contributions usually took a year or so to catch on, after which larger research teams did the work of consolidating the ideas and solidifying the evidence.

"You might ask what is large, and what is small," said James A. Evans, a sociologist at the University of Chicago who led the study. "The answer is that this relationship holds no matter where you cut the number: between one person and two, between 10 and 20, between 25 and 28."

It also holds within every field in science, whether physics, psychology, computer science, mathematics, or zoology, he added: "You see it within field, within topics. And two-thirds of the effect we found is within the individual. That means that if I'm writing a paper, and I partner with one other person, or two, the result is less disruptive with each person I add."

Psychologists have found that people working in larger groups tend to generate fewer ideas than when they work in smaller groups, or when working alone, and become less receptive to ideas from outside. Why that would be isn't entirely clear, but it runs counter to intuition, said Suparna Rajaram, a professor of psychology at Stony Brook University near New York City.

"We find that the product of three individuals working separately is greater than if those three people collaborate as a group," Dr. Rajaram said. "When brainstorming, people produce fewer ideas when working in groups than when working alone."

There are upsides to working in groups, Dr. Rajaram said. Over time, group members learn a lot from each other, and incorporate that knowledge. "But overall, this new study provides findings on a large scale that are consistent with the underlying principles of our work," she said.

The study suggests that a new kind of funding approach may be needed, one that takes more risk and spends the time and money to support promising individuals and small groups, Dr. Evans said.

"Think of it like venture capitalists do," he said. "They expect a 5 percent success rate, and they try to minimize the correlation between the business they fund. They have a portfolio, one that gives them a higher risk-tolerance level, and also higher payoffs."

BRENDAN BANNON FOR THE NEW YORK TIMES

Large groups are best suited to confirming findings rather than generating them, researchers found.

The smaller the group, the more novel the ideas.

2019

2-3 March NEW YORK TIMES International weekly