Improving Radio Astronomy Using High Altitude Balloons as Calibration Sources

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Near Space Research

TREVECCA NAZARENE UNIVERSITY

Outline

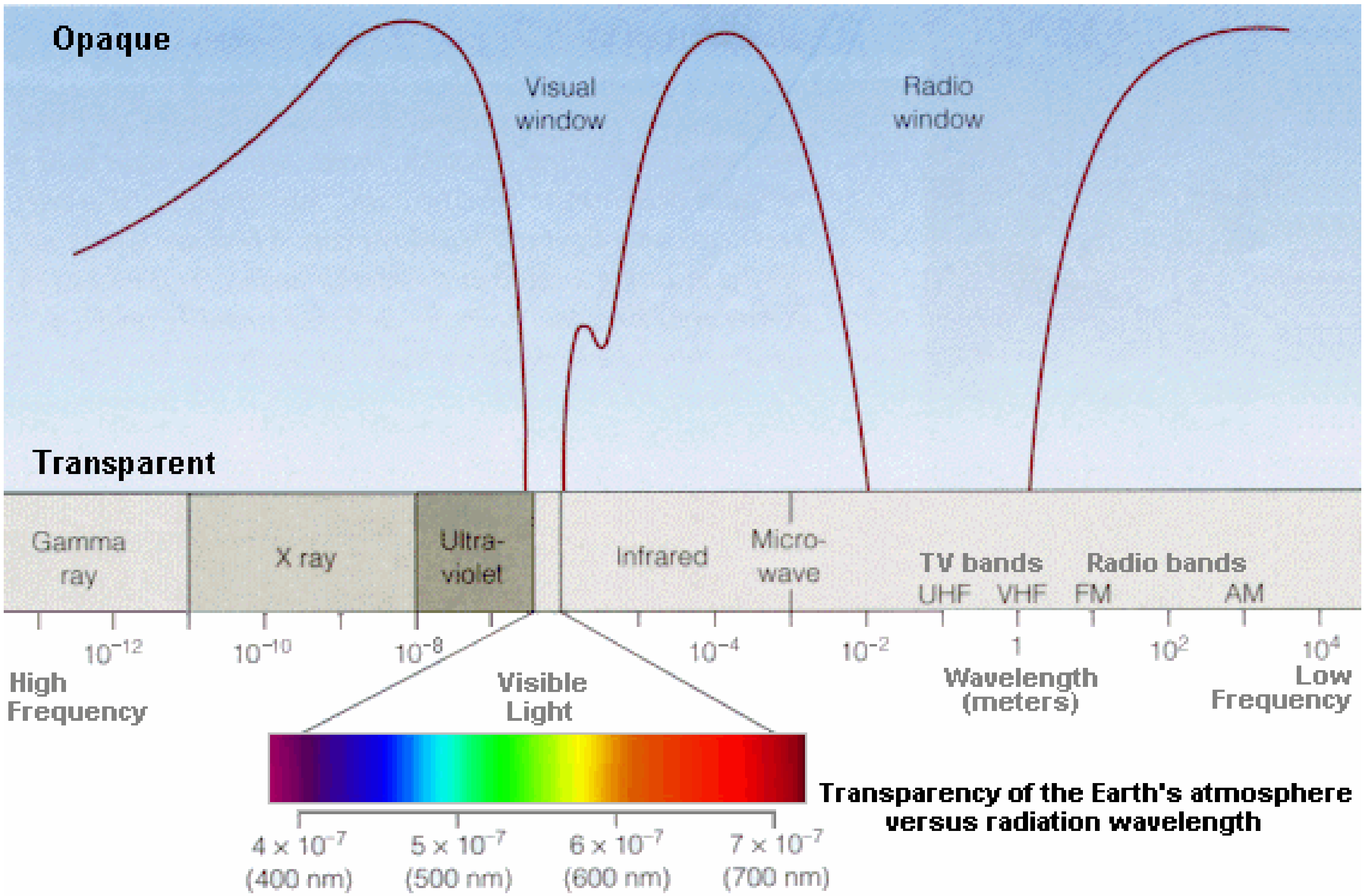
- Preliminary Information on Radio Astronomy
  - Atmospheric Windows
  - Angular Resolution
  - Aperture Synthesis
- Problems Introduced by the Atmosphere
  - Atmospheric Seeing
  - Wavefront Distortion
- Solutions
  - High-Altitude Observatories
  - Guide Stars
  - Interferometry

Outline

- Solutions through the use of High-Altitude Balloons
  - Problems
  - Solutions

- Next Steps
  - Develop More Software Tools
  - Flight Predictions
  - Better Control During Flights
  - Collaboration with Radio Astronomers

Atmospheric Windows



Transparency of the Earth's atmosphere versus radiation wavelength

Angular Resolution

- The minimum angle at which two points in an image can be resolved

$$\sin\theta = 1.220\frac{\lambda}{D}$$

θ = angular resolution
λ = wavelength
D = telescope diameter

Aperture Synthesis

- The use of multiple telescopes to maximize angular resolution.

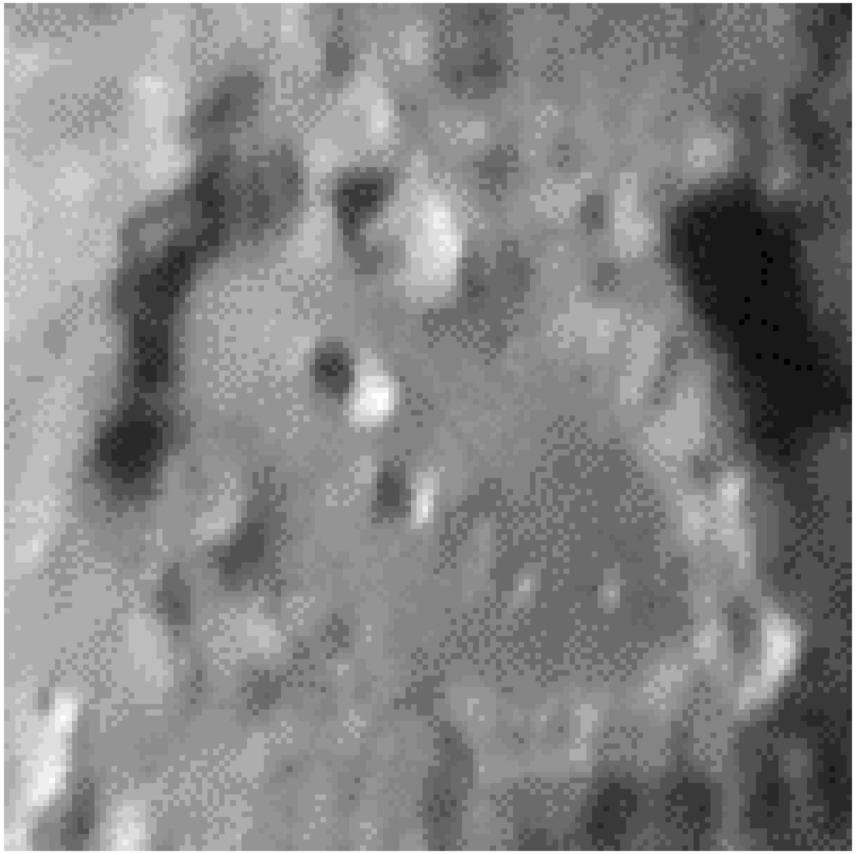
ALMA array in Chilean
Andes Mountains

Atmospheric Seeing

- Distortion of an image due to variations of the refractive index of the atmosphere.

- Causes:
  - Turbulence
  - Temperature
  - Density
  - Humidity

Atmospheric Seeing



An animated image of the surface of the Moon showing the effects of the Earth's atmosphere

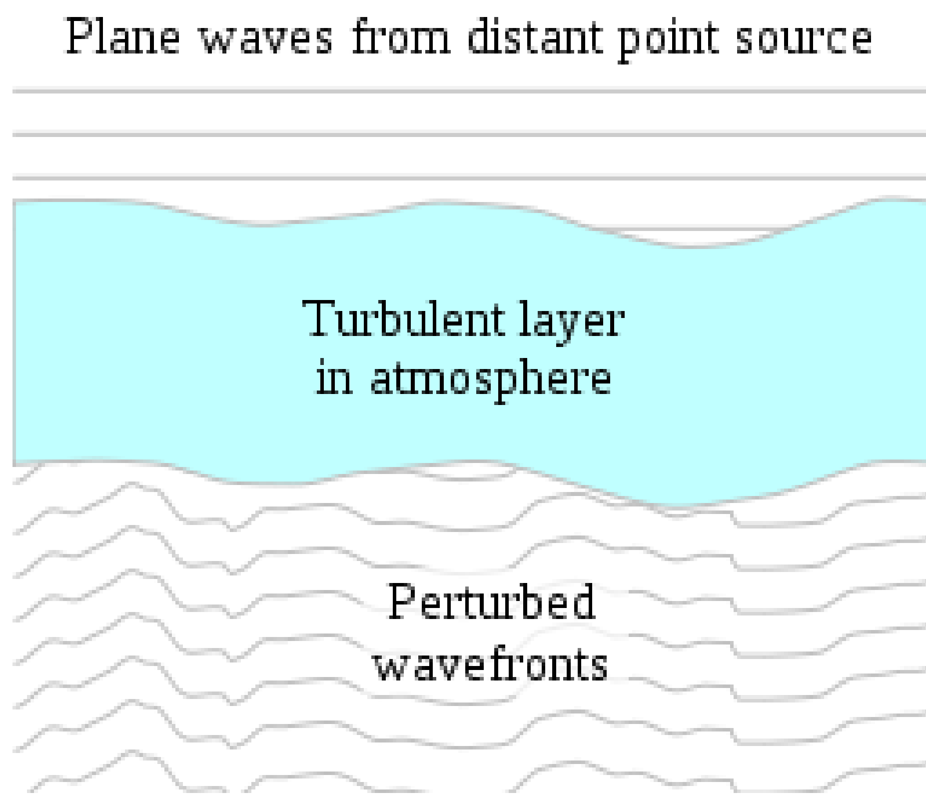
Atmospheric Seeing

Before the turbulence, the light is in phase (coherent)

(The light reaches the observer at the same time and from the same direction)

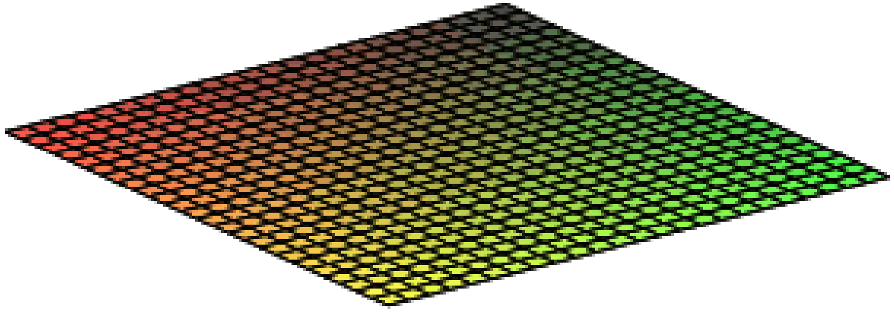
After the turbulence, the light is no longer in phase

(The light arrives at different times from different directions)



Wavefront distortion caused by atmospheric seeing

Atmospheric Seeing



High-Altitude Observatories

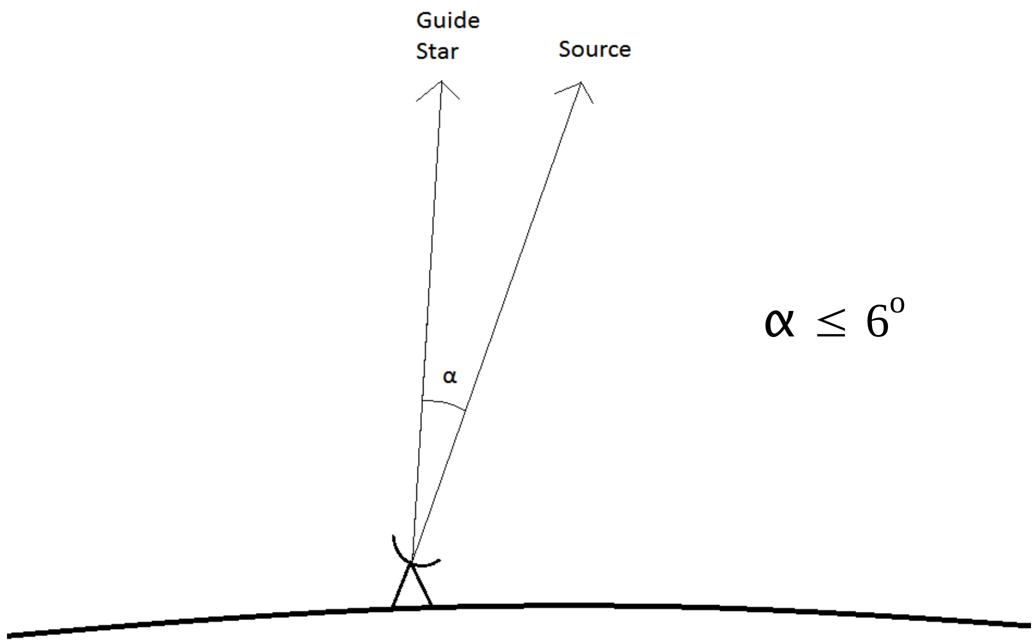
- Mountain-based telescopes are useful in eliminating much of the distortion caused by the atmosphere

Keck Observatory in Mauna Kea

NOAO's Cerro Tololo Interamerican Observatory in Chile

Guide Stars

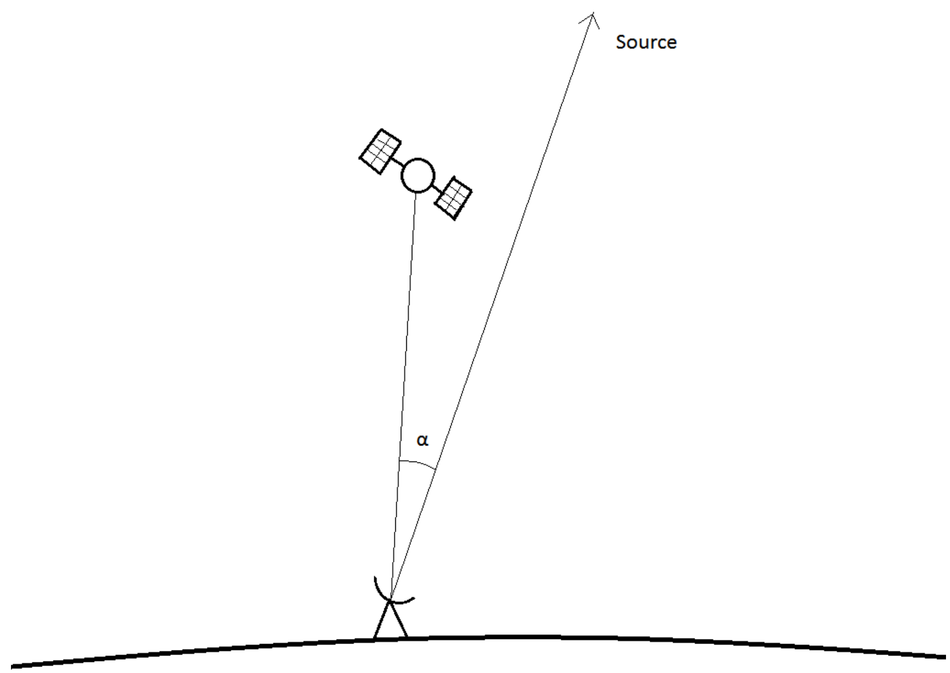
- Bright objects within a small angular distance from the source which provide a signal with enough intensity to accurately measure the wavefront distortion



$$\alpha \leq 6^{o}$$

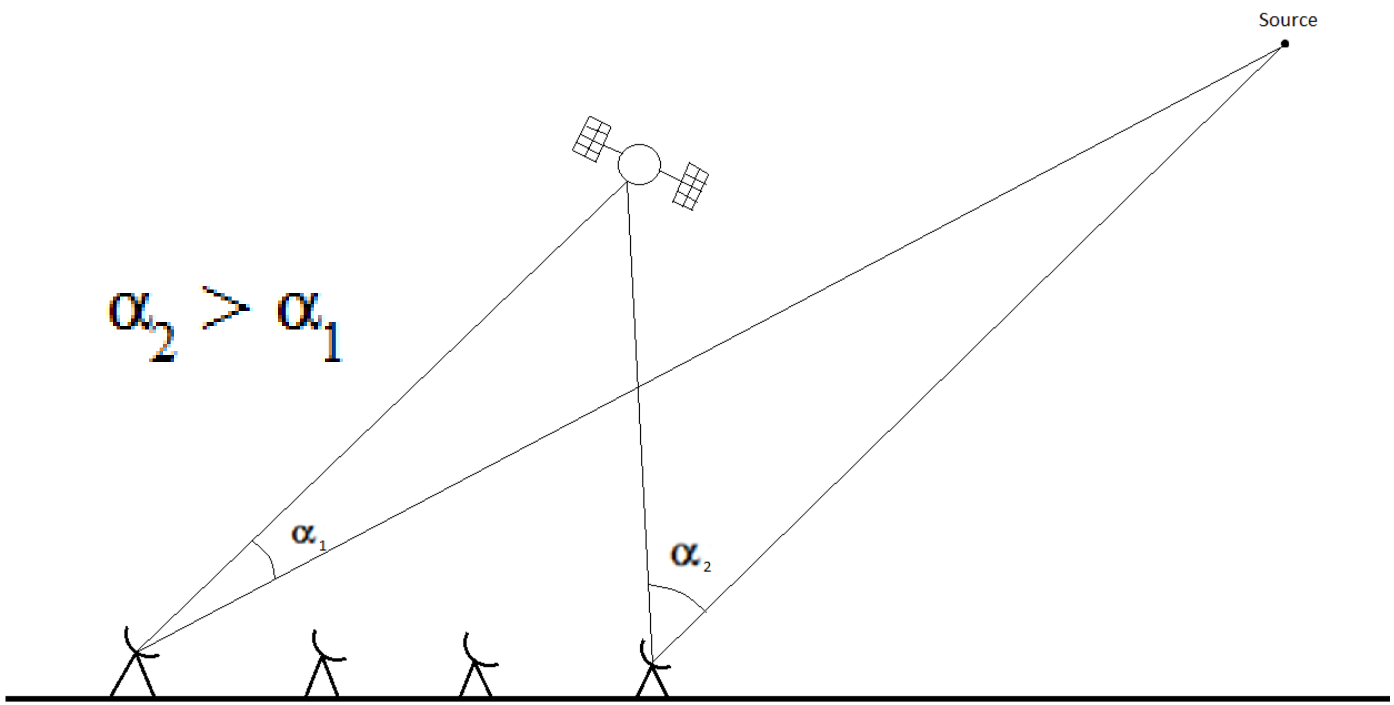
Problems using Satellites as Artificial Guide Stars

- It is complicated and expensive to ensure satellite is in line of sight between observatory and source.



Problems using Satellites as Artificial Guide Stars

- Aperture Synthesis:



High-Altitude Balloons as Artificial Guide Stars

- Advantages:
  - Lower cost
  - Easier to operate

- Disadvantages:
  - Inability to control flights

Mathematical Problems

- The Angle Problem
- The Set of Solutions Problem
- Altitude and Azimuth Calculation

Parameters:

$\alpha =$ Balloon Angle
$\delta =$ Source Declination
$HA =$ Source Hour Angle
$R_E =$ Radius of the Earth

$B_{alt} =$ Balloon Altitude
$B_{lat} =$ Balloon Latitude
$B_{long} =$ Balloon Longitude
$T_{alt} =$ Telescope Altitude
$T_{lat} =$ Telescope Latitude
$T_{long} =$ Telescope Longitude

The Set of Solutions Problem

A necessary piece of information before flight would be the set of all locations where the balloon can be and still accomplish its task

The Set of Solutions Problem

First, we apply this coordinate transformation,

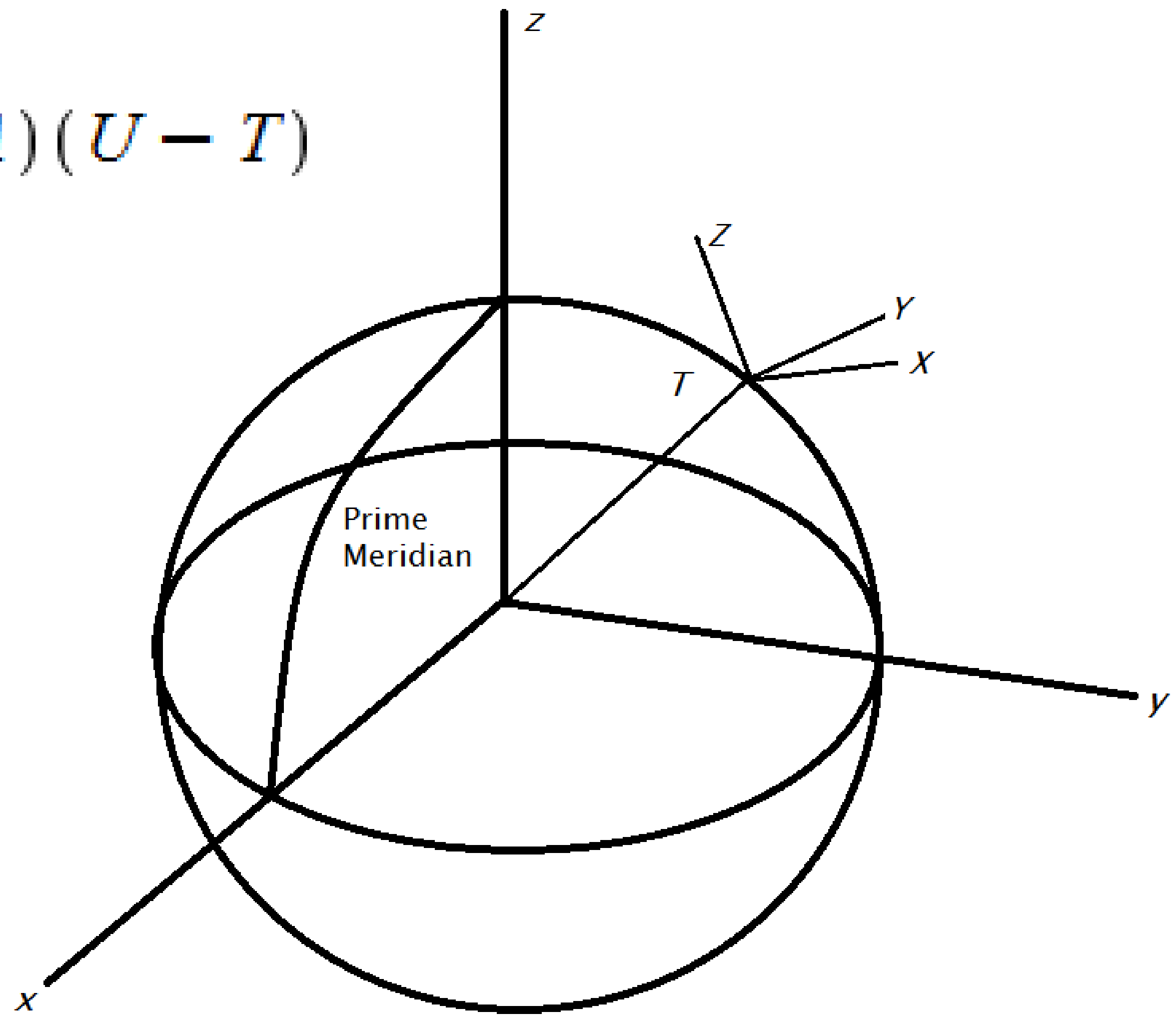
$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} \cos(\delta) & 0 & \sin(\delta) \\ 0 & 1 & 0 \\ -\sin(\delta) & 0 & \cos(\delta) \end{bmatrix} \begin{bmatrix} \cos(HA) & \sin(HA) & 0 \\ -\sin(HA) & \cos(HA) & 0 \\ 0 & 0 & 1 \end{bmatrix} \left(\begin{bmatrix} x \\ y \\ z \end{bmatrix} - T \right)$$

$$V = R_y(\delta) R_z(-HA)(U - T)$$

$$T = \begin{bmatrix} (T_{alt} + R_E) \cos(T_{long}) \cos(T_{lat}) \\ (T_{alt} + R_E) \sin(T_{long}) \cos(T_{lat}) \\ (T_{alt} + R_E) \sin(T_{lat}) \end{bmatrix}$$

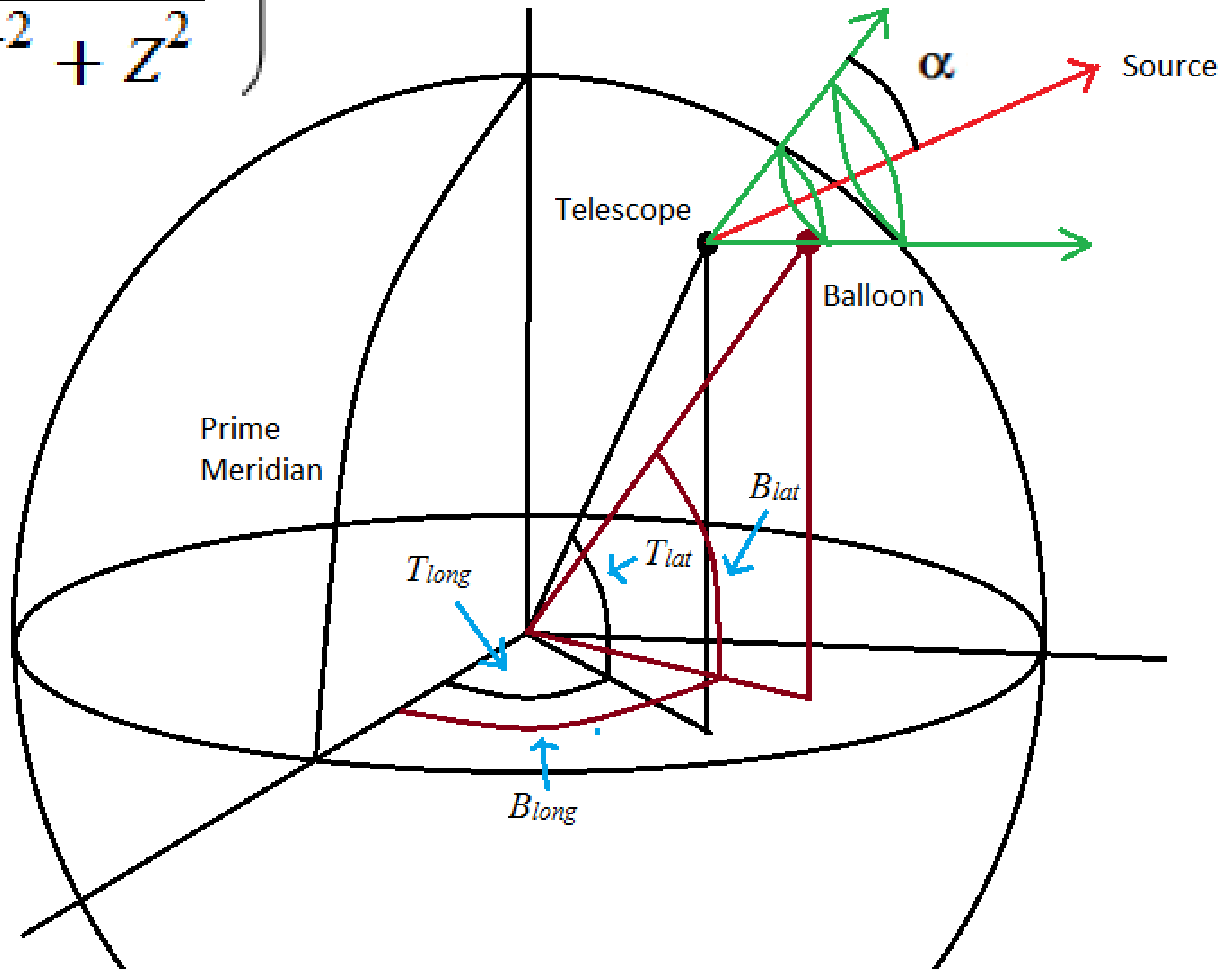
The Set of Solutions Problem

$$V = R_y(\delta) R_z(-HA)(U - T)$$



The Set of Solutions Problem

$$\alpha = \arccos\left(\frac{X}{\sqrt{X^2+Y^2+Z^2}}\right)$$

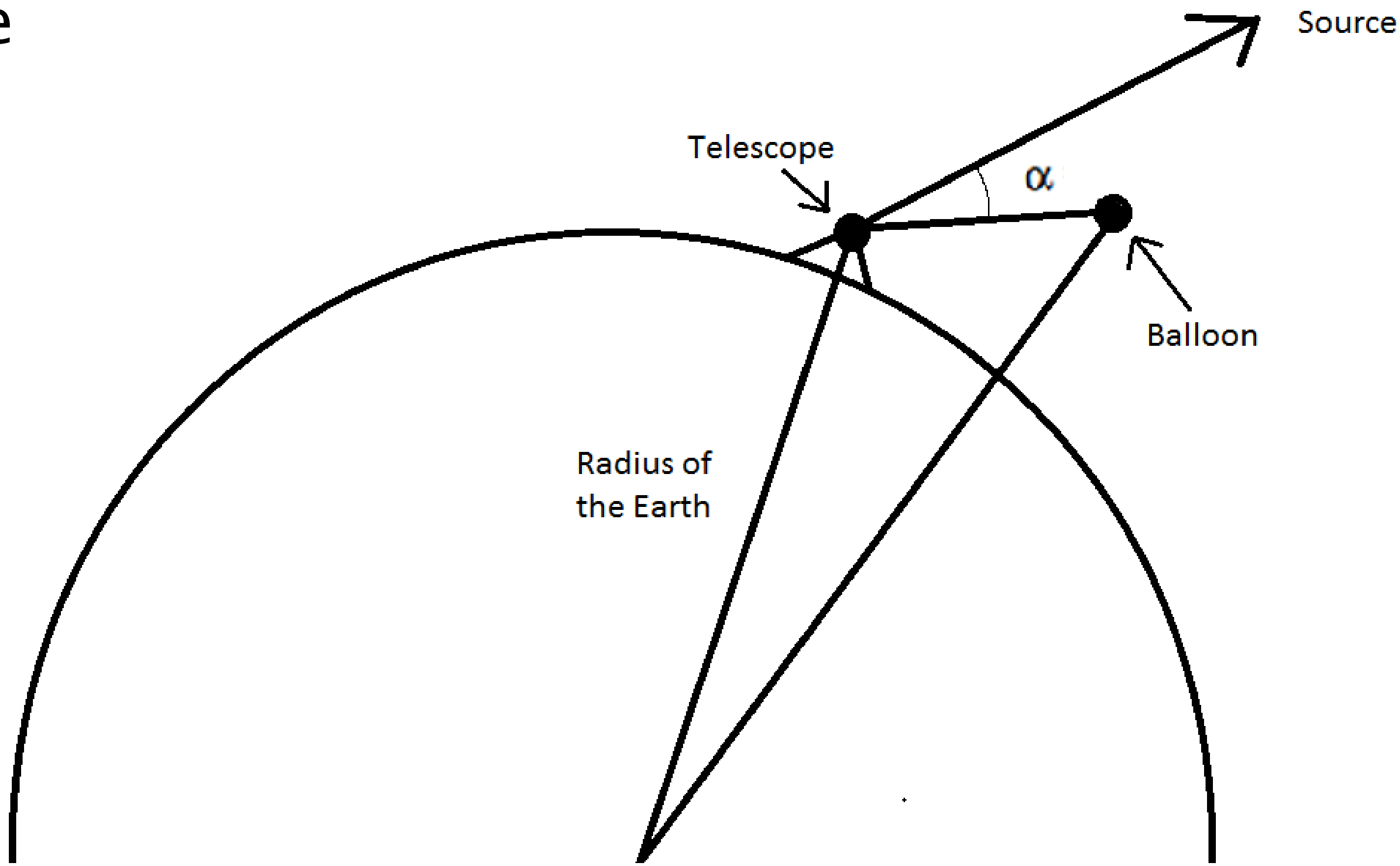


The Set of Solutions Problem

$$\alpha = \arccos\Big(\big(\cos(HA)\sin(\delta)\,\big((B_{alt}+R_E)\cos(B_{long})\cos(B_{lat}) - (T_{alt}+R_E)\cos(T_{long})\cos(T_{lat})\big) + \cos(HA)\cos(\delta)\,\big((B_{alt} + R_E)\sin(B_{long})\cos(B_{lat}) - (T_{alt}+R_E)\sin(T_{long})\cos(T_{lat})\big) + \sin(HA)\,\big((B_{alt}+R_E)\sin(B_{lat}) - (T_{alt}+R_E)\sin(T_{lat})\big)\big) \Big/ \Big(\big(\cos(HA)\sin(\delta)\,\big((B_{alt}+R_E)\cos(B_{long})\cos(B_{lat}) - (T_{alt}+R_E)\cos(T_{long})\cos(T_{lat})\big) + \cos(HA)\cos(\delta)\,\big((B_{alt} + R_E)\sin(B_{long})\cos(B_{lat}) - (T_{alt}+R_E)\sin(T_{long})\cos(T_{lat})\big) + \sin(HA)\,\big((B_{alt}+R_E)\sin(B_{lat}) - (T_{alt}+R_E)\sin(T_{lat})\big)\big)^2 + \big(-\cos(\delta)\,\big((B_{alt}+R_E)\cos(B_{long})\cos(B_{lat}) - (T_{alt}+R_E)\cos(T_{long})\cos(T_{lat})\big) + \sin(\delta)\,\big((B_{alt}+R_E)\sin(B_{long})\cos(B_{lat}) - (T_{alt}+R_E)\sin(T_{long})\cos(T_{lat})\big)\big)^2 + \big(-\sin(HA)\sin(\delta)\,\big((B_{alt}+R_E)\cos(B_{long})\cos(B_{lat}) - (T_{alt} + R_E)\cos(T_{long})\cos(T_{lat})\big) - \sin(HA)\cos(\delta)\,\big((B_{alt}+R_E)\sin(B_{long})\cos(B_{lat}) - (T_{alt}+R_E)\sin(T_{long})\cos(T_{lat})\big) + \cos(HA)\,\big((B_{alt}+R_E)\sin(B_{lat}) - (T_{alt}+R_E)\sin(T_{lat})\big)\big)^2\Big)^{1/2}\Big)$$

The Angle Problem

- We also must check if the balloon is within the range of allowable angles in real-time



The Angle Problem

$$\alpha = \cos^{-1}\left(\frac{TB \cdot TS}{|TB||TS|}\right) \qquad TS = \begin{bmatrix} \cos(HA)\sin(90-\delta) \\ \sin(HA)\sin(90-\delta) \\ \cos(90-\delta) \end{bmatrix}$$

$$TB = \begin{bmatrix} (B_{alt}+R_E)\cos(B_{long})\sin(90-B_{lat}) - (T_{alt}+R_E)\cos(T_{long})\sin(90-T_{lat}) \\ (B_{alt}+R_E)\sin(B_{long})\sin(90-B_{lat}) - (T_{alt}+R_E)\cos(T_{long})\sin(90-T_{lat}) \\ (B_{alt}+R_E)\cos(90-B_{lat}) - (T_{alt}+R_E)\cos(90-T_{lat}) \end{bmatrix}$$

α = Balloon Angle

R_E = Radius of the Earth

B_{alt} = Balloon Altitude

B_{lat} = Balloon Latitude

B_{long} = Balloon Longitude

T_{alt} = Telescope Altitude

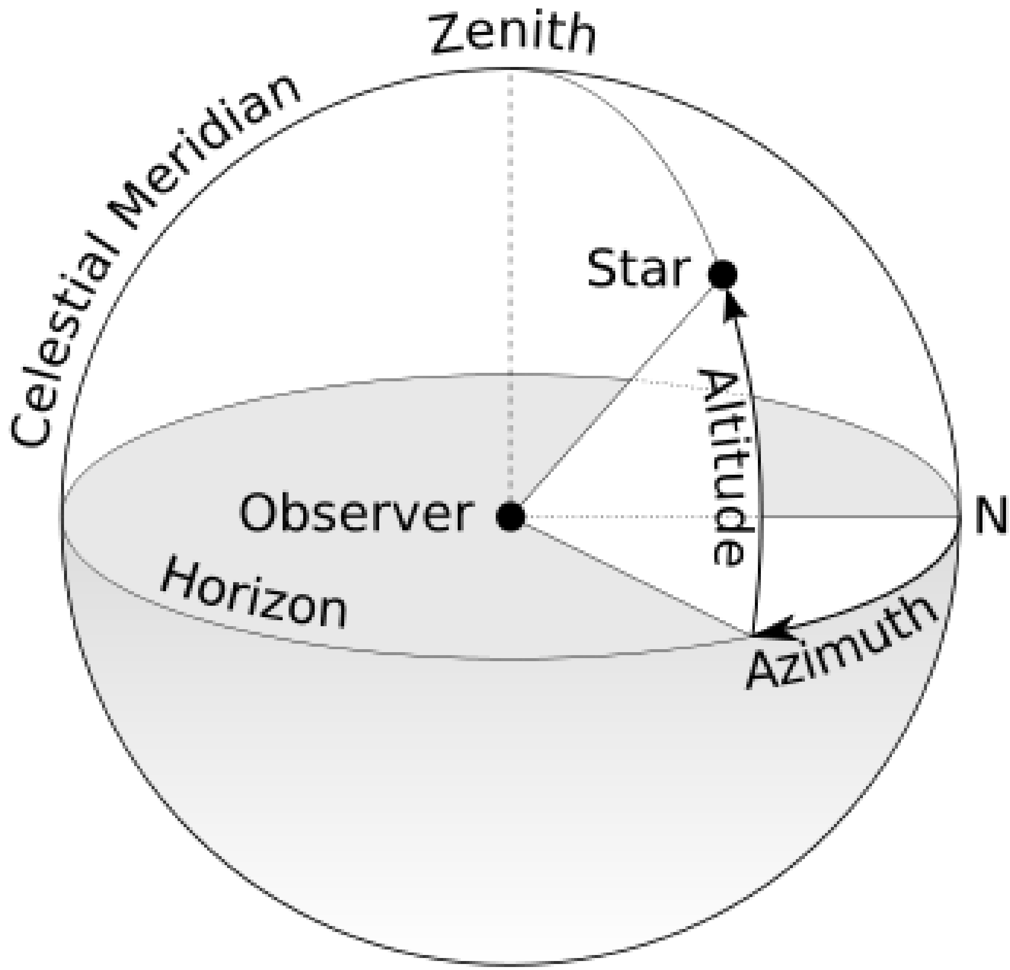
T_{lat} = Telescope Latitude

T_{long} = Telescope Longitude

δ = Source Declination

HA = Source Hour Angle

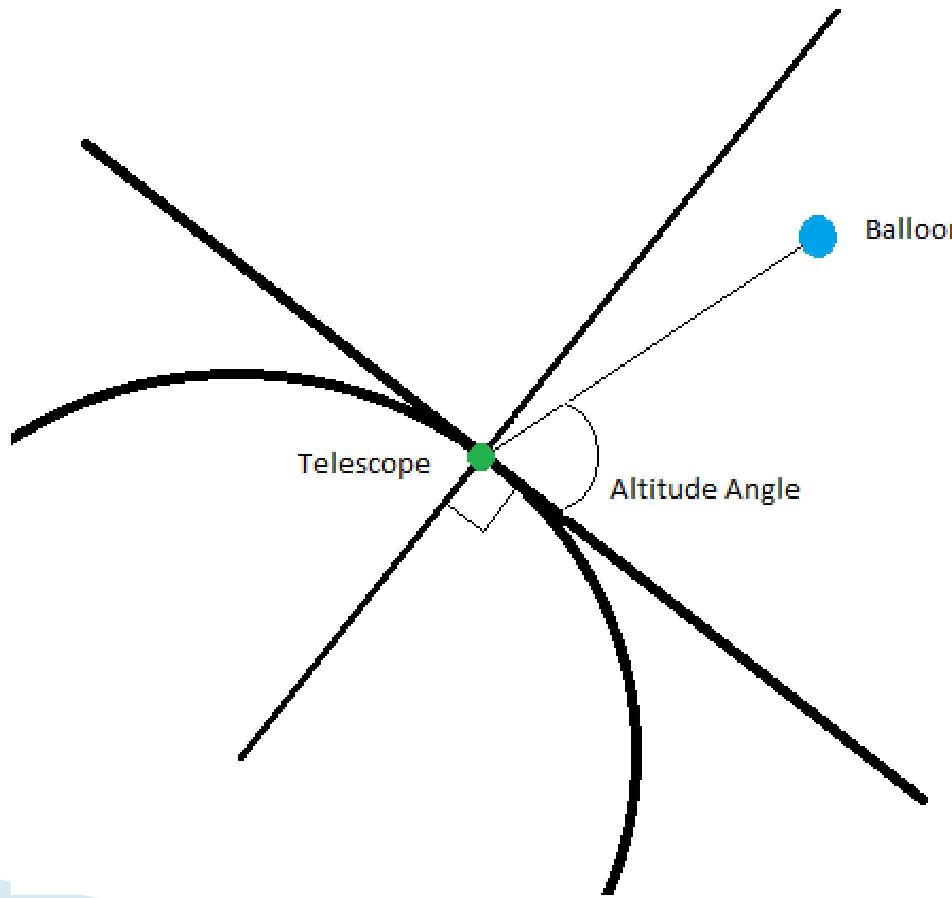
Altitude and Azimuth



Altitude Angle Calculation

The angle between the horizon and the balloon

$$alt = \arccos\left(\frac{-T \cdot TB}{|T||TB|}\right) - 90^{\circ}$$



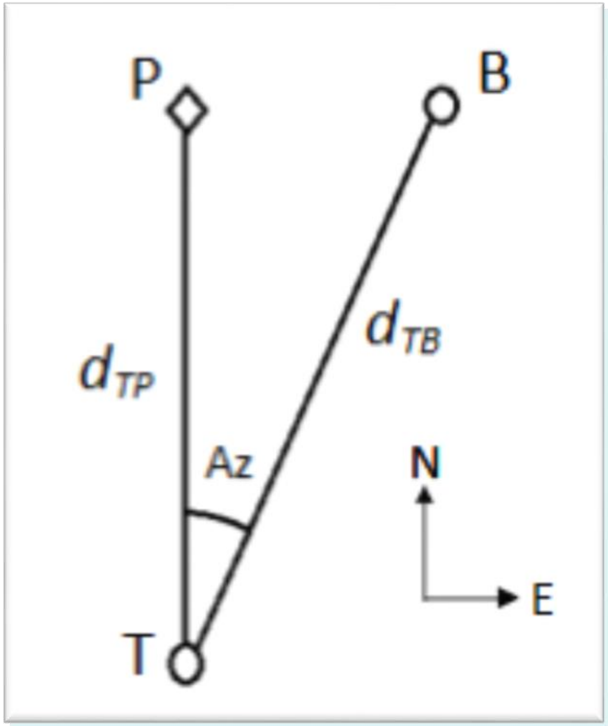
Azimuth Angle Calculation

The angle between the balloon and North, measured to the East

$$\cos(\psi_{TP}) = \frac{T \cdot P}{|T|\,|P|} \qquad \cos(\psi_{TB}) = \frac{T \cdot B}{|T|\,|B|}$$

$$\underbrace{d_{TP} = R_E \psi_{TP} \qquad d_{TB} = R_E \psi_{TB}}$$

$$az = \arccos\left(\frac{d_{TP}}{d_{TB}}\right) = \arccos\left(\frac{\psi_{TP}}{\psi_{TB}}\right)$$



Next Steps

- Develop more software tools
- Better flight predictions
- Design a guidance system to put on the balloon which will allow more control over the flight path
- Collaboration with radio astronomers

Sources

- Zauderer, Ashley. “Sub-Arcsecond Molecular Gas Imaging and Phase Correction.”
- Lamb, James. “Beating atmospheric scintillation at millimeter and submillimeter wavelengths.”
- Woody, David. “Adaptive Optics for Radio Interferometers.”

Interferometry and Convolution

- Convolution compares the relative phase of two signals

$$[f * g](a) \equiv \int_0^a f(a-t) \cdot g(t)\, \mathrm{d}t$$