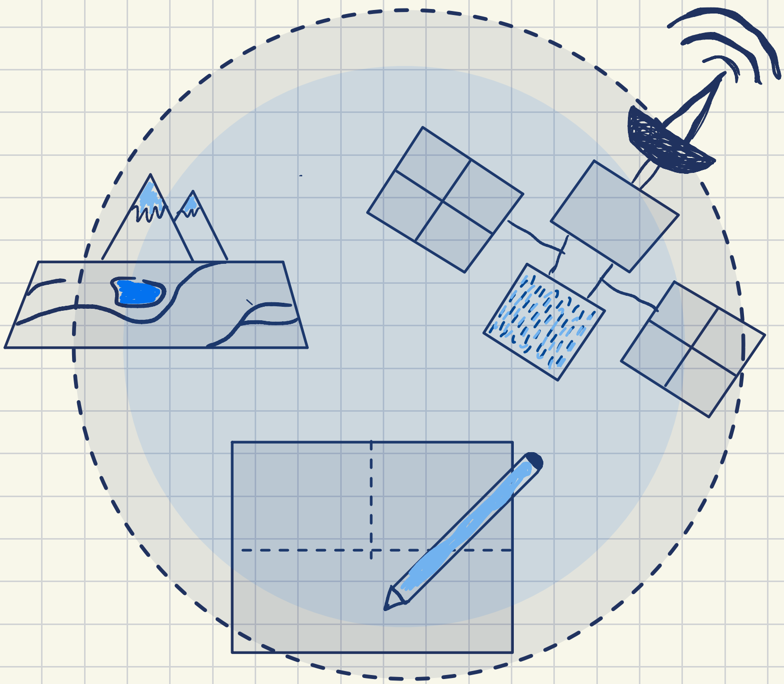
RSGNSS



Estimate Precipitable Water Vapor (PWV)

Steps

First: Tropospheric delay estimation using ERA5 data

↓

Second: Tropospheric hydrostatic delay computation using an empirical model

↓

Third: Tropospheric wet delay calculation

↓

Fourth: Tropospheric delay extraction from IGS product

↓

Fifth: Precipitable water vapor estimation

First: Tropospheric delay estimation using ERA5 data :

Site

https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-pressure-levels?tab=form

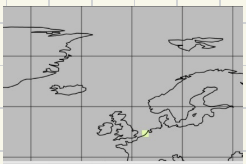
Weather data has been downloaded from the specified geographical location considering parameters such as temperature, geopotensial, and relative humidity at the time of 19-July-2018.

Using the "Panoply" software temperature, relative humidity, geopotential, and pressure layers are extracted from the meteorological data.

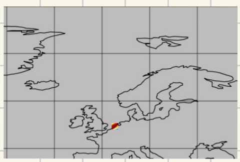
The geopotential data needs to be converted to the height parameter (by driving it by 9.8).

plotting parameters in Panoply software :

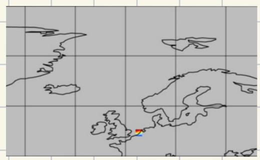
- Relative humidity



- Temperature



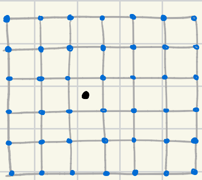
- Geopotential



Additionally, for interpolation we need the coordinates(x,y) of the desired station. (coordinats obtain from site).

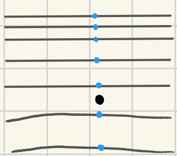
for station's elevation, first determine the DEM of the region where the station is located. Then using the "Global Mapper" software, obtain the point's elevation.

2D (X,Y)



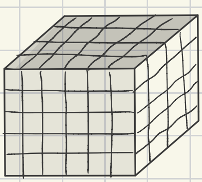
Horizenta --> Kriging

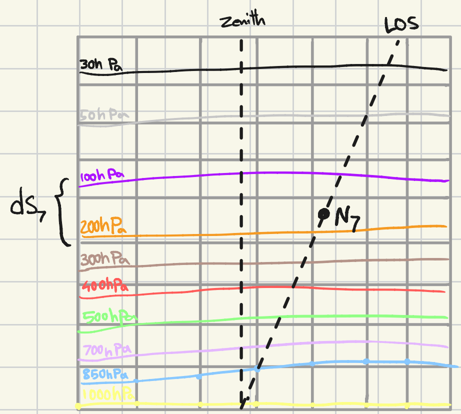
1D(z)



Vertical --> Spline

3D





Estimating Zenith Total Delay (ZTD) :

$$ZTD = 10^{-6} \int_S N(s)\, ds \rightarrow ZTD = 10^{-6} \sum_{i=1}^{n} N_i(s)\, ds_i \quad * \quad N = K_1 \left(\frac{P_d}{T}\right) Z_d^{-1} + K_2 \left(\frac{P_w}{T}\right) Z_w^{-1} + K_3 \left(\frac{P_w}{T}\right) Z_w^{-1}$$

$P_w \rightarrow$ Water Vapor Pressure (mbar)

$P_d \rightarrow$ Dry air Pressure (mbar)

Z_w, Z_d } Compressibility parameters for dry & water Vapor are Considered, typically assumed to be approximately 1 for both.

$$N_{dry} = K_1 \left(\frac{P_d}{T}\right) Z_d^{-1} \qquad N_{wet} = K_2 \left(\frac{P_w}{T}\right) Z_w^{-1} + K_3 \left(\frac{P_w}{T}\right) Z_w^{-1}$$

$$K_1 = (77.604 \pm 0.014)\ \mathrm{K/mbar} \qquad K_2 = (64.79 \pm 0.08)\ \mathrm{K/mbar} \qquad K_3 = 10^5 (3.776 \pm 0.004)\ \mathrm{K/mbar}$$

ZTD:

To calculate ZTD, initially, due to the atmospheric parameters being available in grid networks & the point is not precisely on this grid, We need to interpolate the atmospheric parameters. Both horizental and Vertical interpolation are required in this context.

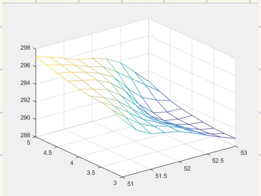
The troposphere has two components, Wet & Dry. For calculating the Refractivity delay, We separately calculate the delays for the wet & dry components.

For interpolation, calculate the water Vapor pressure:

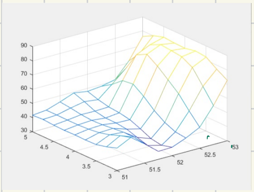
$$\underbrace{RH}_{\text{Relative Humidity}} = 100 \times \frac{\overbrace{P}^{\text{Water Vapor Pressure}}}{P_s} \qquad \underbrace{P_s}_{\text{Saturation Vapor pressure}} = 6.11 \times 10^{\left(\frac{17.27\, T}{273.3 + \underbrace{T}_{\text{Temperature}}}\right)}$$

Plotting interpolated atmospheric parameters:

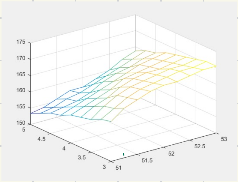
▨ Temperature



▨ Relative Humidity



▨ Height



Second: Tropospheric hydrostatic delay (ZHD) Computation using Saastamoinen model:

$$ZHD = \frac{0.002277\, P_s}{(1 - 0.026 \cos(2\varphi) - 0.00000028\, H)}$$

Dry air pressure (mbar)

Station elevation above sea level

Geographical latitude

Third: Tropospheric wet delay calculation:

Tropospheric delay consists of both dry & wet components. Therefore, to calculate the tropospheric delay the folowing formula is used:

$$\boxed{ZWD = ZTD - ZHD}$$

Fourth: Tropospheric delay extraction from IGS product:

https://cddis.nasa.gov/Data_and_Derived_Products/GNSS/atmospheric_products.html

ftp://cddis.nasa.gov/gnss/products/troposphere/zpd/

ftp://www.igs.org/pub/data/format/sinex_tropo.txt

Download the tropospheric data for the specified station from the IGS website, considering the desired time & location. The compare the downloaded file with estimated ZTD (with MATLAB) based on their times.

Compare this with meteorological data, which was downloaded on July 19, 2018, at 12:00.

Also the IGS tropospheric data corresponds to the 179th day, meaning July 19, 2018.

The IGS data is collected every 300 seconds, or every 5 minutes, on this day.

To compare the obtained ZTD through programming (MATLAB) with the ZTD available in the IGS file, we need to synchronize the time scales. In the IGS station data, locate the time 12:00, reference time being 00:00, and since each hour is 3600 seconds, 12:00 corresponds to the second 43200. Therefore, in the row where the time is 43200, it corresponds to the meteorological data on July 19, 2018, at 12:00. The ZTD parameter is found in the TroTot column.

Fifth: Precipitable water vapor estimation:

$$\boxed{PWV = \Pi\,(T_m).ZWD}$$

$$\Pi = \frac{10^6}{\underbrace{\rho}_{\text{Density of water}}\, \underbrace{R_v}_{\text{Specific gas constant for water vapor}}\,[(K_3/T_m) + K_2']}, \quad K_2' = 24 \pm 11$$

$\rho = 997\ \mathrm{Kg/m^3}$

$R_v = 461.5\ \mathrm{J/kg.K}$

$$T_m = \frac{\int \left(\frac{P_v}{T}\right) dz}{\int \left(\frac{P_v}{T^2}\right) dz}$$

P_v: Water Vapor Pressure

T_m: Weighted average temperture of the atmosphere

References:

1. Green, J., Atmospheric Dynamics. Cambridge Atmospheric and Space Science Series. 1111, Cambridge: Cambridge University Press.

2. Smith, E.K. and S. Weintraub, The constants in the equation for atmospheric refractive index at radio frequencies. Proceedings of the IRE, 1191. 11(8): p. 9 101 - . 10118

3. Lawrence, M.G., The relationship between relative humidity and the dewpoint temperature in moist air: A simple conversion and applications. Bulletin of the American Meteorological Society, 2009. 88(2): p. 229 -211 .

4. Huang, J., A Simple Accurate Formula for Calculating Saturation Vapor Pressure of Water and Ice. Journal of Applied Meteorology and Climatology, 2018. 91(8): p. 1289 - 1212 .

5. Tang, X., et al., Precipitable water vapour retrieval from GPS precise point positioning and NCEPCFSv 2 dataset during typhoon events. Sensors, 2018. 18(11): p. 1811 .

6. Bevis, M., et al., GPS meteorology: Mapping zenith wet delays onto precipitable water. Journal of applied meteorology, 1111. 11(1): p. 111 -

MATLAB CODE & Data

MATLAB CODE 1

```
clc
clear all
close all
%%%% step 1
%%%%%%%load ERA-5 data
%%%load latitude

latt=fopen('latitude.txt');
formatspec='%f %f'; %column
lattt=textscan(latt,formatspec,'Headerlines',1);
latitude=cell2mat(lattt); %convert to matrix
fclose(latt);
```

latitude

latitude	latitude
53.0	53.0
52.75	52.75
52.5	52.5
52.25	52.25
52.0	52.0
51.75	51.75
51.5	51.5
51.25	51.25
51.0	51.0

```
%%%load longitude

longg=fopen('longitude.txt');
formatspec='%f %f';
longgg=textscan(longg,formatspec,'Headerlines',1);
longitude=cell2mat(longgg);
fclose(longg);
```

longitude

longitude	longitude
3.0	3.0
3.25	3.25
3.5	3.5
3.75	3.75
4.0	4.0
4.25	4.25
4.5	4.5
4.75	4.75
5.0	5.0

```
%%%load temperature

tt=fopen('t.txt');
formatspec='%f %f %f %f %f';
ttt=textscan(tt,formatspec,'Headerlines',1);
temperature=cell2mat(ttt);
fclose(tt);
```

t

time	level	latitude	longitude	t
1039164	1	53.0	3.0	269.48417231630316
1039164	1	53.0	3.25	269.71529001550266
1039164	1	53.0	3.5	269.94890628442323
1039164	1	53.0	3.75	270.1725282744595
1039164	1	53.0	4.0	270.36866599756394
1039164	1	53.0	4.25	270.53107302943386
1039164	1	53.0	4.5	270.652253660906
1039164	1	53.0	4.75	270.72721075253827
1039164	1	53.0	5.0	270.7596921589123
1039164	1	52.75	3.0	269.8789463322331
1039164	1	52.75	3.25	270.11880902545636
1039164	1	52.75	3.5	270.3399324457716
1039164	1	52.75	3.75	270.5260758899917
1039164	1	52.75	4.0	270.66599579437195

```
%%%load geopotential

zz=fopen('z.txt');
formatspec='%f %f %f %f %f';
zzz=textscan(zz,formatspec,'Headerlines',1);
geopotential=cell2mat(zzz);
fclose(zz);
```

z

time	level	latitude	longitude	z
1039164	1	53.0	3.0	482824.4051617482
1039164	1	53.0	3.25	482831.75
1039164	1	53.0	3.5	482831.75
1039164	1	53.0	3.75	482824.4051617482
1039164	1	53.0	4.0	482809.7154852445
1039164	1	53.0	4.25	482795.02580874093
1039164	1	53.0	4.5	482772.9912939855
1039164	1	53.0	4.75	482758.30161748186
1039164	1	53.0	5.0	482736.2671027264
1039164	1	52.75	3.0	482772.9912939855
1039164	1	52.75	3.25	482765.6464557337
1039164	1	52.75	3.5	482750.95677923004

```
%%%load Pressurelevel

ll=fopen('level.txt');
formatspec='%f %f';
l=textscan(ll,formatspec,'Headerlines',1);
Pressurelevel=cell2mat(l);
fclose(ll);
```

level

level	level
1	1
2	2
3	3
5	5
7	7
10	10
20	20
30	30
50	50
70	70
100	100
125	125
150	150
175	175
200	200
225	225
250	250
300	300
350	350
400	400
450	450
500	500
550	550
600	600
650	650
700	700
750	750
775	775
800	800
825	825
850	850
875	875
900	900
925	925
950	950
975	975
1000	1000

```
%%%load relative humidity

rr=fopen('r.txt');
formatspec='%f %f %f %f %f';
rrr=textscan(rr,formatspec,'Headerlines',1);
relativehumidity=cell2mat(rrr);
fclose(rr);
```

r

time	level	latitude	longitude	r
1039164	1	53.0	3.0	1.246414467459544 5E-4
1039164	1	53.0	3.25	1.2464144674595445E-4
1039164	1	53.0	3.5	1.2464144674595445E-4
1039164	1	53.0	3.75	1.2464144674595445E-4
1039164	1	53.0	4.0	1.2464144674595445E-4
1039164	1	53.0	4.25	1.2464144674595445E-4
1039164	1	53.0	4.5	1.2464144674595445E-4
1039164	1	53.0	4.75	1.2464144674595445E-4
1039164	1	53.0	5.0	1.2464144674595445E-4
1039164	1	52.75	3.0	1.2464144674595445E-4
1039164	1	52.75	3.25	1.2464144674595445E-4
1039164	1	52.75	3.5	1.2464144674595445E-4
1039164	1	52.75	3.75	1.2464144674595445E-4
1039164	1	52.75	4.0	1.2464144674595445E-4
1039164	1	52.75	4.25	1.2464144674595445E-4
1039164	1	52.75	4.5	1.2464144674595445E-4
1039164	1	52.75	4.75	1.2464144674595445E-4
1039164	1	52.75	5.0	1.2464144674595445E-4
1039164	1	52.5	3.0	1.2464144674595445E-4

MATLAB CODE 2

```
%%%%% Separate the parameters

r=relativehumidity(:,5);
z=geopotential(:,5);
t=temperature(:,5);
lat=latitude(:,1);
long=longitude(:,1);
level=Pressurelevel(:,1);
h=z./(9.8); %%Convert Geopotential to Height

%Creat Meshgrid for 2D Interpolation

[latmeshgrid,longmeshgrid]=meshgrid(lat,long);
%Station coordinates
ydelf=4.3874583;
xdelf=51.9860194;
zdelf=-0.152;

%interp 2D temperature

for i=1:37
    t_layers(1:81,i)=t(i*81-80:i*81,1);
   for j=1:9
    t_regular(1:9,j,i)=t_layers((9*j)-8:9*j,i);
   end
t_interp2(i,1:9)=interp2(latmeshgrid,longmeshgrid,t_regular(:,:,i),xdelf,ydelf,'spline');
end

%interp 2D relativehumidity

for i=1:37
    r_layers(1:81,i)=r(i*81-80:i*81,1);
   for j=1:9
    r_regular(1:9,j,i)=r_layers((9*j)-8:9*j,i);
   end
r_interp2(i,1)=interp2(latmeshgrid,longmeshgrid,r_regular(:,:,i),xdelf,ydelf,'spline');
end

%%%interp 2D Height

for i=1:37
    h_layers(1:81,i)=h(i*81-80:i*81,1);
   for j=1:9
    h_regular(1:9,j,i)=h_layers((9*j)-8:9*j,i);
   end
h_interp2(i,1)=interp2(latmeshgrid,longmeshgrid,h_regular(:,:,i),xdelf,ydelf,'spline');
end '
```

MATLAB CODE 3

```
%%plot internalized parameters

for i=1:37
 mesh(latmeshgrid,longmeshgrid,t_regular(:,:,i));
 mesh(latmeshgrid,longmeshgrid,r_regular(:,:,i));
 mesh(latmeshgrid,longmeshgrid,h_regular(:,:,i));
end
t_interpolation=t_interp2(:,1);
r_interpolation=r_interp2(:,1);
h_interpolation=h_interp2(:,1);

%Calculate the actual water vapor pressure

tcel=t_interpolation-273;   % kelvin-273=celcius
for i=1:37
   Ps(i,1)=6.11*exp(17.27*tcel(i,1)/(237.3+tcel(i,1)));% saturation vapor pressure
   P(i,1)=r_interpolation(i,1)*Ps(i,1)/100; %the actual water vapor pressure
end

%1D interpolation parameters

r_interp=interp1(h_interpolation,r_interpolation,zdelf,'spline'); %Station relativehumidity
t_interp=interp1(h_interpolation,t_interpolation,zdelf,'spline'); %Station temperature
p_interp=interp1(h_interpolation,level,zdelf,'spline');%Station Height

%%%Estimation ZTD
%constant values

k1=77.604;
k2=64.79;
k3=3.776*(10^5);
for i=1:36
    Pmean(i,1)=((P(i,1)+P(i+1,1)))./2; %Average water vapor pressure
    Tmean(i,1)=(((t_interp2(i,1)+t_interp2(i+1,1)))./2);%Average temperature
    Levelmean(i,1)=(level(i,1)+level(i+1,1))./2;%Average pressure Levels
    dz(i,1)=(h_interp2(i+1,1)-h_interp2(i,1)); %Height between layer
    Nd(i,1)=k1*(Levelmean(i,1)./(Tmean(i,1))); %Dry tropospheric delay
    Nw(i,1)=k2*(Pmean(i,1)./Tmean(i,1))+k3*(Pmean(i,1)./((Tmean(i,1))^2));%Wet tropospheric
delay
    ZTD=(sum(-1*(10^-6*Nd.*dz))+sum(-1*(10^-6*Nw.*dz))); %%-1 because of Delay

%%%% Step 2_____Calculate ZHD using the experimental formula

ZHDs=(0.002277*p_interp)/(1-0.0026*cosd(2*ydelf)-0.00000028*(zdelf));
```

MATLAB CODE 4

```
%%%Step 3_____Calculate Zenith Wet Delay

ZWD=ZTD-ZHDs;

%%%Step 4_____read IGS file

DELF=fopen('dlf11790.18zpd');
formatspec='%s %s %f %f %f %f %f %f';
fileIGS=textscan(DELF,formatspec,'Headerlines',44);
fclose(DELF);
b=fileIGS(:,3);
ZTD_I=b{:,:};
ZTD_IGS=ZTD_I(145,1);
Difference=ZTD_IGS./1000-ZTD; %1000 because of Unit

%%% Step 5____Calculate Percipitable Water Vapor (PWV)

%%% Calculate Tm

for i=1:36
soorat(i,1)=((P(i,1)+P(i+1,1))/2)/((t_interpolation(i,1)+t_interpolation(i+1,1))/2);
makhraj(i,1)=((P(i,1)+P(i+1,1))/2)/(((t_interpolation(i,1)+t_interpolation(i+1,1))/2)^2);
end
dzz=dz(:,1);
sorat=soorat(:,1).*dzz(:,1);
makh=makhraj(:,1).*dzz(:,1);
sigma_soorat=sum(sorat); % Integral
sigma_makhraj=sum(makh); % Integral
Tm=sigma_soorat./sigma_makhraj;
Rv=461.5; % Gas constant of water vapor
DW=997; %Density water
k_prim=24;
coefficient=(10^6)/(DW.*Rv.*((k3./Tm)+k_prim));
pwv=coefficient.*ZWD(1,1);


%%%%THE END%%%%
%%Written by Mahdieh Nezamzadeh
```