FORWARD SCATTER AIRCRAFT DETECTION WITH AMATEUR RADIO NETWORK WSPRNET

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Abstract — Using reflections off the Earth's ionosphere, a layer of electrons in the upper atmosphere formed from the sun's radiation, radio waves can travel long distances. This enables Over-The-Horizon-Radar (OTHR), to perform surveillance at long ranges. Following the disappearance of MH370, Weak Signal Propagation Reporter Network (WSPRnet), a record of amateur radio transmissions, has been suggested to be used to locate the missing aircraft. Unlike traditional OTHR systems, which are large, high-power, expensive and located at single locations, amateur radio stations are small, low-power, inexpensive, and distributed over a global network. Despite the weaker amateur radio transmissions, detection may still be possible using the forward scatter phenomenon. This is due to signal gain from larger forward scatter radar cross section (RCS) and long integration time. To use WSPRnet as a network of forward scatter radars for air surveillance, we detect signal anomalies due to aircraft between a pair of transmitting and receiving stations, then locate the intersection of anomalous links. We study the feasibility of such a system empirically using signal records from WSPRnet, historical flight data from flightradar24 and ionosphere propagation prediction tool VOACAP. We also examined the system power budget and the forward scatter RCS for a theoretical analysis.

I. INTRODUCTION

While traditional Over-The-Horizon-Radars (OTHRs) allow for air surveillance at long distances, using reflections off the Earth's ionosphere, they are typically large, high power, expensive, and fixed to single locations. In contrast, a network of small, low power, inexpensive, globally distributed amateur radio transmitter-receivers, such as the Weak Signal Propagation Reporter Network (WSPRnet) may also be used for long range air surveillance [6, 7]. In addition, the forward scatter phenomenon provides a larger forward scatter radar cross section (RCS) and longer integration time which melds nicely with the WSPR protocol, improving the feasibility of using WSPRnet for air surveillance [1, 9].

To detect and localize an aircraft using data from WSPRnet, existing literature suggests drawing trip lines between trans mitting and receiving amateur radio stations, detecting signal anomalies, and locating intersections of multiple anomalous links [6, 7]. Existing case studies attempt to match anomalous intersections to aircraft, but with the large number of detections generated in existing algorithms and the large number of aircraft around the world, it is not valid to conclude based upon existing work that WSPRnet can be used to detect and localize aircraft.

The ionosphere has been observed that to be stable for aircraft detection using HF skywave OTHR [12]. Detecting multiple aircraft in a range over 6000km using the Doppler shifted carrier of AM radio broadcasts has been shown to be possible [3]. Improvements to coordinate registration of aircraft to 10km root mean squared error (RMSE) using ionosphere height and tilt corrections computed from the scattering of known reference points (KRPs) has also been demonstrated [4]. Signal anomalies have been observed when aircraft intersect WSPR links [7]. An existing algorithm, called Global Detection and Tracking of Aircraft Anywhere Anytime (GDTAAA), takes into account 3D intersection geometry, using ionosphere propagation ray-tracing and aircraft cruising altitude, demonstrated WSPR detection of aircraft via case studies. In the same study, it was also observed that WSPR is a noisy sensor with an area under receiver operator characteristics curve (AUC) of approximately 60% [7].

On the other hand, it has been theorized that WSPR for aircraft detection is feasible but not at the long distance and low power claimed by the authors of GDTAAA. Various noise sources, Doppler rate, aircraft scattering, signal propagation characteristics, and the minimum SNR of-30 dB needed to decode WSPR signals, were not considered [10, 11]. In addition, other sources of information such as KiwiSDR, also used by amateur radio operators, were not considered [13].

To the best of our knowledge, existing algorithms are not extensively researched and have not been successfully replicated. In this work, we attempt to verify the utility of WSPRnet as an air surveillance tool by accounting for inaccuracies in existing work and by improving on existing algorithms, with empirical and theoretical justification.

The outline of the paper is as follows: we first recap the relevant background on skywave propagation and forward scatter in Section II. We then detail the algorithms and improvements in Section III. The empirical results and theoretical analysis are presented in Section IV. Finally, we summarize the paper with a discussion of the limitations and future work in Section V.

II. BACKGROUND

High frequency (HF) band (3 to 30MHz) extends the radar range beyond the horizon, 1,000 km to 3,700 km, using skywave propagation, where the ionosphere can be thought of as a 'mirror', as shown in Fig. 1.

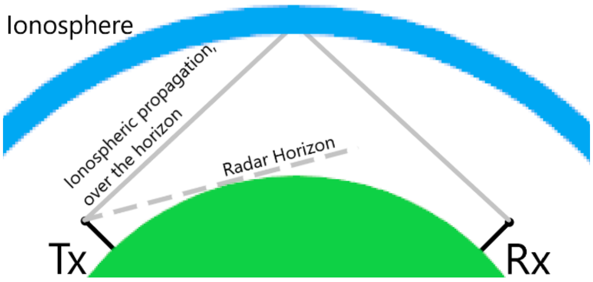


Figure 1: Skywave propagation with the ionosphere as a 'mirror'.

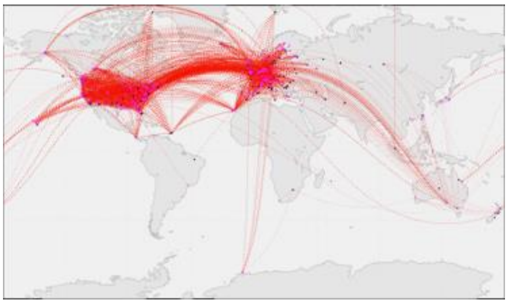


Figure 2: Links between transmitting and receiving stations of the Weak Signal Propagation Reporter Network (WSPRnet) [5].

Figure 3: Global flight routes line up with links of WSPRnet [5].

Weak Signal Propagation Reporter (WSPR) is a protocol for communications between amateur radio operators (opportunistic, small, low power, low cost). The distribution of WSPR operators aligns with global flight routes, especially in Europe and North America, as shown in Fig. 2 and 3. When an aircraft intersects a signal propagation path, anomalies in signal strength —due to interference of the direct signal and scattered signal —and frequency — due to Doppler shift from the aircraft's velocity — may be observed, such as in Fig. 4. Intersecting of these anomalous links localizes the aircraft, as shown in Fig. 5.

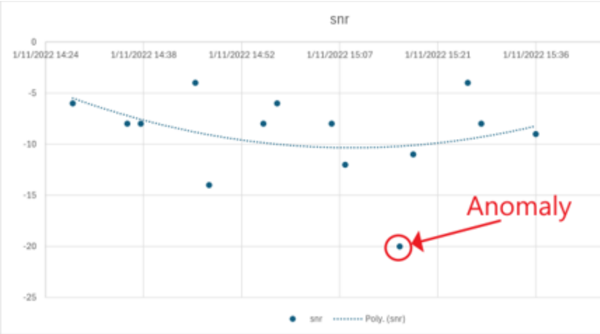


Figure 4: An example of a signal strength anomaly in a WSPR link. The x-axis is time, the y-axis is the signal-to-noise ratio (SNR) in decibels (dB).

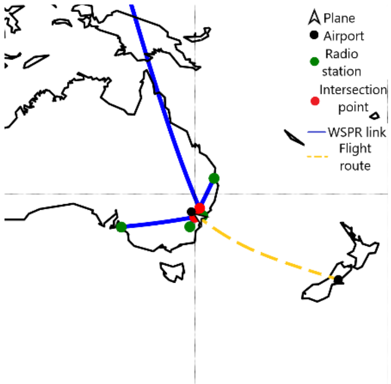


Figure 5: An example of aircraft detection and localization using multiple anomalous links

WSPRlinks are usually assumed to propagate via the shortest great-circle path. However, although unlikely, signals may also propagate via the longer great-circle path. Existing work considers both short path and long path propagation in their algorithms [6], an assumption that needs to be verified.

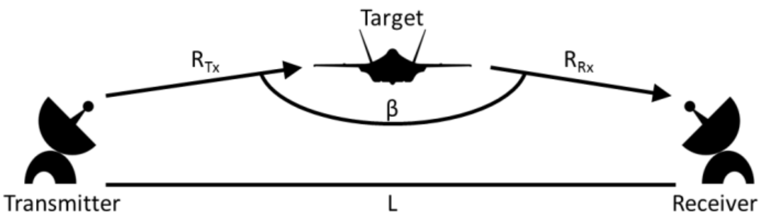


Figure 6: Forward scatter radar (FSR) geometry [2].

A forward scatter radar (FSR) is a bistatic radar with a bistatic angle approaching 180 degrees, as shown in Fig. 6. Taking advantage of Babinet's principle, this results in much higher RCS, which is coherent over a long integration time [2, 9].

III. METHOD

We first present a general algorithm for detecting signal anomalies and locating the short path intersection of multiple anomalous links, then present our improvements on the general algorithm. Details of the algorithms can be found in the Appendix, the code is also available at https://github.com/cadenlyy/WSPR.

A. General Algorithm

1) Data Collection and Anomaly Detection: We pull data from https://wspr.live/ and group the records by receiver, transmitter and band, to form time series of SNR, frequency and

their squares. We then compute the sliding mean and standard deviation and identify disturbances using a threshold on the standard score.

2) Location Estimation: For the same time instance, we find points of short path intersections of multiple anomalous links, using a line sweep. We only use short path intersections to 2 account for the deficiencies in existing algorithms mentioned in literature [10]

B. Improvements on General Algorithm

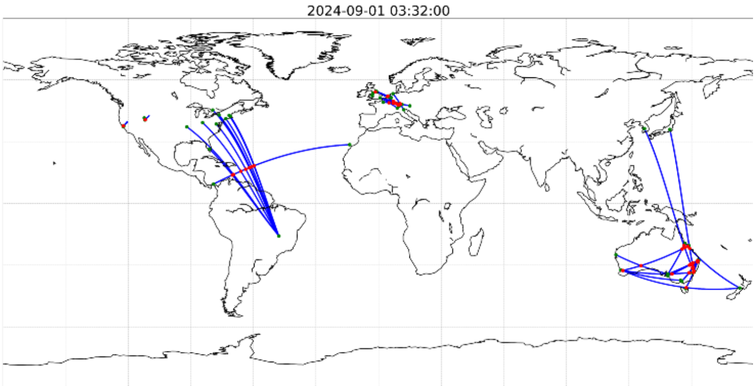


Figure 7: Plot of short path intersections.

Due the use of only short path intersections, very few intersections are generated. Furthermore, these intersections are located near clusters of WSPR stations, and since these clusters coincide with major flight routes, it is difficult to associate intersections to aircraft, making it impossible to detect or track specific aircraft. An example of considering only short path intersections is shown in Fig. 7.

To generate more intersections and consider more propagation paths, we include long path intersections with SNR >-30dB, calculated from an optimistic power budget detailed in Section IV-B2.

While existing studies computed SNR anomalies from units in decibels (dB), to highlight the anomalies, we computed SNR anomalies from units in watts (W). While existing studies considered the frequency drift record in WSPR, the estimation of this quantity is typically inaccurate and excluded in our algorithm.

Existing work, focusing on case studies, first finds an aircraft, then locates all intersections within 3.7 km of the aircraft [7]. This is not possible in a system whose objective is to detect aircraft. In addition, the 3.7 km radius is possible as they have a database of antenna locations accurate up to ±3.7 km.

As we do not have these antenna locations, we are limited to using the 6 character maidenhead grid codes, our location accuracy is thus at best ±5 km. We verify aircraft detection by comparing to historical flight data from flightradar24 with a detection window of ±5 km from the transmitter-receiver ’trip-line’.

IV. RESULTS

We first present the results of our empirical study followed by a theoretical analysis.

A. Empirical Study

1) Detecting SNR and Frequency Anomalies:

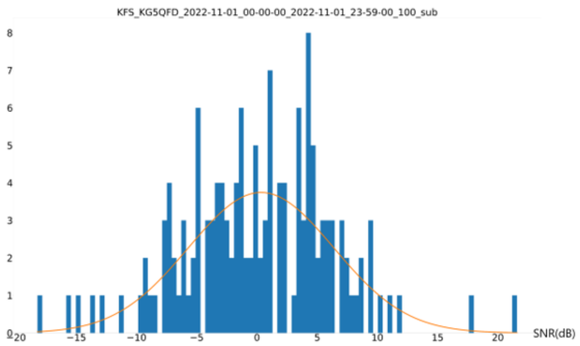


Figure 8: Histogram of SNR(dB) between KFS and KG5QFD.

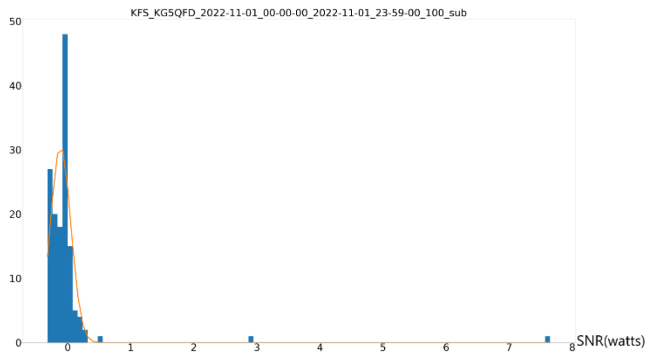


Figure 9: Histogram of SNR(W) between KFS and KG5QFD.

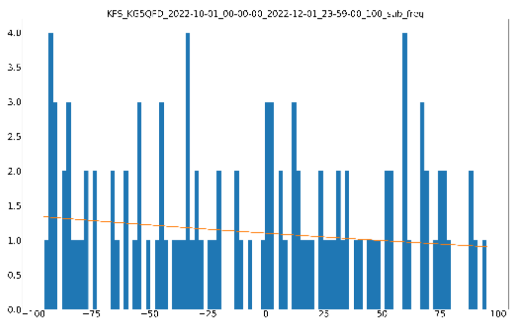


Figure 10: Histogram of frequency between KFS and KG5QFD.

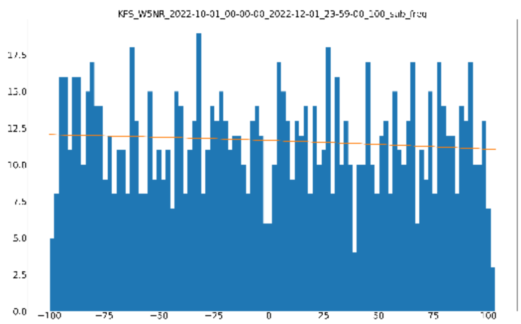


Figure 11: Histogram of frequency between KFS and W5NR.

To verify that we can use a threshold on the standard score to find anomalies, we need to verify that the data is unimodal and that there is a significant distance between the bulk of the distribution and anomalies. We first compute the data trend using a moving average of 100 data points and then subtract the trend from the data to account for changes in ionospheric conditions. We then plotted a histogram and curve fit on the detrend data.

For SNR, we can see in Fig. 8 that SNR in units of decibels form a unimodal distribution. Furthermore, from Fig. 9 we can see that anomalies are highlighted when we represent SNR in units of Watts.

For frequency, we have to take note to use only data from the same transmission band. To compensate for the reduction in data points, we used a longer data window. Fig. 10 and Fig. 11 show that the frequency data is spread and not unimodal, thus anomalies are difficult to detect.

2) Removing Detections with Calculated SNR < −30dB: GDTAAA uses all long and short path intersections, without checking the feasibility of detections at long distances [8]. This would create around a 50% error rate, as great-circles intersect at 2 opposing points. For every intersection that may correspond to an aircraft, there would be another intersection that does not correspond to any aircraft. This is observed in Fig. 12 where points are reflected about an axis due to this aliasing.

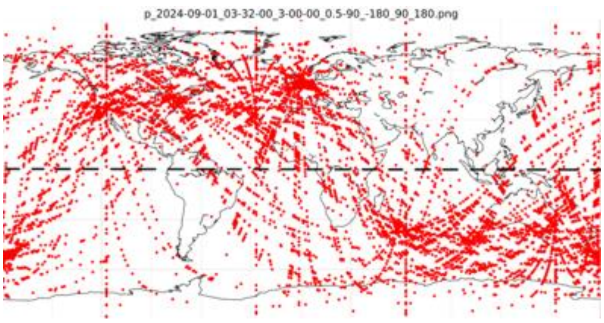


Figure 12: Plot of all intersections with >0.5 standard score

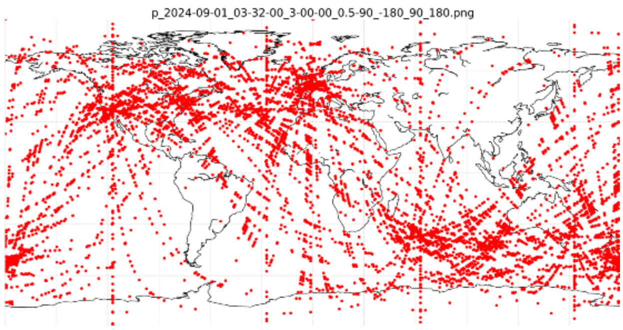


Figure 13: Plot of possible intersections with >0.5 standard score, based on calculated SNR > −30dB.

It can also be seen that the points are mainly around clusters of WSPR stations and do not correspond to major flight routes, especially in Asia. Furthermore, we calculated a drop in the number of intersections from 12324 points in Fig. 12 to 11804 points in Fig. 13 when accounting for an optimistic calculated SNR of at least <-30dB. This shows that at least 520 points will not have been possible.

3) Minimum Distance from Aircraft to Intersection:

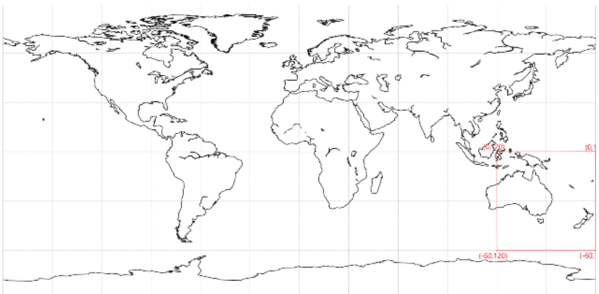


Figure 14: Window on Australia

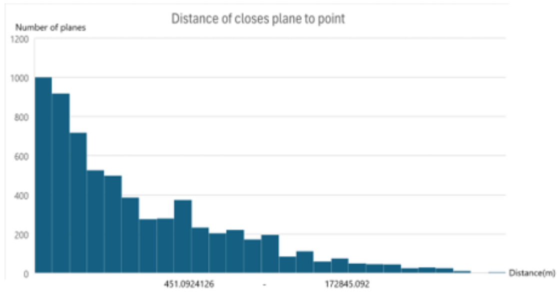


Figure 15: Histogram of minimum distance between aircraft and intersection for the window on Australia.

Using Australia as an example of a place with fewer WSPR links and flights, data from latitude [-60, 0], longitude [120, 180], 30min on 4/12/2024. The average minimum distance between an aircraft and an intersection is 345713m with the minimum of 450m and a maximum of 1687350m. The large range of distances is likely due to the low amount of links and aircraft in the area. For future research, a comparison to a location with more links and aircraft, such as Europe or North America, should be conducted.

4) Verifying QTR901 Case Study [7]:

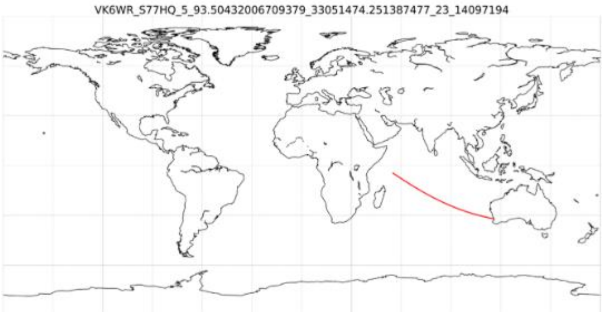
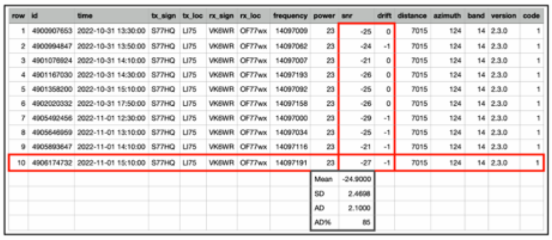


Figure 16: WSPR link between S77HQ and VK6WR.



row	id	time	tx_sign	tx_loc	rx_sign	rx_loc	frequency	power	snr	drift	distance	azimuth	band	version	code
1	4900907653	2022-10-31 13:30:00	S77HQ	LI75	VK6WR	OF77wx	14097009	23	-25	0	7015	124	14	2.3.0	1
2	4900994847	2022-10-31 13:50:00	S77HQ	LI75	VK6WR	OF77wx	14097062	23	-24	-1	7015	124	14	2.3.0	1
3	4901076924	2022-10-31 14:10:00	S77HQ	LI75	VK6WR	OF77wx	14097007	23	-21	0	7015	124	14	2.3.0	1
4	4901167030	2022-10-31 14:30:00	S77HQ	LI75	VK6WR	OF77wx	14097193	23	-26	0	7015	124	14	2.3.0	1
5	4901358200	2022-10-31 15:10:00	S77HQ	LI75	VK6WR	OF77wx	14097092	23	-25	0	7015	124	14	2.3.0	1
6	4902020332	2022-10-31 17:50:00	S77HQ	LI75	VK6WR	OF77wx	14097158	23	-26	0	7015	124	14	2.3.0	1
7	4905492456	2022-11-01 12:30:00	S77HQ	LI75	VK6WR	OF77wx	14097000	23	-29	-1	7015	124	14	2.3.0	1
8	4905646959	2022-11-01 13:10:00	S77HQ	LI75	VK6WR	OF77wx	14097034	23	-25	-1	7015	124	14	2.3.0	1
9	4905893647	2022-11-01 14:10:00	S77HQ	LI75	VK6WR	OF77wx	14097116	23	-21	-1	7015	124	14	2.3.0	1
10	4906174732	2022-11-01 15:10:00	S77HQ	LI75	VK6WR	OF77wx	14097191	23	-27	-1	7015	124	14	2.3.0	1
								Mean	-24.9000						
								SD	2.4698						
								AD	2.1000						
								AD%	85						

Table 43: SNR Anomalous WSPRnet link S77HQ to VK6WR at position 15:10 UTC.

Figure 17: Data and anomaly of WSPR link between S77HQ and VK6WR from [7].

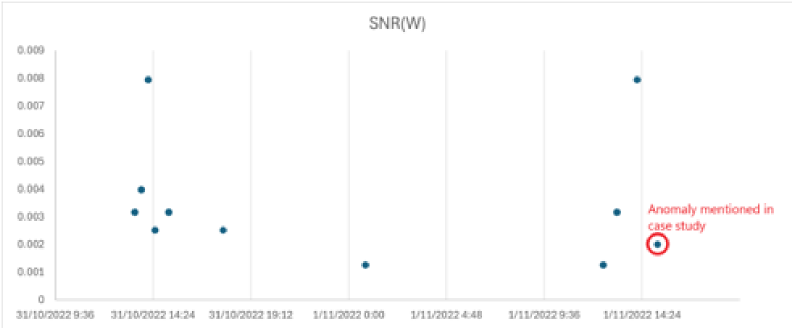


Figure 18: SNR data of WSPR link between S77HQ and VK6WR.

We analysed the case study in [7]. Only 1 intersection, from the WSPR link between S77HQ and VK6WR, as shown in Fig. 16, was from short path propagation. Taking a look at the data, there were no more records during the duration of the flight after the last record at 15:10, right as the aircraft takes off. This last record also happens to be flagged as an anomaly in the study, as shown in Fig. 17. However from a plot of the data, as shown in Fig. 18, the record does not appear to be anomalous.

B. Theoretical Study

1) Doppler Shift: When an aircraft's flight path intersects the signal propagation path, the frequency will be shifted due to the Doppler effect, creating anomalies. This Doppler shift can be calculated for HF band to be within ±25 Hz using the following equation:

$$f_d = 2 f_c \frac{v}{c} \tag{1}$$

where f_d is the Doppler frequency, f_c is the carrier frequency, v is the relative velocity of the aircraft and c is the speed of light.

2) Signal-to-Noise Ratio (SNR): To verify that a signal can be decoded by WSPR, we ensure that the signal to noise ratio is more than-30dB. The equation used to calculate this is can be derived using the radar equation. Firstly, the power reaching the target P_{TxTgt} from the transmitter is:

$$P_{TxTgt} = \frac{P_{Tx} G_{Tx}}{4\pi R_{TxTgt}^2} \tag{2}$$

Where P_{Tx} is transmission power, G_{Tx} is gain of transmitter's antenna and R_{TxTgt} is the distance from transmitter to target.

The power reaching the receiver through the target can then be calculated to be:

$$P_{TxTgt}P_{RxTgt}A_{effRx} = \frac{P_{Tx}G_{Tx}}{4\pi R_{TxTgt}^2}\frac{\sigma}{4\pi R_{TgtRx}^2}\frac{G_{Rx}\lambda^2}{4\pi} \quad (3)$$

where P_{TgtRx} is the power from target to receiver, A_{effRx} is the aperture of the receiver's antenna, σ is RCS of target, R_{TgtRx} is distance from target to receiver, G_{Rx} is the gain of receiver's antenna and λ is wavelength of signal.

The power reaching the receiver directly from the transmitter can also be calculated by:

$$P_{TxRx}A_{effRx} = \frac{P_{Tx}G_{Tx}}{4\pi R_{TxRx}^2}\frac{G_{Rx}\lambda^2}{4\pi} \quad (4)$$

We considering the noise from thermal agitation which is given by:

$$N = kTBF_n \quad (5)$$

where k =1.38×10^{-23} J/deg, T = 290K, B is the bandwidth in Hz and F_n is the noise factor

We can calculate an SNR where power of forwards scattered signal is similar to that of the direct signal to be,

$$SNR = 10log_{10}(\frac{P_{DP}P_{Tgt}}{(P_{DP}+P_{Tgt})P_N}) \quad (6)$$

where $P_{DP} = P_{TxRx}A_{effRx}$, $P_{Tgt} = P_{TxTgt}P_{TgtRx}A_{effRx}$, $P_N = kTBF_n$.

Otherwise, if power of forward scattered signal is much weaker than the direct signal, SNR is,

$$SNR = 10log_{10}(\frac{P_{Tgt}}{P_n}) \quad (7)$$

We take the maximum of the above two SNRs, and include a coherent integration gain of 30 seconds — a third of the WSPR integration time of 110.6s — for an additional $10log_{10}(30)$ = 14.8 dB gain. On the other hand, from a preliminary calculation, it is possible for the aircraft to remain within the forward scatter main lobe during the entire integration time of 110.6s.

3) Forward Scatter Radar Cross Section: Existing methods use the RCS of 45dBm2 for a Boeing 777 at 14MHz [5]. To verify this we make a comparison of a Boeing 777 at HF, to a Cessna-172 at FM using the ratio of lengths and frequencies to calculate the forward scatter RCS:

$$\sigma = \frac{4\pi A^2}{\lambda^2} \quad (8)$$

From the equation for FSRCS (8), a ratio of FM at 93MHz frequency to HF at 14MHz, will result in an RCS 44 times smaller. On the other hand, the Cessna-172 has a length of 8.28m, and a height of 2.72m. The Boeing 777 has a length of 73.9m, and a height of 18.5m, resulting in an RCS 3685 times bigger. Thus, the net increase is 83 times. Compared to 22dBm^2 RCS at 93MHz for Cessna-172 [1], the RCS of a Boeing 777 is 41dBm^2 at 14MHz. Thus, using an RCS of 45dBm^2 would be valid. Repeating the calculations for the FSRCS of a Cessna-172 from literature at 223Mhz and 650Mhz of 30dBm^2 and 37dBm^2 [1], yield similar results.

4) Maximum Possible Propagation Distance for Detecting Aircraft: We can invert the radar equation to compute the maximum possible signal propagation distance for detecting aircraft. We use a frequency of 14MHz, RCS of 45dBm^2, integration time of 30s, temperature of 290K, bandwidth of 6Hz, transmission power of 1W, gain of Rx and Tx antenna of 0, a noise figure of 0 and a minimum SNR of-30dB.

To consider the distance increase due to the signal hopping between the ionosphere and the Earth, we first take the transmitter as the north pole, and let $\overrightarrow{p1}$ be the vector from the center of the earth to the transmitter and $\overrightarrow{p2}$ to be the vector from the the center of the earth to the point of reflection on the first hop.

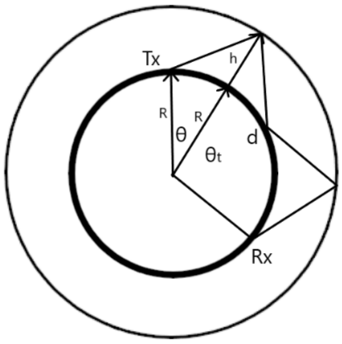


Figure 19: Ionospheric propagation diagram

$$\overrightarrow{p1} = [0, R]^T \tag{9}$$

$$\overrightarrow{p2} = [(R+h)\sin\theta, (R+h)\cos\theta]^T \tag{10}$$

Subtracting these 2 vectors and finding the magnitude of the resultant vector gives us the half the distance travelled in 1 hop.

$$d_h = \sqrt{2R(R+h)(1-\cos\frac{d}{2Rn}) + h^2} \tag{11}$$

Where $n >= \frac{d}{2R\cos^{-1}\frac{R}{R+h}}$, R is the radius of the earth, h is the height of the ionosphere and n is the number of hops.

The maximum propagation distance is calculated to be 19,561,698m when aircraft is in the middle of the baseline between the transmitter and receiver. Accounting for ionosphere reflections and the spherical Earth, the great-circle distance is calculated to be 19,460,143m.

This suggest that long path propagation and detection is indeed possible under ideal circumstances, such as the availability of the ionosphere.

5) Intersection between Skywave Propagation and Cruising Altitude: Ionosphere reflection occurs at about 100km altitude and cruising aircraft are at about 10km altitude. So WSPR signal will only spend around 10% of its propagation time in the same altitude as cruising aircraft [5]. [1]

V. CONCLUSION

We are unable to conclusively verify that data from WSPRnet can be used to detect and localize aircraft. Our preliminary verification suggests that using standard score to find anomalies in SNR could be used to detect a aircraft flying through a WSPR link. However more research needs to be done to incorporate more data to resolve remaining inaccuracies.

A. Limitations

We used antenna locations recorded by WSPRnet which has a ±5km error range from the 6-letter maidenhead grid. We also assumed the earth to be perfectly round leading to further 6 location inaccuracies

The inability to predict signal propagation and hops intro duces uncertainty in dead zones caused by the signals not being at the cruising altitude of aircraft. We also did not consider the variety of antennas and aircraft.

B. Future work

To account for inaccuracies and to gather more data we can look at ray-tracing software, such as PropLab pro, and other sources of data, such as kiwiSDR. We can also acquire more accurate antenna locations and account for the earth not being completely spherical, such as by using the WGS-84 model.

We can extend the preliminary results with more test cases to derive conclusive results, possibly calculating Mean Squared Error (MSE), comparing the distance between aircraft and intersections at different places. And through this possibly come up with a probability model of detection given information on ionosphere, WSPR link and aircraft.

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APPENDIX

We provide details of the algorithm in the appendix, the code is also available at https://github.com/cadenlyy/WSPR.

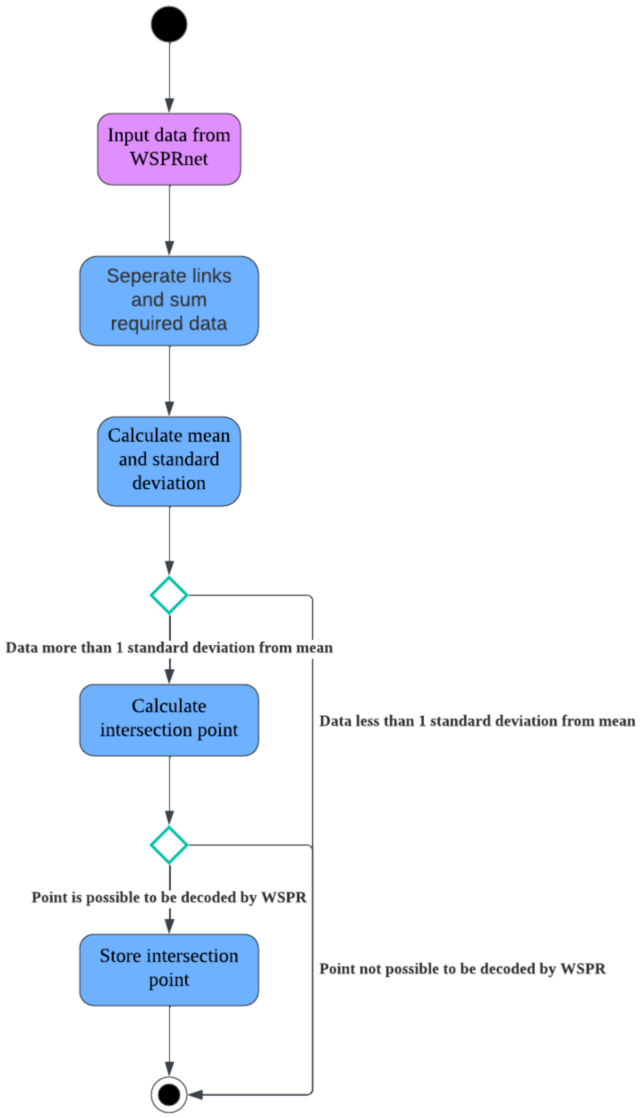

Figure 20: Flowchart of the general algorithm to detect signal anomalies. Multiple anomalous links are then used to localize aircraft.

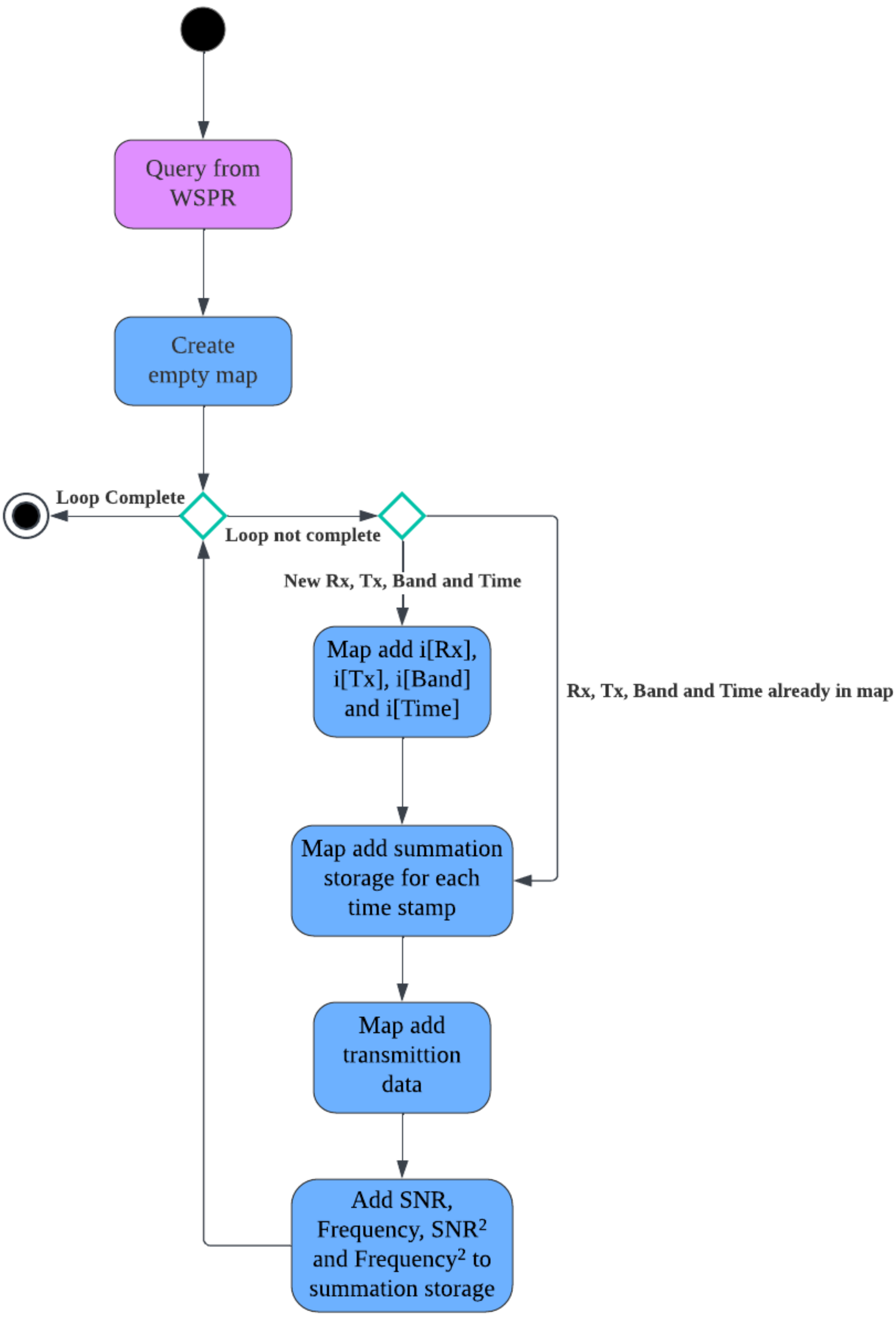

Figure 21: Flowchart for querying and summing data.

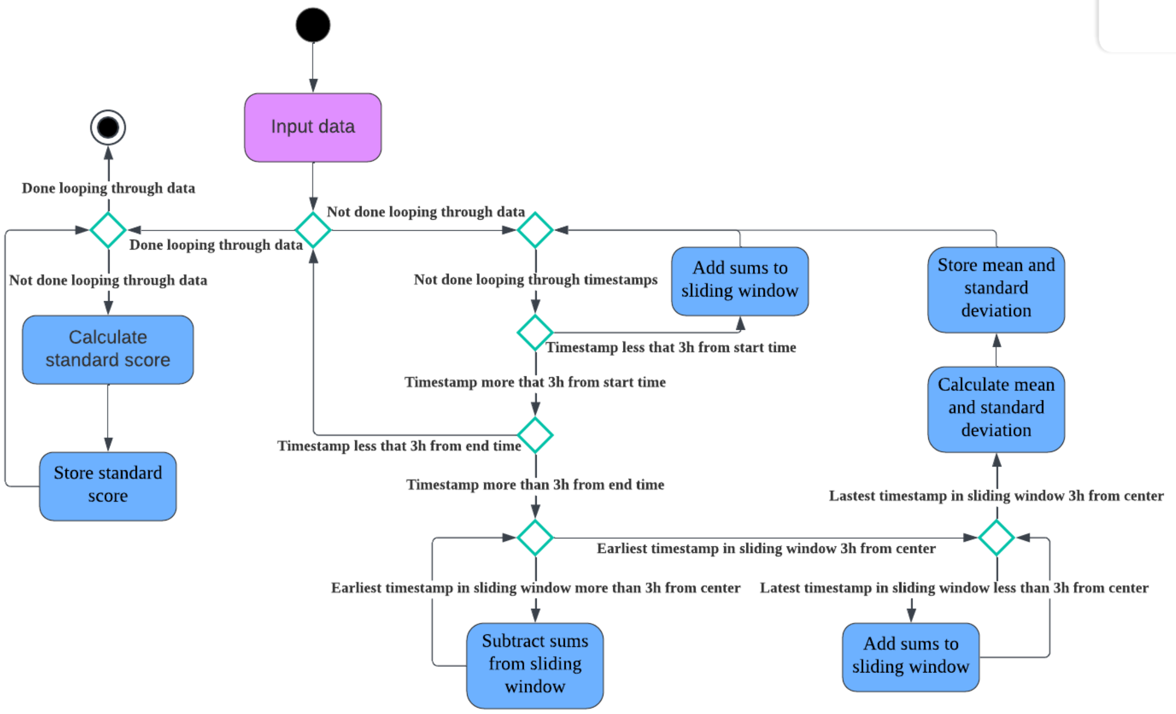

Figure 22: Flowchart for finding anomalies using standard score.

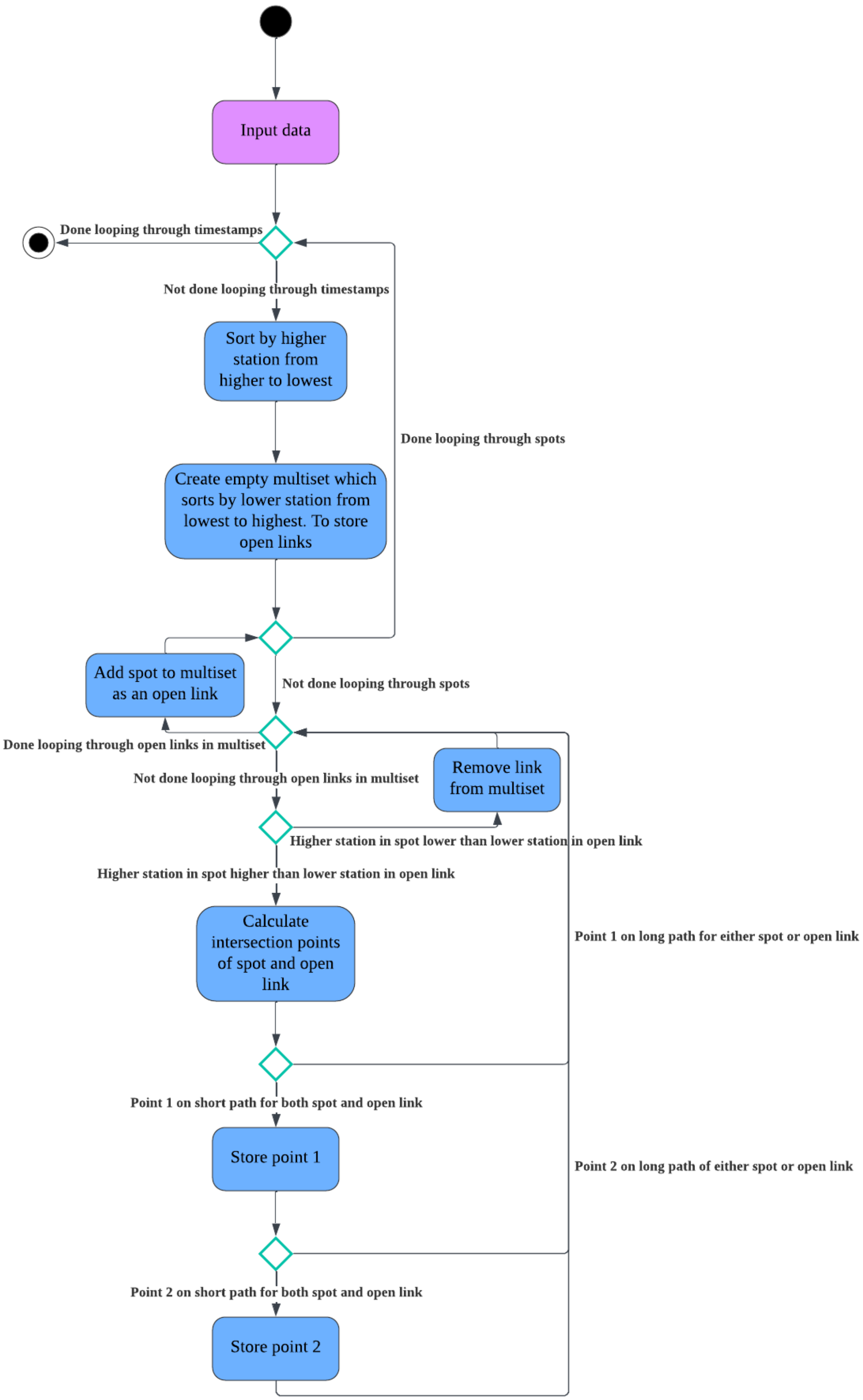

Figure 23: Flowchart for finding short path intersections.

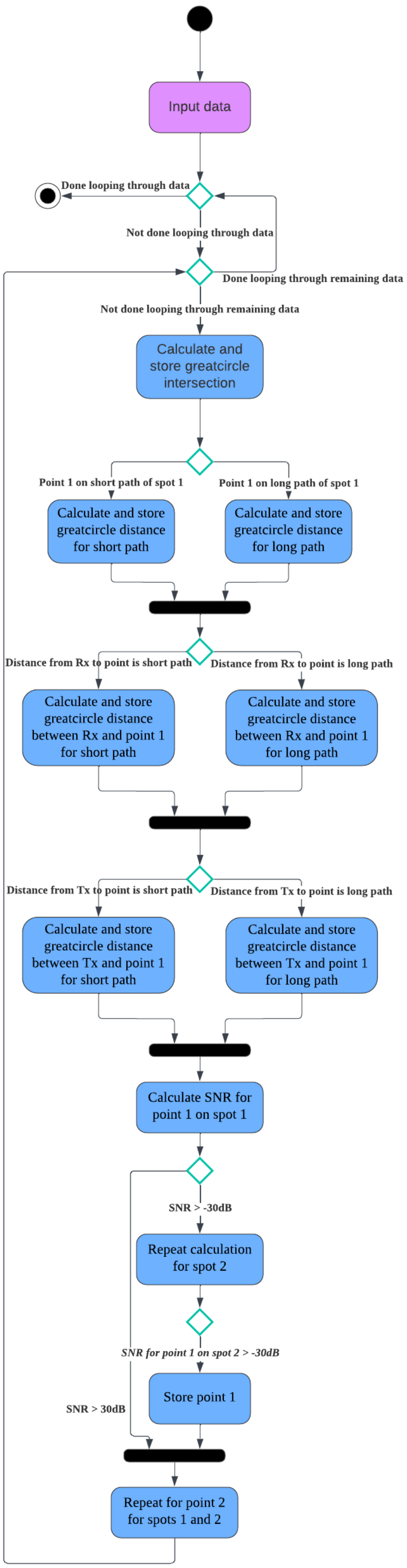

Figure 24: Flowchart for finding intersections with SNR > -30dB.

Algorithm 1 Data collection and summation of data

```
q =QueryFromWSPR
for rx in q do
        if data find i[rx] then
                data ←i[rx]
        end if
        if data[i[rx]] find i[tx] then
                data[i[rx]] ← i[tx] : ()
        end if
        if data[i[rx]][i[tx]] find i[time] then
                data[i[rx]][i[tx]] ← i[time] : ()
        end if
        if data[i[rx]][i[tx]][i[time]] find i[band] then
                data[i[rx]][i[tx]][i[time]] ← i[band] : ([[],[]])
        end if
        data[i[rx]][i[tx]][i[time]][i[band]][data] ← i
        data[i[rx]][i[tx]][i[time]][i[band]][sum][snr]+i[snr]
        data[i[rx]][i[tx]][i[time]][i[band]][sum][ freq]+i[freq]
        data[i[rx]][i[tx]][i[time]][i[band]][sum][snr2]+i[snr2]
        data[i[rx]][i[tx]][i[time]][i[band]][sum][ freq2]+i[freq2]
end for
```

Algorithm 2 Calculation of mean, standard deviation and standard score with sliding window

```
for b in t in r in data do                                  ▷ band in tx in rx in data
    slidingWindow = [0,0,0,0]                               ▷ snr, freq,snr2, freq2
    num=0                                                   ▷ Number of spots
    left =starttime                                         ▷ Left most index
    right = starttime                                       ▷ Right most index
    for time in b do
        if time−starttime < range then
            slidingWindow+time[sum]
            num+lengthoftime[data]
            right =time[time]
        else if end time- time < range then
            break
        else
            for i in b[left to time] do
                if time[time]−i[time] > range then
                    slidingWindow−i[sum]
                    num−length of i
                else
                    left = i[time]
                    break
                end if
            end for
            for i in b[right to end time] do
                if i[time]−time[time] > range then
                    slidingWindow+i[sum]
                    num+length of i
                else
                    right = i[time]
                    break
                end if
            end for
```

time[mean] = $\frac{slidingWindow}{num}$

time[SD] = $\sqrt{\frac{\sum time[data]^2 - time[mean]^2 \cdot num}{num-1}}$

```
        end if
    end for
end for
for i in t in b in t in r in data do:          ▷ spot in time in band in tx in rx in data
    data[i[rx]][i[tx]][i[time]][i[band]][SS] = i[data]−i[mean]
end for
```

Algorithm 3 Check if intersection is on the short path between transmitter and receiver

```
procedure POINT ON SHORT PATH(tx,rx,p)
    lp = min(tx[lon],tx[lon]) )                              ▷ Left point
    rp = max(tx[lon],tx[lon])                                ▷ Right point
    sd = min(rp- lp, 360 + lp- rp                            ▷ Shorter distance
    return sd > |p−lp| and sd >|p−rp|
end procedure
```

Algorithm 4 Finding short path intersections

```
p =[]
for time in data do
    sort(time)
    o =orderedlist
    for i in time do                                         ▷ data
        for j in o do                                        ▷ Links that are open
            if lastnode(j) > firstnode(i) then:
                o.pop()                                      ▷ Removing closed spots
            else
                point = intersectionofgreat −circle(i, j)
                if point[0] on short path of i and j then
                    p ←point[0]
                end if
                if point[1] on short path of i and j then
                    p ←point[1]
                end if
            end if
        end for
        o ←i
    end for
end for
```

Algorithm 5 Calculating intersections of great-circles

```
procedure INTERSECTION GREAT-CIRCLE(rx1,tx1,rx2,tx2)
                                                        ▷ Put in polar coordinates
    xrx1 =cos(rx1[lat])∗cos(rx1[lon])
    yrx1 =cos(rx1[lat])∗sin(rx1[lon])
    zrx1 = sin(rx1[lat])
    xtx1 = cos(tx1[lat])∗cos(tx1[lon])
    ytx1 = cos(tx1[lat])∗sin(tx1[lon])
    ztx1 = sin(tx1[lat])
    Repeat for point 2
                                                        ▷ Find normal of both planes
```

$\overrightarrow{rx1}$ =[xrx1,yrx1,zrx1]
$\overrightarrow{tx1}$ =[xtx1,ytx1,ztx1]
$\overrightarrow{rx2}$ =[xrx2,yrx2,zrx2]
$\overrightarrow{tx2}$ =[xtx2,ytx2,ztx2]
$\overrightarrow{N1} = \overrightarrow{rx1} \times \overrightarrow{tx1}$
$\overrightarrow{N2} = \overrightarrow{rx2} \times \overrightarrow{tx2}$

▷ Find line of intersection between two planes

$L = \overrightarrow{N1} \times \overrightarrow{N2}$

▷ Find two intersection points

$\overrightarrow{X1} = L/\sqrt{L[0]^2 + L[1]^2 + L[2]^2}$

```
    X2=−X1
    lat1 = arcsin(X1[2])
    lon1 =arctan(X1[1] X1[0])
    lat2 = arcsin(X2[2])
    lon2 =arctan(X2[1] X2[0])
    return [lat1, lon1, lat2, lon2]
end procedure
```

Algorithm 6 Calculation of SNR

```
procedure SNR CALCULATION(rtx,rrx,Dgctotal)
    N =round up(Dgctotal/(2Rarccos(R/R+H))))
    noise = 10log(kt0B)
    signal = p − 30 + 20logλ + 10logσ − 30log(4π) − 20log(rrx)−20log(rtx)+10log(N)
    return signal −noise
end procedure
```

```
Algorithm 7 Finding possible long and short path intersection
p =[]
for i in t do                                                        ▷ data at each timestamp
    for j in t[i:] do                                          ▷ data that has not been compared
        point = intersect great −circle(i, j)                              ▷ point 1 link 1
        if rx−tx > point[0]−rx and > point[0]−tx then              ▷ point[0] on short path
            Dgctotal11 = sp calculation
        else
            Dgctotal11 = 2·π ·R−sp calculation
        end if
                                                 ▷ ensuring correct distance from rx to target
        if point[0] − tx > rx −txandpoint[0] − tx > rx − point[0] then
            Rrx11 =short path calculation
        else
            Rrx11 =2·π·R−short path calculation
        end if
                                                 ▷ ensuring correct distance from tx to target
        if point[0] − rx > rx −tx and point[0] − rx > rx − point[0] then
            Rtx11=short path calculation
        else
            Rtx11=2·π·R−short path calculation
        end if
        SNR11=SNR calculate(data)
        if SNR11 >−30 then
            Repeat with spot 2
            if SNR12 >−30 then
                p ←point[0]
            end if
        end if
        Repeat with point 2
    end for
end for
```