Aircraft Scatter on VHF, UHF, and Microwave Frequencies: Increasing Understanding and Using Improved Tools to Increase Communications Distance and Maximize Success
   by Roger Rehr, W3SZ

I. Basics and Review This paper is an update to a paper first given in 2014 [1]. A link to that paper is provided as the first reference so that the reader can review that document prior to beginning this one.

Aircraft Scatter (AS) is defined for our purposes as the use of aircraft to redirect or "scatter" RF that would otherwise be lost in space in order to increase communications distance and received signal strength over what would otherwise be possible.

Aircraft Scatter was accidentally discovered in 1930 by L.A. Hyland at the U.S. Naval Research Laboratory in June, 1930 using a CW signal at approximately 33 MHz. The first mention of aircraft scatter in the amateur radio literature that I could find was by Henry Root, W1QNG, in QST in 1967 [2]

Aircraft scatter has been widely used by radio amateurs in Europe, and at the antipodes Rex Moncur, VK7MO has been extremely active both with the practice of AS, extending QSO range to 842 km on 10 GHz and to 427 km on 24 GHz [3] and also with the publication of several excellent theoretical papers on the subject [4]. Guy Fletcher, VK2KU also wrote an excellent theoretical paper on this subject [5]

Bistatic Radar Equation The description of AS path loss is based on the bistatic radar equation. Bistatic radar is radar that uses separate sites for the transmitter and the receiver, as is shown below:

RADAR HORIZON
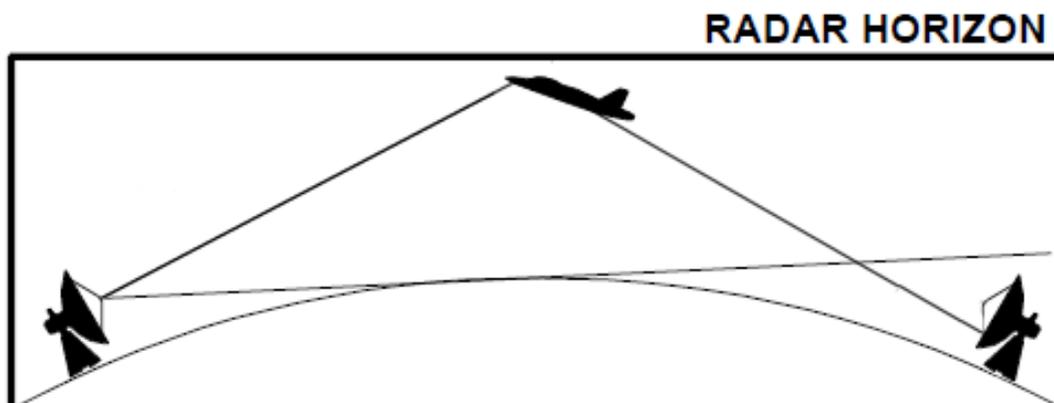
The bistatic radar path loss equation, expressed in dB, is:

L = 10 log((lambda**2)*S/(((Rt**2)*(Rr)**2))) − 153

where:
L = total loss (dB)
Rt = distance from transmitter to reflector (km)
Rr = distance from receiver to reflector (km)
Lambda = wavelength (m)
S = radar cross section of aircraft (sq m)

As an example, for lambda = 2M

with an aircraft at the midpoint of the path between two stations 900 km apart and therefore with Rt = Rr = 450km

and with S = 63 (the value used for a Boeing B747)

this equation gives AS Path Loss = - 235 dB. This compares with a Free Space Loss of -135 dB, a Troposcatter Loss of -241 dB (with take off angle 0 degrees, antenna gain 15 dBi for both stations, and Ns (index of refraction) = 310), and an EME path loss of -252 dB.

Radar Cross Section There are limited resources available for determining the radar cross sections (RCS) of aircraft. In the ARRL UHF/Microwave Experimenter's Manual, Emil Pocock, W3EP gave values of 2 m^2 for a Lear Jet, 8 m^2 for a Douglas DC-9, 16 m^2 for a Boeing 707, and 63 m^2 for a Boeing 747, without attribution [6]. In his textbook on radar systems [7] Skolnik gave values of 1 for a small single engine aircraft, 2 for a 4-passenger jet, 20 for a medium jet airliner, 40 for a large jet airliner, and 100 for a jumbo jet. He indicated that these values were "examples" and should not be used if actual data were available.   By comparison, he gave RCS values of 1 m^2 for a man, .001 to .01 m^2 for birds, and 10^{-4} to 10^{-5} m^2 for insects. A B-2 bomber reportedly has an RCS of 0.01 m^2, and an F-117 fighter an RCS of 0.1 m^2.

For calculations both in this paper and in my AircraftScatterSharp [8] software I have combined the aircraft-type designations and RCS values given by Emil Pocock and Skolnik. I have also constructed a model for estimating RCS based on the values they reported and have used this model to assign estimated RCS values to more than 100 commonly spotted commercial aircraft.

Skolnik noted, "It is difficult to determine precisely all the important factors that must be included in the radar equation and it is difficult to establish a set of controlled, realistic experimental conditions in which to test the calculations. Thus it might not be worthwhile to try to obtain too great a precision in the individual parameters of the radar equation". One of the parameters that it is

difficult to know accurately is what RCS a plane is presenting to each radio station at any given time. The RCS varies markedly as the view aspect of an aircraft changes, and the concept of there being a single RCS value for an aircraft is an oversimplification. More accurate would be to consider an aircraft as an array of reflectors with their characteristics, number, and relative phase angles dependent on the view aspect of the aircraft in 3 dimensions at a given instant in time.

As an illustrative example, below is a graph showing the changes in the RCS of a Cessna 150L as the view aspect is rotated through 360 degrees. Note that the greatest RCS is obtained when the plane is viewed from the sides. This is consistent with the visual profile of the plane as is seen in the two photos below.
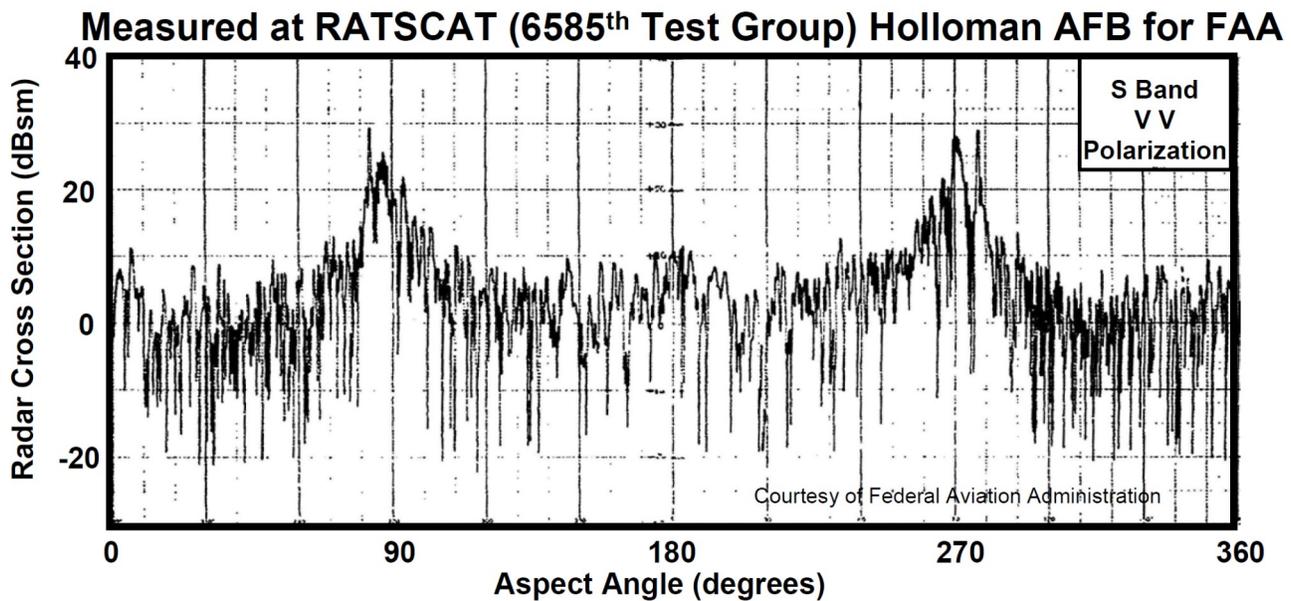
There is also a variation in RCS with the frequency of the incident RF that is not reflected in the available aircraft RCS values. Some of this variation is geometric and some of it is due to differences in the reflectivity and absorbance for RF that some materials exhibit as the frequency of the incoming RF is varied.

Both the variation in RCS with view aspect and the variation with frequency add unknowns and more imprecision to our attempts to predict the signal strengths and signal margins that can be obtained with AS in any given situation.

II. Competing Modalities When deciding when to use AS to further our communications range, we need to consider whether or not it is the best tool to use in any particular circumstance, or whether there are other tools more suited for the job. As has been discussed elsewhere [9] , AS is generally at least 20 dB better than EME in terms of signal margins so we can immediately dispense with EME as a possible competitor. Meteor scatter (MS) and troposcatter (TS) are AS's primary competitors.

The following table shows the distance and frequency dependence of TS, MS, and AS path loss with frequency.

Modality	Frequency	Distance
Aircraft Scatter	$(F2/F1)^2$	km^4
Troposcatter	30 log(F2/F1) dB	9dB/100 km
Meteor Scatter	$(F2/F1)^3$	Best at 800-2000 km

So MS is strongest at distances largely beyond the range of AS, and a weak competitor above 144 MHz due to its strong frequency dependence.

TS has a stronger dependence on both distance and frequency than does AS, so we would expect that as we go to longer distances and higher frequencies AS will improve its performance relative to TS, but these two modalities are close enough in path loss that we need to compare them carefully over the full distance and frequency ranges of interest in order to decide which is likely to be the best tool for each situation. We also need to consider to what extent changes in parameters that affect the efficacy of each of these modalities might change the ranking of which is superior for a given situation.

Detailed Comparison of Aircraft Scatter vs Troposcatter As a first approximation of the expected performance of aircraft scatter, the path loss for communications over a given path between two stations when AS is used will be calculated using the bistatic radar equation. We shall subsequently see that this provides a lower bound to the expected performance of AS. We will use RCS values of 40 m^2 (the value given by Skolnik for a large jet airliner) and 63 m^2 (the value given by Pocock for an "original" Boeing 747; newer versions are much larger). TS loss will be calculated using the Yeh model. The Yeh model for TS path loss as well as other models of TS loss are discussed in these references [10] [11] [12]. For the TS calculations a take-off angle of zero degrees will be used for both the Home and the DX stations, as well as a refractive index (N) of 310.

Because the TS loss is affected by the aperture-medium coupling loss, and because this loss is related to the gains/bandwidths of the Home and DX Stations' antennas, a decision had to be made regarding how to choose the antenna gain parameter in order to allow a fair comparison of AS and TS. Using a single value for all frequencies would not reflect actual practice and depending on what value was chosen this method could unfairly favor one modality or the other. In this analysis I chose for each band the gain of a moderate-sized, typical antenna for that band. The choices that I made are given below:

Frequency	Gain (dBi)	Frequency	Gain (dBi)
50 MHz	11.54	2304 MHz	23.4
144 MHz	14.9	3456 MHz	25
222 MHz	17.4	5760 MHz	28
432 MHz	19.44	10368 MHz	33
902 MHz	20.5	24192 MHz	35
1296 MHz	21		

The actual calculations of TS and AS loss were done using Aircraft Scatter Sharp in most cases, although for a few calculations I did make use of my calculator software that I described in reference 10 for the TS loss calculations, as that allowed me to feed in arrays of data in order to most expeditiously evaluate path losses at multiple frequencies and distances.

Below on the next pages are plots of TS loss (in red) and AS loss (in blue) for frequencies from 50 MHz through 24 GHz, for distances of 300, 500, 700, and 900 miles.
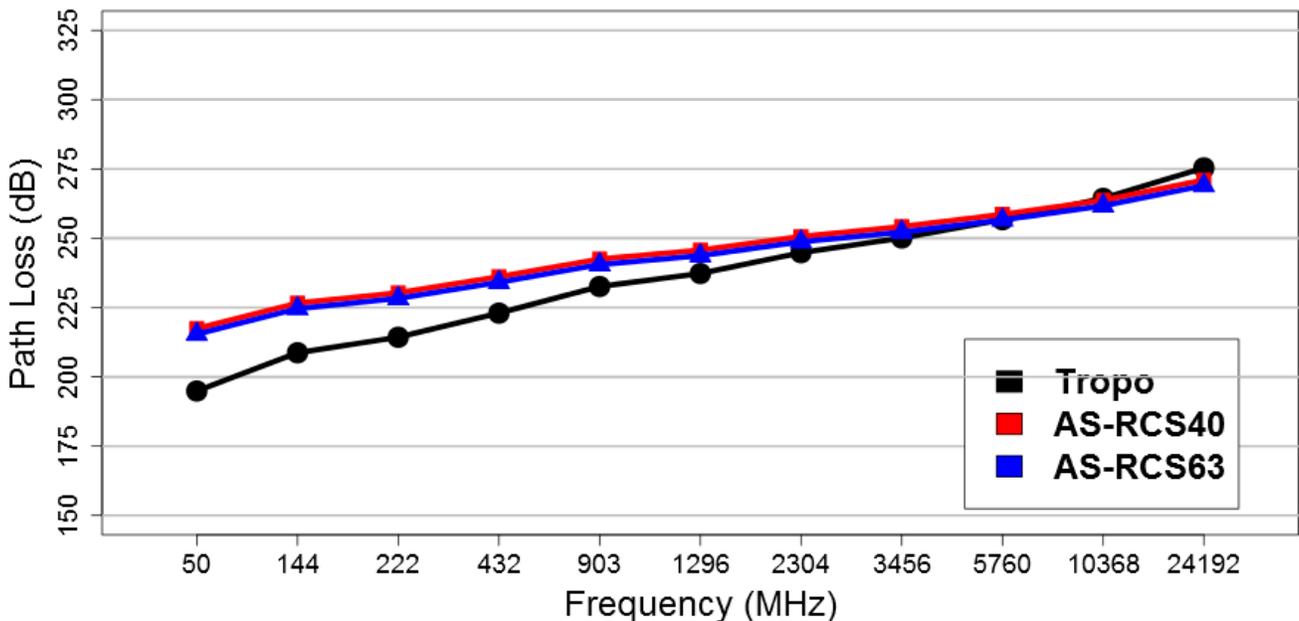
You can see that at 300 km inter-station distance the path loss for AS is inferior to TS at all frequencies. TS's advantage vs AS with a 63 m^2 RCS ranges from 28 dB at 50 MHz to only 2 dB at 24 GHz. You can also see that the difference in signal levels between aircraft with RCS values of 40 m^2 and those with RCS values of 63 m^2 is minimal (less than 2 dB). Comparisons in the text between TS and AS given below will for brevity and clarity use the values calculated for RCS 63 m^2.

Path Loss at 300 km vs Frequency
**Troposcatter & Aircraft Scatter**
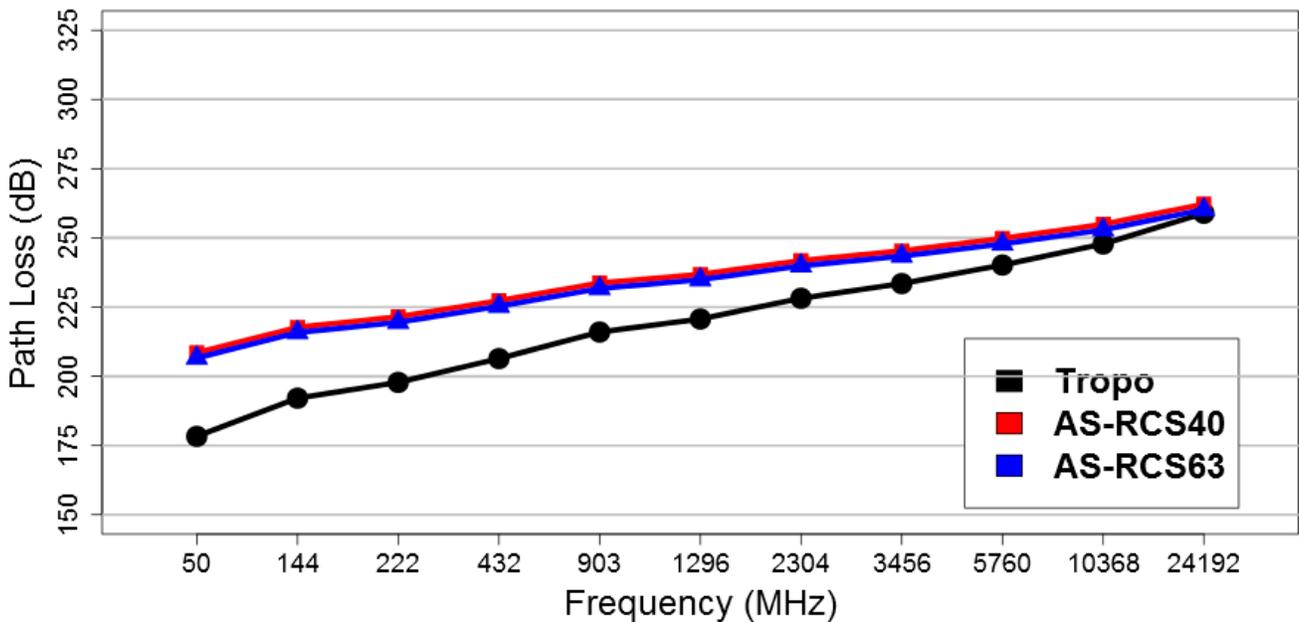
As is shown below, at 500 km TS is superior at 3456 MHz and below with its advantage ranging from 21 dB at 50 MHz to only 2 dB at 3456 MHz. At 5760 the two techniques' losses are within 1 dB of each other. At 10 GHz AS is 4 dB better, and at 24 GHz AS is 8 dB better than TS.

Path Loss at 500 km vs Frequency
**Troposcatter & Aircraft Scatter**

Below you can see that at an inter-station distance of 700 km the crossover point is just above 432 MHz. Below that, TS shows a 10 dB advantage at 50 MHz and a

3 dB advantage at 222 MHz. At 432 MHz the techniques are essentially equivalent, and above that AS is superior, with a 3 dB advantage at 903 MHz increasing to a 19 dB advantage at 24 GHz.

Path Loss at 700 km vs Frequency
Troposcatter & Aircraft Scatter
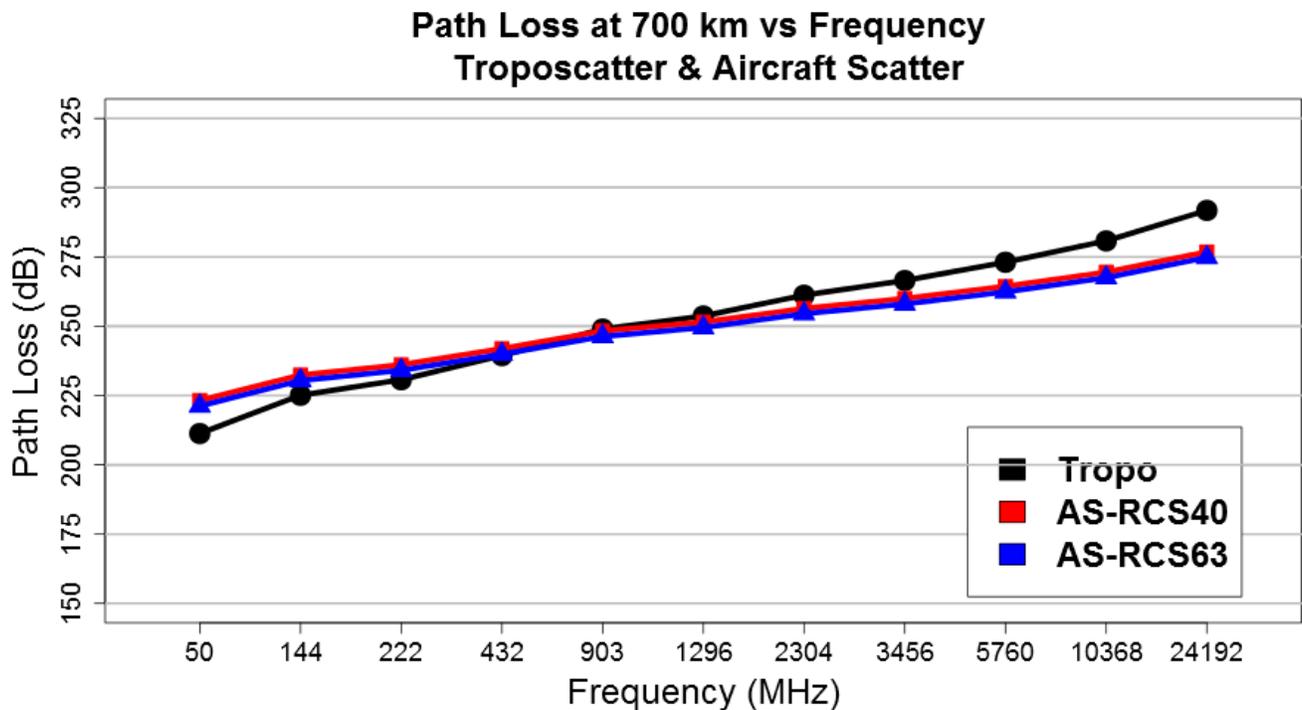
The graph below shows that at 900 km TS is inferior to AS at all frequencies, with a 1 dB deficit at 50 MHz growing to a 32 dB deficit at 24 GHz.

Path Loss at 900 km vs Frequency
Troposcatter & Aircraft Scatter
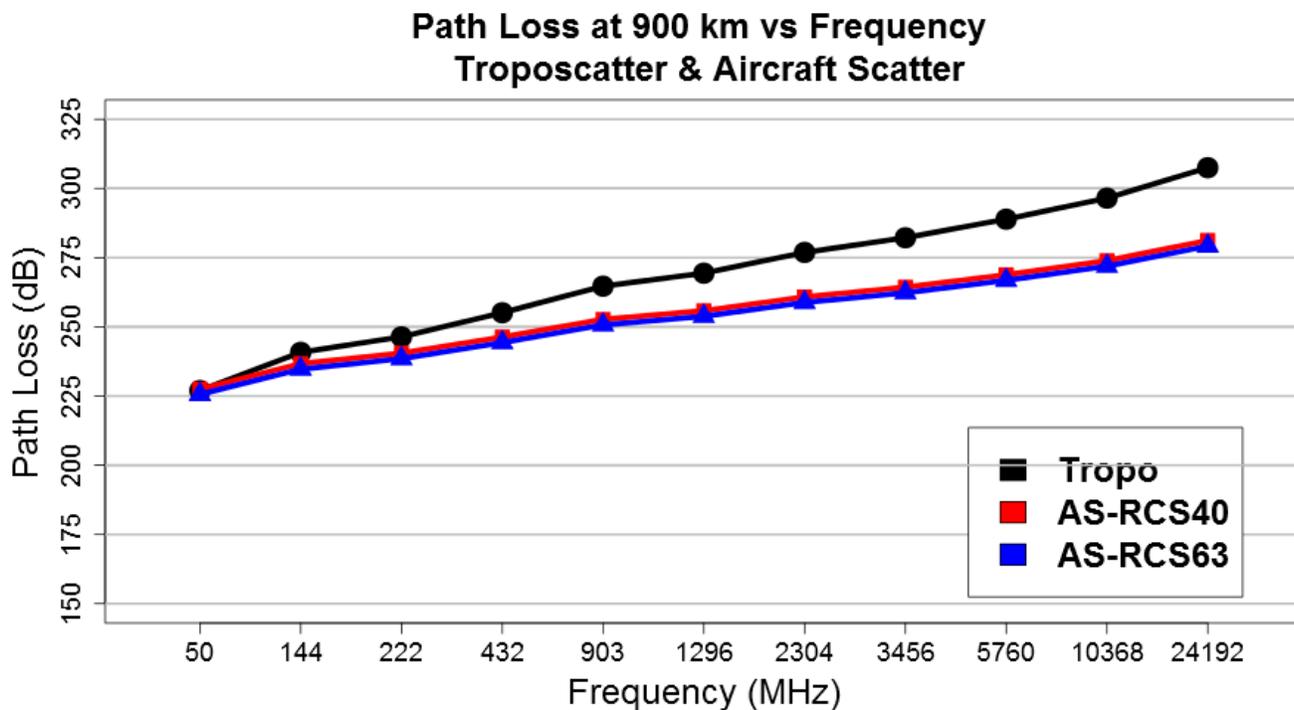
Many stations will have a take-off angle of more than zero degrees. When take-off angle is greater than zero, TS performance will suffer. Around the zero-degree point, troposcatter path loss is extremely sensitive to changes in take-off angle. Going from zero degrees to one degree take-off angle will result in an additional 11 dB of TS loss. On the other hand, if one can reduce one's take-off angle from zero degrees to minus one degree, that will reduce TS loss by 11 dB. These relationships are shown in the graph below for both the Yeh and the Collins methods of calculating TS loss.

### Troposcatter Loss vs Total Takeoff Angle
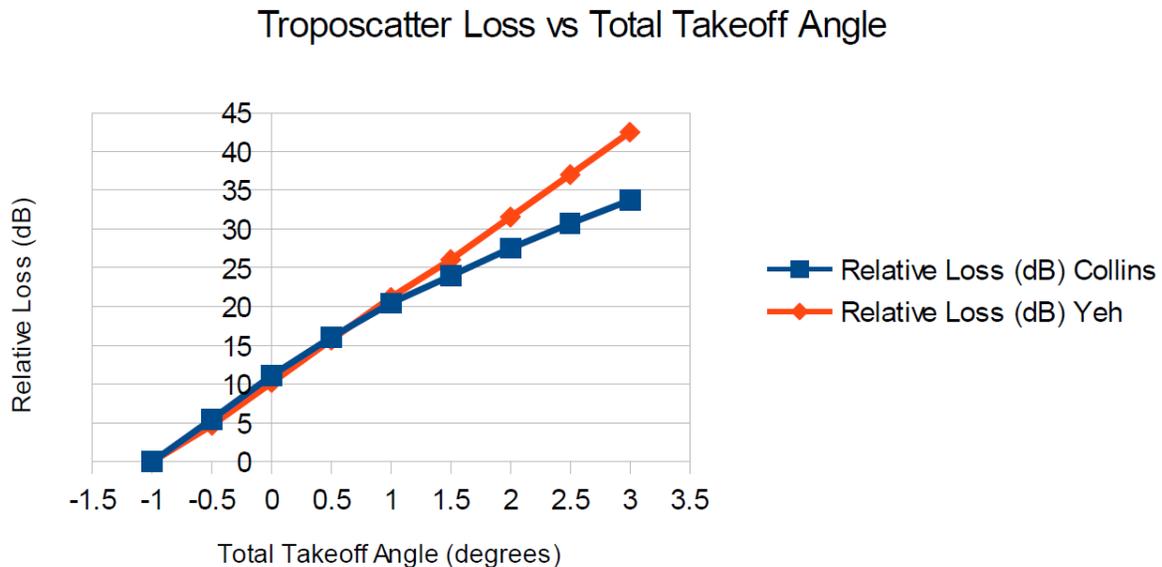
So if you have a take-off angle that is different from zero degrees, then your TS loss curve will be shifted from the above graphs comparing TS and AS by the amount of TS loss added to or subtracted from the loss at zero degrees that is given by the graph immediately above. Note that if you use Aircraft Scatter Sharp with the SRTM-3 files then Aircraft Scatter Sharp will calculate your take-off angle for you and in fact will completely calculate your troposcatter loss for any path as well as calculating your AS losses. All of this is described in reference 8.

Of course, if you over-estimate the RCS of the aircraft that you will be using for AS, then you will be underestimating the AS path losses and if you under-estimate the RCS you will overestimate the AS path losses.

The graph on the next page shows the path losses at 677 km (the distance between W3SZ and W4DEX) for the 4 aircraft sizes given by Emil Pocock in reference 6, superimposed on the TS path loss curve for that distance, with take-off angle of zero degrees as usual.

Various SIzed Aircraft Scatter vs Troposcatter

677 km Interstation Path, Plane Alt 10000m
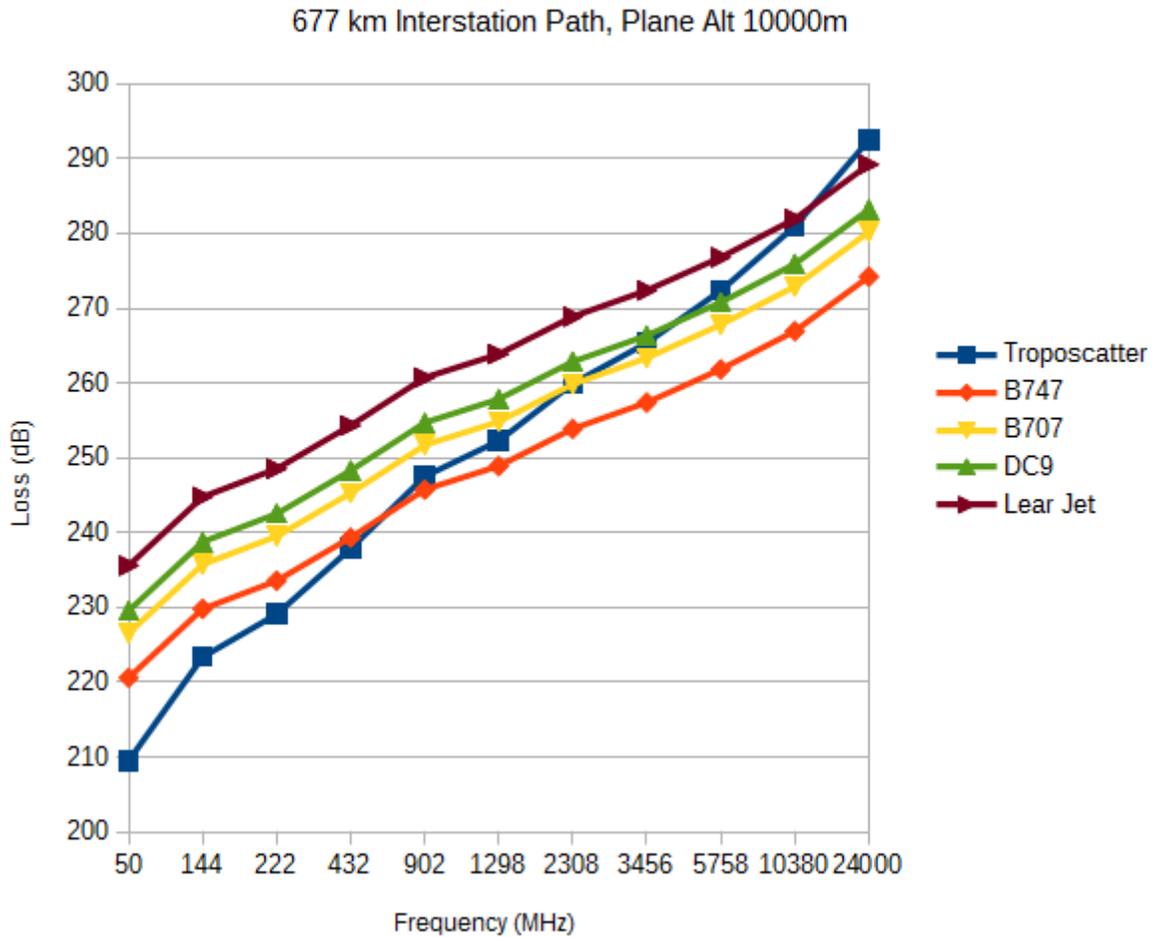
Forward Scatter Enhancement For the special case where angle between the incident signal striking the target and departing signal leaving the target is 180 degrees, there is marked enhancement of the scattered signal. This enhancement is equal to 4*Pi*(A/λ) where A is the projected area of the target and λ is the wavelength. We will see that forward scatter enhancement (FSE) provides an upper bound to the expected performance of aircraft scatter.

A complication regarding forward scatter enhancement arises because with AS the signal sent from transmitter to the aircraft is not horizontal but has an elevation angle dependent on the height of the plane, the height of the transmitter, and the distance between the transmitter and the plane. As a result, the direction of the signal departing from the aircraft is always upwards into space rather than back down toward the receiving station. So even if the transmitting station, the aircraft, and the receiving station are perfectly aligned along the inter-station path in two dimensions, in the third and vertical direction they will never be aligned. Thus the maximum forward scatter enhancement that would be seen when the signal departing from the aircraft has an angle that is

both 180 degrees from the incident signal in all dimensions and also directly pointed at the receive station can never be realized.

The illustration below is taken from Skolnik [13] and shows the relationship between the scattering angle and the amount of forward scatter enhancement, measured in dB:
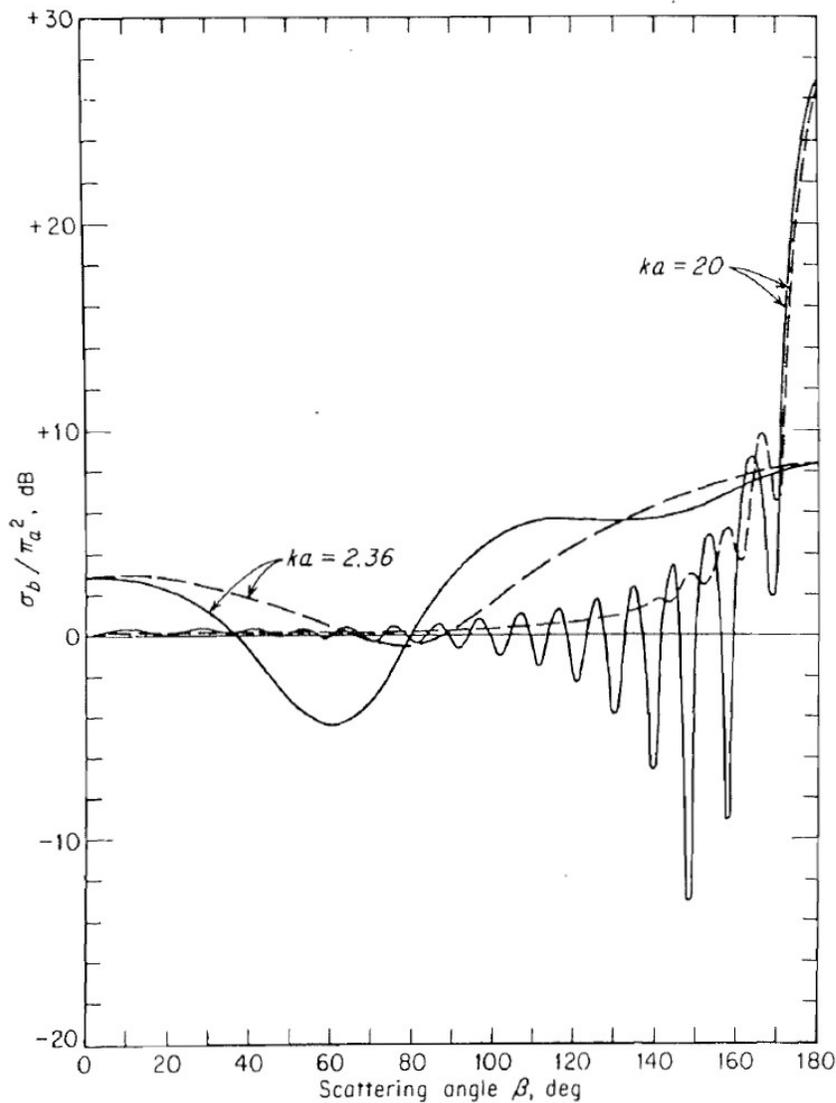

Figure 14.13 Bistatic cross section σ_b of a sphere as a function of the scattering angle β and two values of $ka = 2\pi a/\lambda$, where a is the sphere radius and λ is the wavelength. Solid curves are for the E plane (β measured in the plane of the E vector); dashed curves are for the H plane (β measured in the plane of the H vector, perpendicular to the E vector). [65,69]

You can see from this figure that nearly 30 dB of enhancement occurs when the scattering angle is 180 degrees. However, if the angle changes only by 10 degrees (or possibly less), all but a tiny portion of that enhancement will be lost.

So for our purposes, we need to determine what the geometry is likely to be for our AS attempts, and by how much the forward scatter enhancement (FSE) is affected by that geometry.

The figure below, which is originally from Barton[14] but which I took from reference 4 by Rex Moncur, VK7MO, will help in our discussion of the geometry and allow us to understand a very important parameter, which we will call the "Aircraft Scatter Angle".
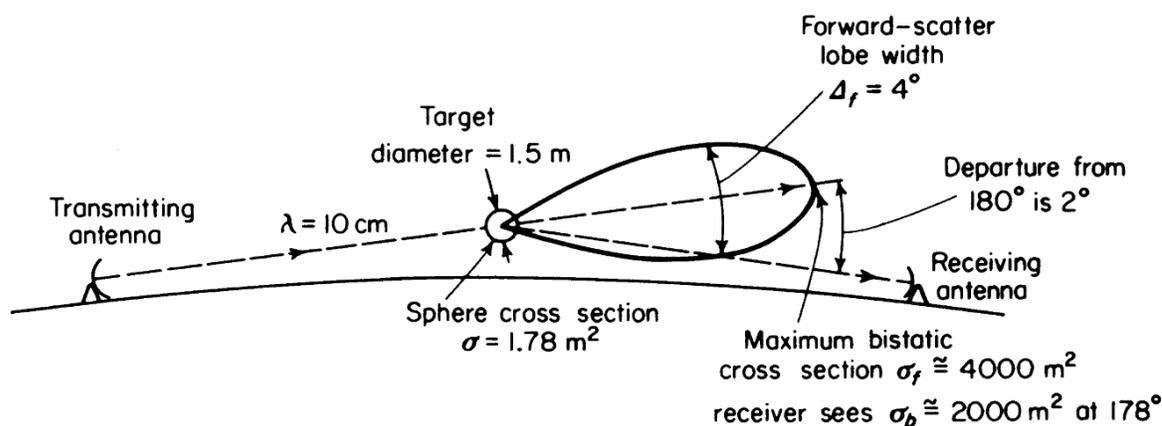
3

Figure 1: An example of bistatic radar where the transmitter and receiver are close to alignment, copied from Barton[9]

In the figure above the angle between the "straight-thru" 180 degree forward enhancement ray and the ray directed from the aircraft to the receiving station is labeled "Departure from 180 degrees is 2 degrees". This angle we will call the "Aircraft Scatter Angle" and is at the crux of calculating the amount of forward scatter enhancement that can actually be realized for a particular transmitter-aircraft-receiver geometry. Note that the "Aircraft Scatter Angle" is not the same as the scattering angle referred to by Skolnik as described above. Rather, it is the **deviation** of the ray directed from the aircraft to the receiver from that angle.

Res Moncur, VK7MO, shows in reference 4 that the maximum FSE for a given aircraft scattering angle is given by the equation:

FSE = -3 + 10 Log$((90/\Delta d)^2)$ dB

where Δd is the departure angle, or what we defined above as the "Aircraft Scatter Angle".

Aircraft Scatter Sharp calculates and then displays the aircraft scatter angle automatically and in real time for every selected aircraft – Home Station – DX Station geometry, using Vincenty's formula[15] [16] and the Law of Cosines[17] and then calculates and displays the maximum FSE that can be achieved for this Home Station-Aircraft-DX Station geometry.

To illustrate the effects of this geometry on aircraft scatter angle and maximum FSE we will look at some examples where the aircraft is situated at the midpoint between the two stations or along a perpendicular to the inter-station line that intersects the midpoint of the inter-station path.

The graph below shows the aircraft scattering angle (Y axis) as a function of the sum of the two station's skew angles (X axis) for inter-station distances of 300 and 700 km and an aircraft altitude of 10,000 km (the skew angle for a given station is just the angle by which the azimuth of the path to the aircraft from that station differs from the azimuth from that station to the other station; so if the aircraft is situated directly over the inter-station path the skew angle is zero for both stations).

Aircraft Scattering Angle vs Sum of Skew Angles
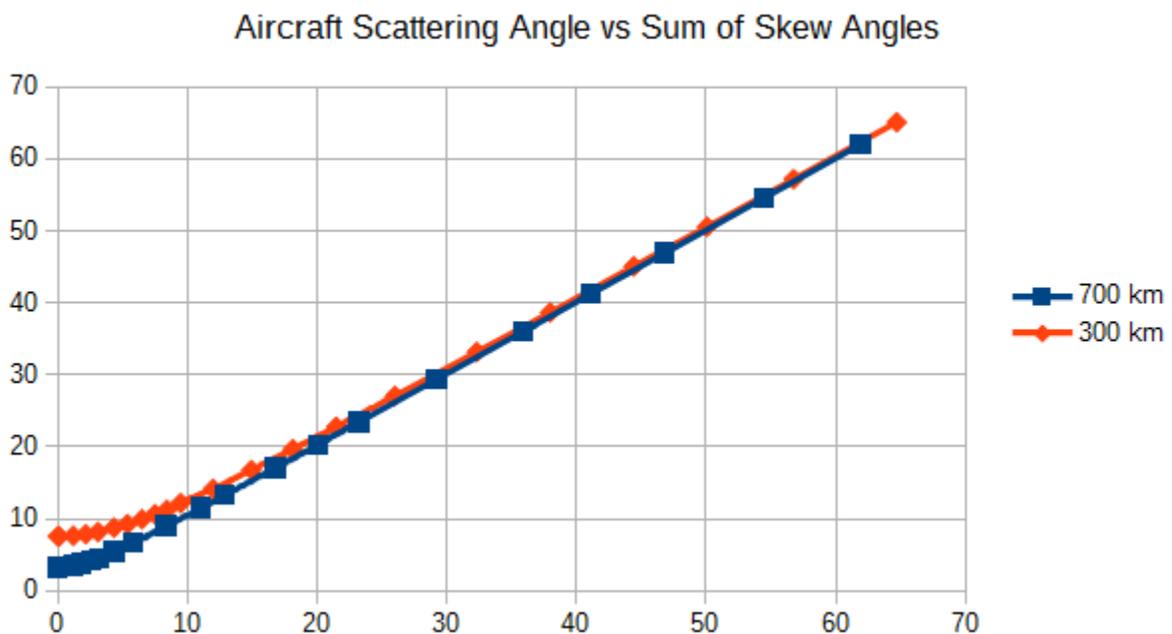
700 km
300 km

You can see that for skew angles greater than approximately 10 degrees for a path length of 700 km or above approximately 20 degrees for a path length of 300 km the aircraft scatter angle is effectively just the sum of the skew angles of the DX and Home stations. As the skew angle decreases, the elevation angle to the aircraft plays a greater role in determining the aircraft scattering angle, and by the time the sum of the skew angles is zero, the aircraft scattering angle is completely determined by the elevation angle. Of course, the shorter the inter-station distance, the greater will be the elevation angle of the plane as seen from

each station and the greater will be the contribution of the aircraft elevation to the aircraft scattering angle for each station, and the greater will be the minimum achievable aircraft scatter angle. Comparing the curves for 300 and 700 km in the graph above illustrates these points.

The next graph shows Forward Scatter Enhancement in dB (Y axis) vs the Aircraft Scatter Angle in degrees (X axis). This relationship is not distance-dependent. You can see the marked decrease in forward scatter enhancement as the aircraft scatter angle increases. One needs to stay below an aircraft scatter angle of approximately 10 degrees in order to avoid losing more than 10 dB of FSE. At an inter-station distance of 700 km that requires that each station's skew angle be less than 5 degrees. As you can see from the above graph, at 300 km the skew angle sum would need to be kept below 6 degrees and so each station's skew angle would need to be less than 3 degrees to meet this requirement.

Forward Scatter Enhancement (dB) vs Aircraft Scatter Angle
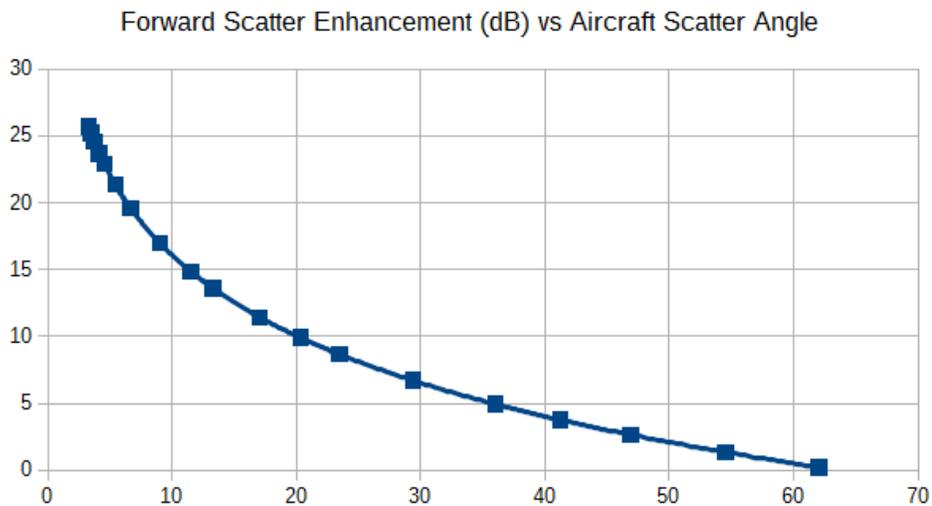
You can see from the graphs and discussion above that the aircraft scatter angle never reaches zero, and that the minimum-achievable aircraft scatter angle determines the maximum possible FSE.

The relationship between minimum achievable aircraft scattering angle and interstation distance is shown in the graph below:

Minimum Aircraft Scattering Angle vs Interstation Distance (km)
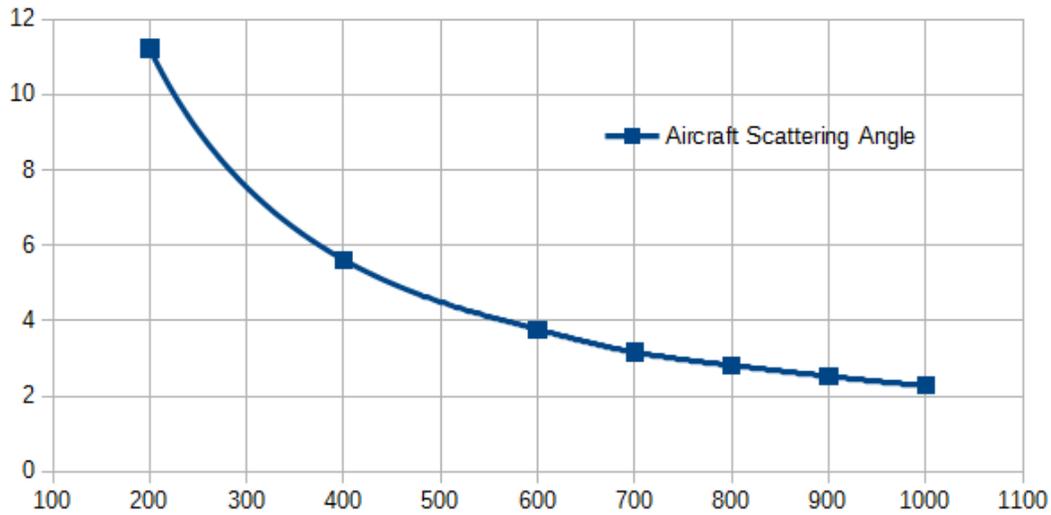
You can see that the minimum scattering angle at 200 km inter-station distance is quite large, nearly 12 degrees, and this means that the maximum FSE achievable at this short distance will be quite a bit less than the achievable FSE at longer distances, as shown in the next graph:

## Maximum Forward Scattering Enhancement (dB) vs Distance (km)
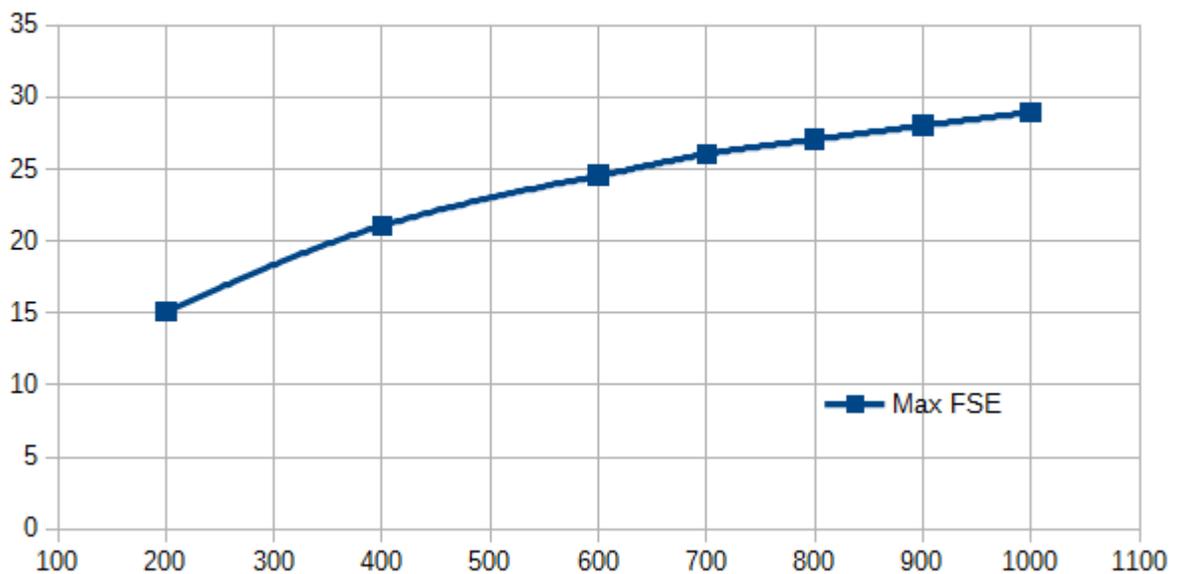
The maximum achievable FSE at 200 km inter-station distance is only 15 dB. This value rises to nearly 30 dB as one reaches an inter-station distance 900- 1000 km. At these longer distances the limiting factor for AS communications is the fact that unless the aircraft is at an extremely high altitude, it will not be above the radio horizon for both stations and thus cannot act as a scattering object.

This FSE data just discussed should make one very important point crystal clear: **in order to minimize the aircraft scatter angle and thus maximize Forward Scatter Enhancement, you want to make use of aircraft that are positioned along or very close to the direct path between the two stations, in order to minimize the skew angle for both stations.**

The aircraft that will give you favorable geometry for the longest duration are those running along and parallel to the inter-station path, and not perpendicular to it.

Unfortunately, one never gets something for nothing, and the case of Forward Scattering Enhancement is no exception. It turns out that the beamwidth of the forward enhancement lobe is proportional to λ/R where R is the radius of the reflecting object and λ is the wavelength of the incident signal. Thus, as one goes to higher and higher frequencies and shorter and shorter wavelengths, the only surfaces that will be able to provide a forward-scatter-enhanced signal with sufficient vertical beamwidth to reach the ground (and thus the receiving station) are those surfaces with smaller and smaller vertical dimensions.

But if these surfaces also have very small horizontal dimensions, then their projected area will be so small as to largely eliminate any enhancement. So the wings and other structures with small vertical but larger horizontal dimensions
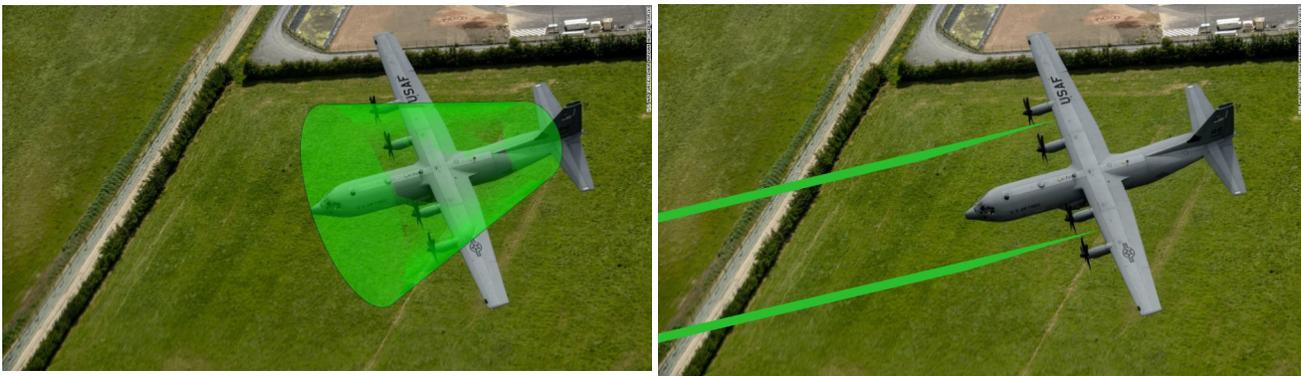
become more important sources of FSE at higher frequencies. A varying number of such structures will produce multiple horizontally narrow but vertically broad fans of forward enhanced scattered signal with varying intensity and relative phase as the transmitter-aircraft-receiver geometry changes, producing a horizontally narrow beam of enhanced signal that intermittently reaches the receiving station's antenna array with sufficient intensity to produce a useful signal. Thus at the higher frequencies the forward scatter enhanced signal will be broken up into short bursts, unlike the situation at the lower frequencies where the beamwidth of the forward scattered signal is substantially larger and where longer duration signal peaks will be seen.

The image on the left above represents the appearance of the forward scattered lobe signal on a lower frequency, say 144 MHz. The beamwidth of the forward-

enhanced lobe is relatively wide and has reasonable axial symmetry. The image on the right represents the situation at a higher frequency, say 10 GHz, where the small vertical dimension of the wings gives a forward enhanced lobe with sufficient vertical beamwidth to reach the ground. But because the wings have a large horizontal dimension, the horizontal beamwidth is greatly reduced compared with the vertical beamwidth. Not added to the right-hand image for clarity and simplicity are the many additional forward enhanced lobes from many other structures with appropriate vertical dimensions, each of which will generate a horizontally narrow beam of signal and all of which will combine in complex fashion to produce a constantly varying forward-enhanced signal.

The overall effect of the complexities of the production of the forward scatter enhanced lobe at higher frequencies is to both reduce the magnitude of forward enhancement that can be achieved at higher frequencies and to also break the signal up into short bursts due to the narrow beamwidths and complex phase relationships of the forward scatter enhanced lobes at the higher frequencies. This reduction cannot be quantitated with the data available to us and so we can only say for the higher frequencies that the expected total AS path loss (and thus signal margin) is somewhere between the value given by the bistatic radar equation alone and the path loss value obtained from the bistatic radar equation minus the maximum forward scatter enhancement. The Aircraft Scatter Sharp data display gives both values of the signal margin for each station..

Rex VK7MO gave an excellent illustration of this phenomenon of short bursts of received signal on 10 GHz in the graph below:
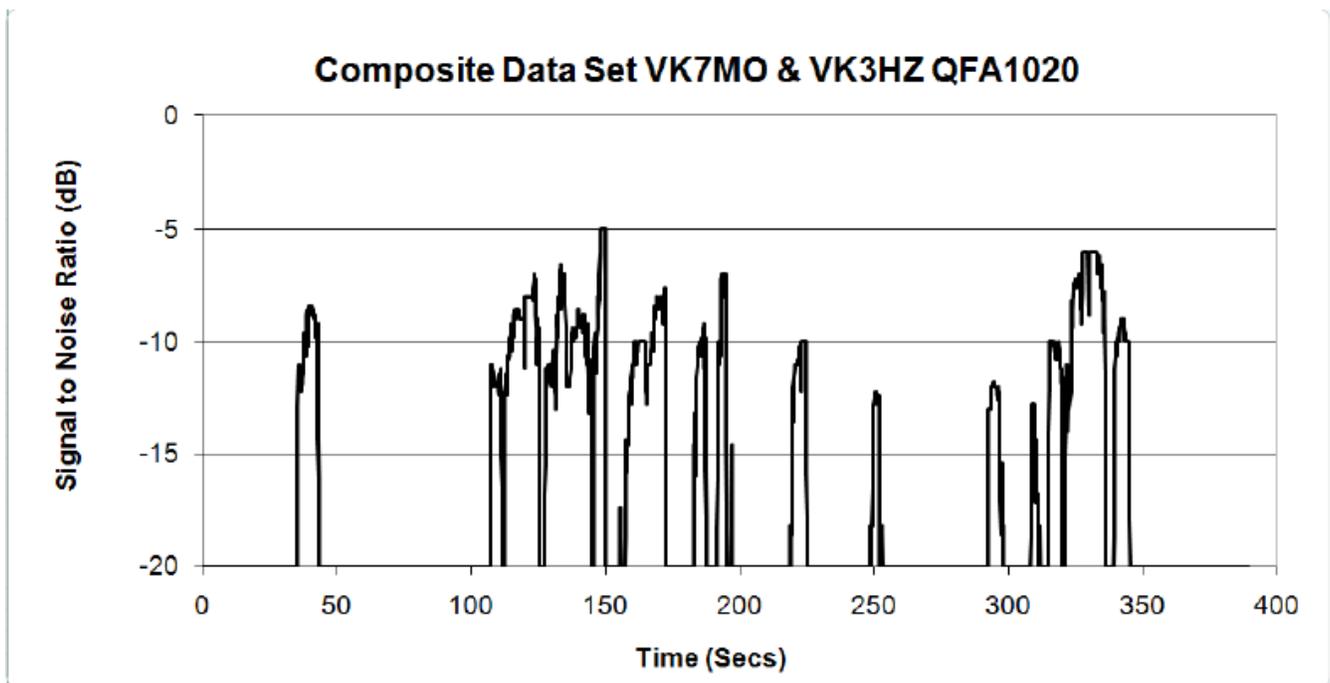

Fig 1: 10 GHz aircraft scatter signals from Werribee in Victoria to Swansea in Tasmania

In this graph the time span from the first signal burst to the last burst is approximately 5 minutes, and you can see that there are nearly 20 peaks of varying but always short duration due to the effect just described. Rex's results shown here suggest that we can achieve at least 15 dB of FSE at 10 GHz.   How to best deal with this strobe effect will be discussed later in this paper; clearly techniques that maximize the speed of data transmission are needed.

There is some experimental data to back up the theory given above. As just noted, Rex VK7MO's work on 10 GHz indicates that there is at least 15 dB FSE obtained at that frequency and that the enhanced signal will appear as short bursts, both of which are consistent with the theory discussed.

In addition, Rex compared results predicted by the model to measured results for 15 well-documented AS contacts on 144, 432, and 1296 MHz. Two contacts were discarded because the aircraft were far off the inter-station path and thus had no potential FSE. Of the remaining 13 cases, in all but one case the theoretical and experimental results were within 10 dB of each other. In the remaining case, the AS signal was 17-23 dB stronger than predicted by the theory. So, even given all of the caveats and confounding issues discussed above, the model presented appears to provide a satisfactory guide to expected signal levels.

The image below is an example from Aircraft Scatter Sharp of a plane flying right down the inter-station path. The selected plane is marked with a black circle around it and is within the large red circle. You can see in the data display on the left that the skew angles are 0.40 and 0.36 for the home and DX stations, the inter-station distance is 640.18 miles, the plane altitude is 9448.8 m, the aircraft scatter angle is 3.5 degrees, and the resulting maximum FSE is 25.3 dB. The


signal margin for both stations is -9.6 dB without FSE and +15.7 dB with maximum FSE. Clearly FSE can make a significant difference in the chance for a successful aircraft scatter contact!

The graphs on the next two pages give more detail on just how much the equation regarding the relative efficacy of TS and AS changes if we add the maximum achievable forward scatter enhancement to the AS results obtained without considering FSE for a variety of frequencies and inter-station distances. The graphs are similar to those presented above, but now on each graph the AS results with and without FSE for both RCS 40 m^2 and RCS 63 m^2 are compared with TS.

The first graph, shown immediately below, is the graph for 300 km. You can see that in contrast to when the effects of FSE were not included and TS was superior for all frequencies at this distance, now with FSE there is a crossover point at 903 MHz, and above that frequency AS with FSE is superior to troposcatter, with the margin of difference reaching 19 dB at 24 GHz.

Path Loss at 300 km vs Frequency
Troposcatter & Aircraft Scatter with/wihout FSE
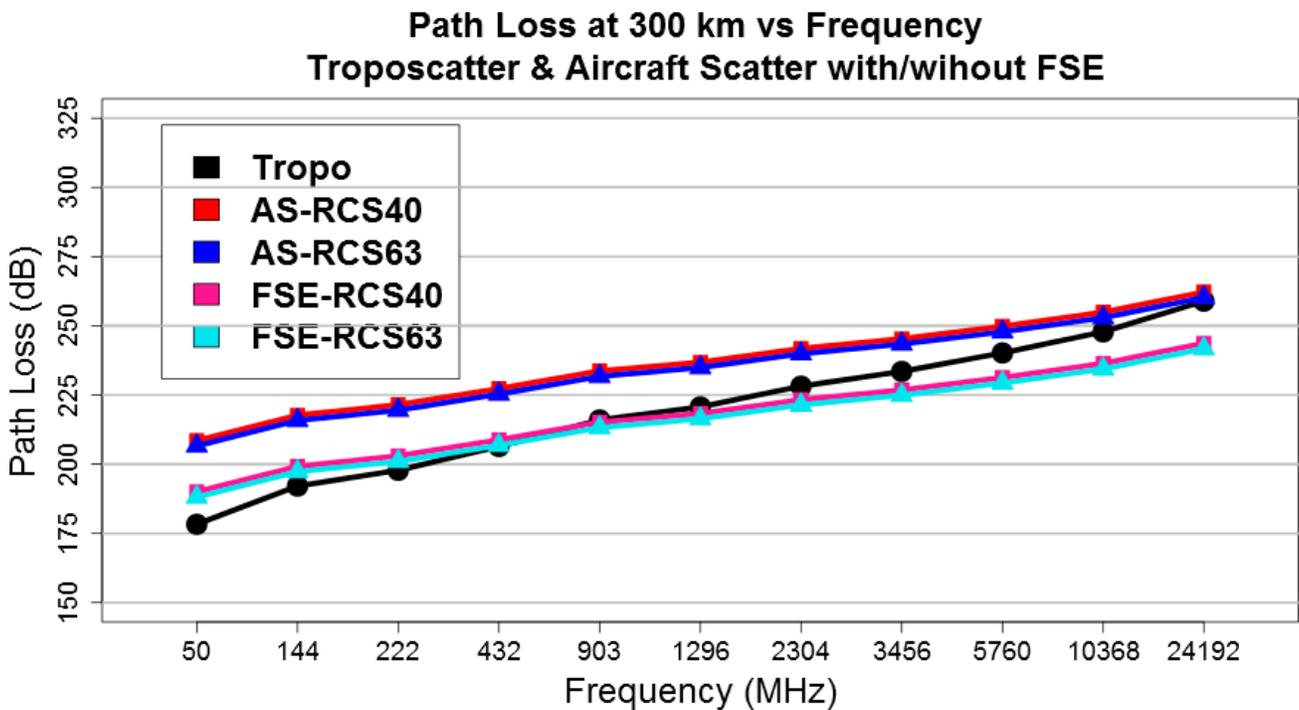
Similarly, as you can see below, whereas for a 500 km inter-station distance without FSE there was previously a crossover point at 3456 MHz, now with FSE AS is superior to TS for all frequencies at this distance, with its advantage ranging from a low of 3 dB at 50 MHz to a maximum of 31 dB at 24 GHz.

Path Loss at 500 km vs Frequency
Troposcatter & Aircraft Scatter with/wihout FSE
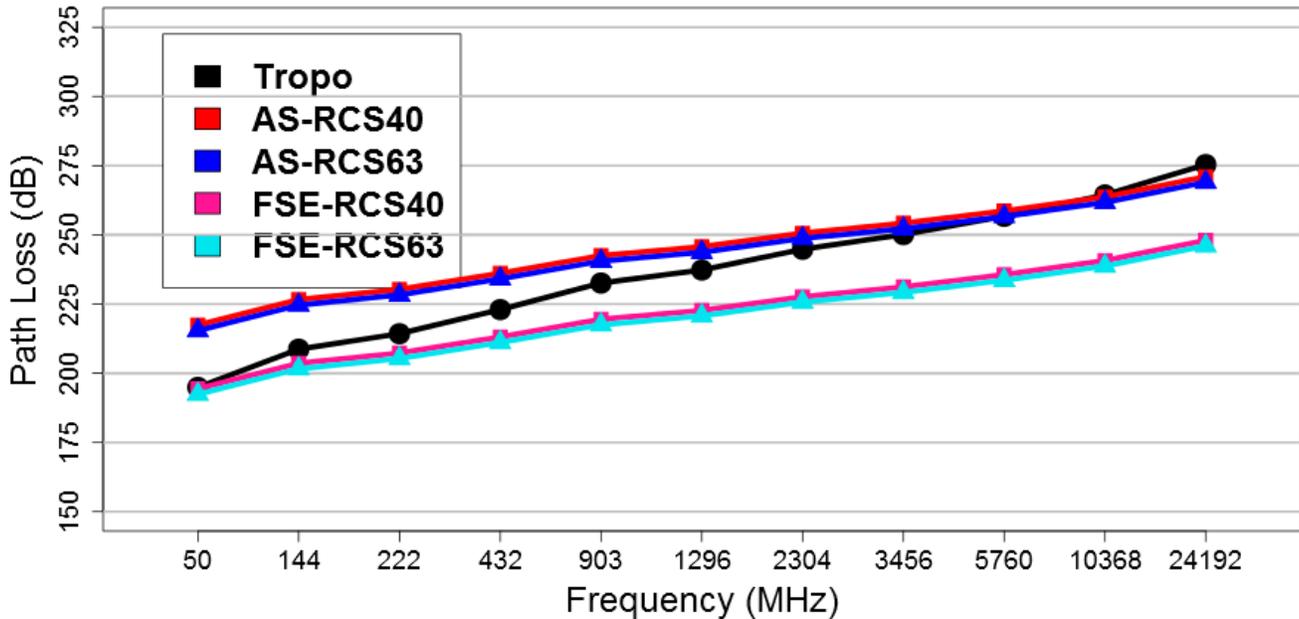
You can see below that at an inter-station distance of 700 km the superiority of AS over troposcatter when FSE is taken into account is even more striking. The AS advantage is 16 dB at 50 MHz and more than 40 dB at 24 GHz. As we have already noted, we do not expect to achieve the maximal value for FSE at the high end of the frequency spectrum, but these results are nevertheless very encouraging..

Path Loss at 700 km vs Frequency
Troposcatter & Aircraft Scatter with/wihout FSE
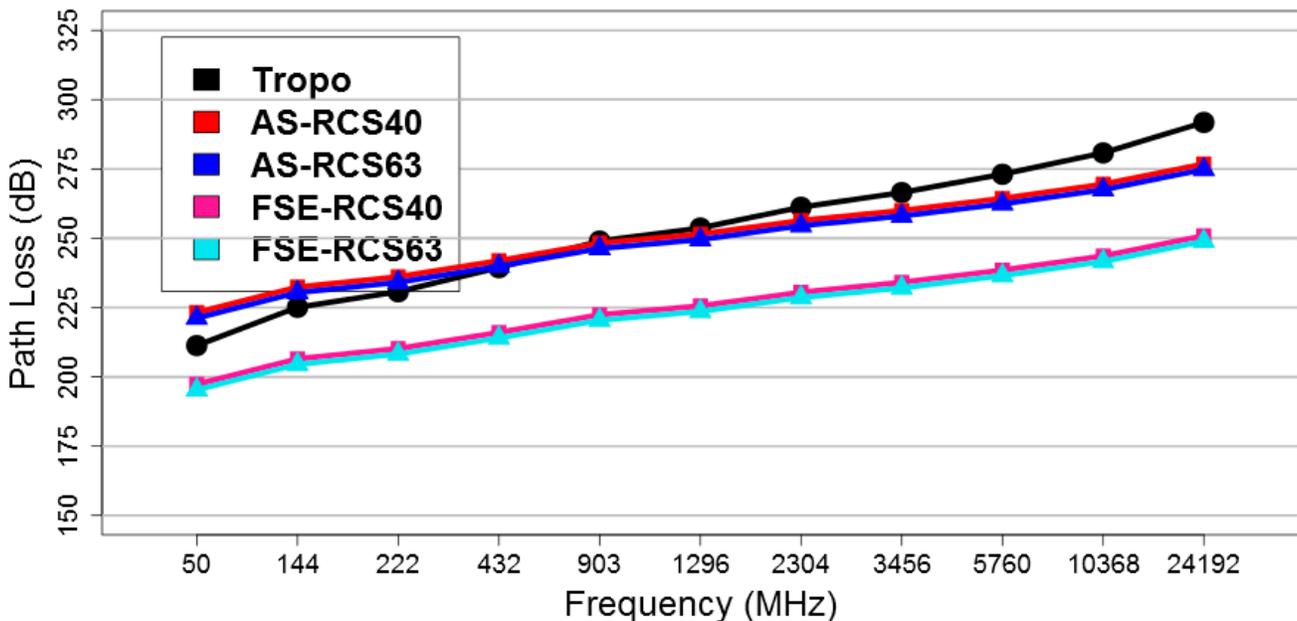
At 900 km, AS with FSE is 29 dB better than TS in terms of path loss at 50 MHz and approximately 60 dB better than TS at 24 GHz.

Path Loss at 900 km vs Frequency
Troposcatter & Aircraft Scatter with/wihout FSE
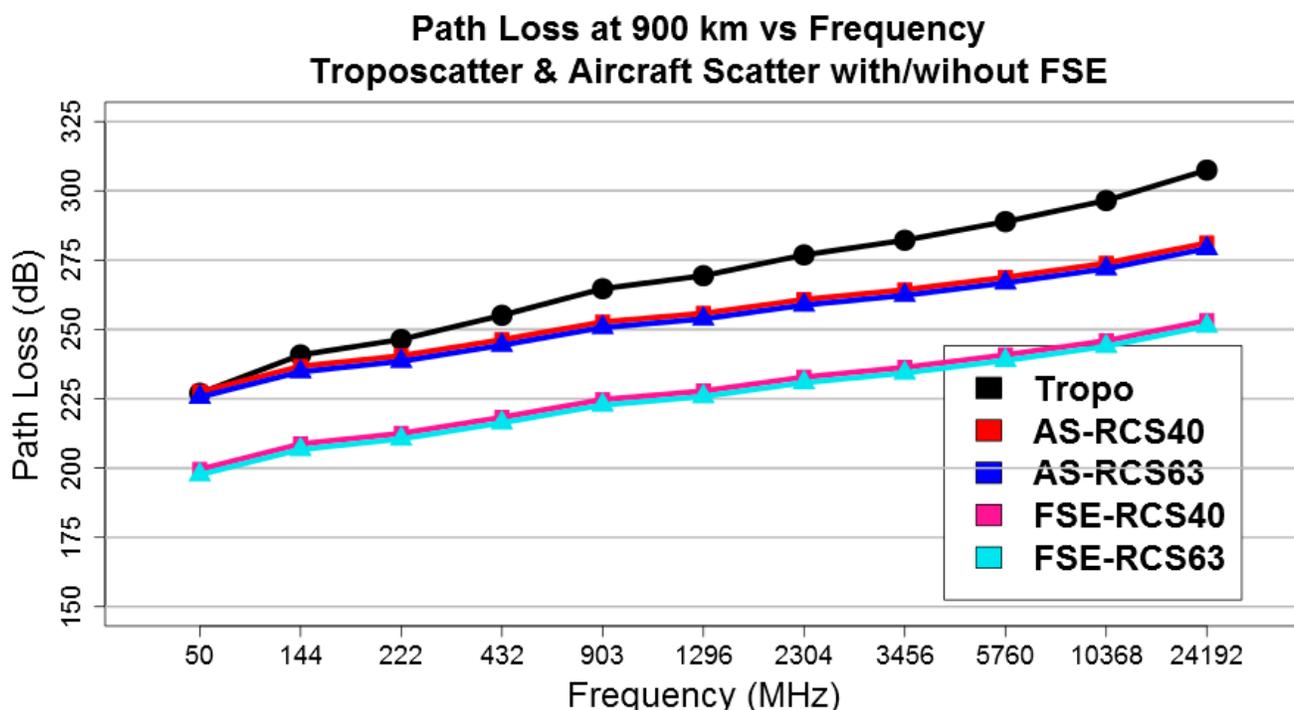
Thus, if one takes into account both the potential benefit that accrues to AS from FSE and the increased loss incurred by TS if the take-off angle is greater than zero, it becomes apparent that AS will have the advantage over TS for all but the shortest distances and lowest frequencies under consideration.

Factors That May Complicate Using Aircraft Scatter

Antenna Pointing A question commonly asked by those new to AS is, "Do I need to point the antenna at the aircraft, and if so do I need elevation control?" The answer to this question is of course, "it depends". What is important here is of course the beamwidth of your antenna array as compared to the deviation of the path from your station to the aircraft from the inter-station path in both the horizontal (skew angle) and vertical (elevation angle) dimensions. If the aircraft remains within your beamwidth when you are pointing at the other station, then you don't need to move your array away from the direct heading to the other station. If the aircraft is not within your beamwidth, then you need to point your array at the aircraft. So as you move higher in frequency and the directivity of your arrays increases, you will increasingly need to point at the aircraft rather than along the inter-station path. Fortunately, Aircraft Scatter Sharp gives you both the azimuth heading and the elevation angle (as well as the skew angle) for the selected aircraft as it appears from each station as is shown below:

	Home	Midpoint	DX Station	Aircraft
Call ○			●	N37273
Grid ◉	FN20AG	FM07VT	○ EM95TG	FM07UR
Lat ○	40.2708333	37.7919259	○ 35.2708333	37.57288
Long	-75.9583333	-78.2412027	-80.375	-78.42076
km to Plane	368.2	30.5	310.1	5.0
AZ	216.27	Set Home and DX Positions	33.88	km to Path
Skew	0.14		0.17	☐ Default Home
EL	0.18	-0.28 -0.08	0.66	☐ Default DX
Alt	330	1	250	☑ Auto Center and Zoom

The azimuth to the selected aircraft from the Home Station is 216.27 degrees, the elevation angle is 0.18 degrees, and the skew angle is 0.14 degrees. The azimuth to the selected aircraft from the DX Station is 33.88 degrees, the elevation angle is 0.66 degrees, and the skew angle is 0.17 degrees. So in this case, antenna pointing away from the direct inter-station path is clearly not necessary.

Whether or not you need elevation control of your array is a function of both aircraft altitude and station-aircraft distance, as these parameters determine the elevation angle. The chart below shows elevation angles for an aircraft flying at 10,000 m and situated near the midpoint of the inter-station path.

QSO Distance	200 km	400 km	600 km	800 km	1000 km
Distance to Aircraft	100 km	200 km	300 km	400 km	500 km
Elevation	5.4°	2.2°	0.9°	0.08°	-0.54°

Doppler Shift Typical commercial aircraft speeds are 600-1100 km/h (370-680 mph). The Doppler shift is described by the equation:

$$\Delta f = (1/\lambda) * (V_{Tx} + V_{rx})$$

where:
λ = wavelength
V_{Tx} = Plane's velocity component along path from aircraft to Tx station
V_{Rx} = Plane's velocity component along path from aircraft to Rx station

When a plane is moving along the direct path between Tx and Rx stations, the two Doppler Velocities cancel out and the Doppler shift is zero. When a plane is moving perpendicular to the direct path between the Tx and Rx stations, the two Doppler Velocities ADD and the Doppler shift is **twice** what it would be if a direct signal transmitted by the plane were being received by the station over the same path. The rate of change of the Doppler shift is also zero for planes flying along the inter-station path but maximized for planes flying perpendicular to this path.

The chart below shows the maximum Doppler shift in Hz for a plane flying perpendicular to the inter-station path for frequencies from 50 MHz to 24 GHz at speeds from 600-1000 km/h.

MHz km/h	600	700	800	900	1000
50	56	65	74	83	93
144	160	187	213	240	267
222	247	288	329	370	411
432	480	560	640	720	800
903	1003	1171	1338	1505	1672
1296	1440	1680	1920	2160	2400
2304	2560	2987	3413	3840	4267
3456	3840	4480	5120	5760	6400
5760	6400	7467	8533	9600	10667
10368	11520	13440	15360	17280	19200
24192	26880	31360	35840	40320	44800

On the next page is an example from Aircraft Scatter Sharp of a plane flying along and parallel to the inter-station path. Note that at 10 GHz the Doppler shift for this example is only -0.2 Hz, and more importantly, the rate of change of the Doppler shift is only -0.006 Hz/second. These values are shown at the bottom of the RF Data section of the GUI on the left. At the lower right of the GUI in the Doppler display you can see that the rate of change of the Doppler shift is essentially constant, as is typical for aircraft with a constant heading.
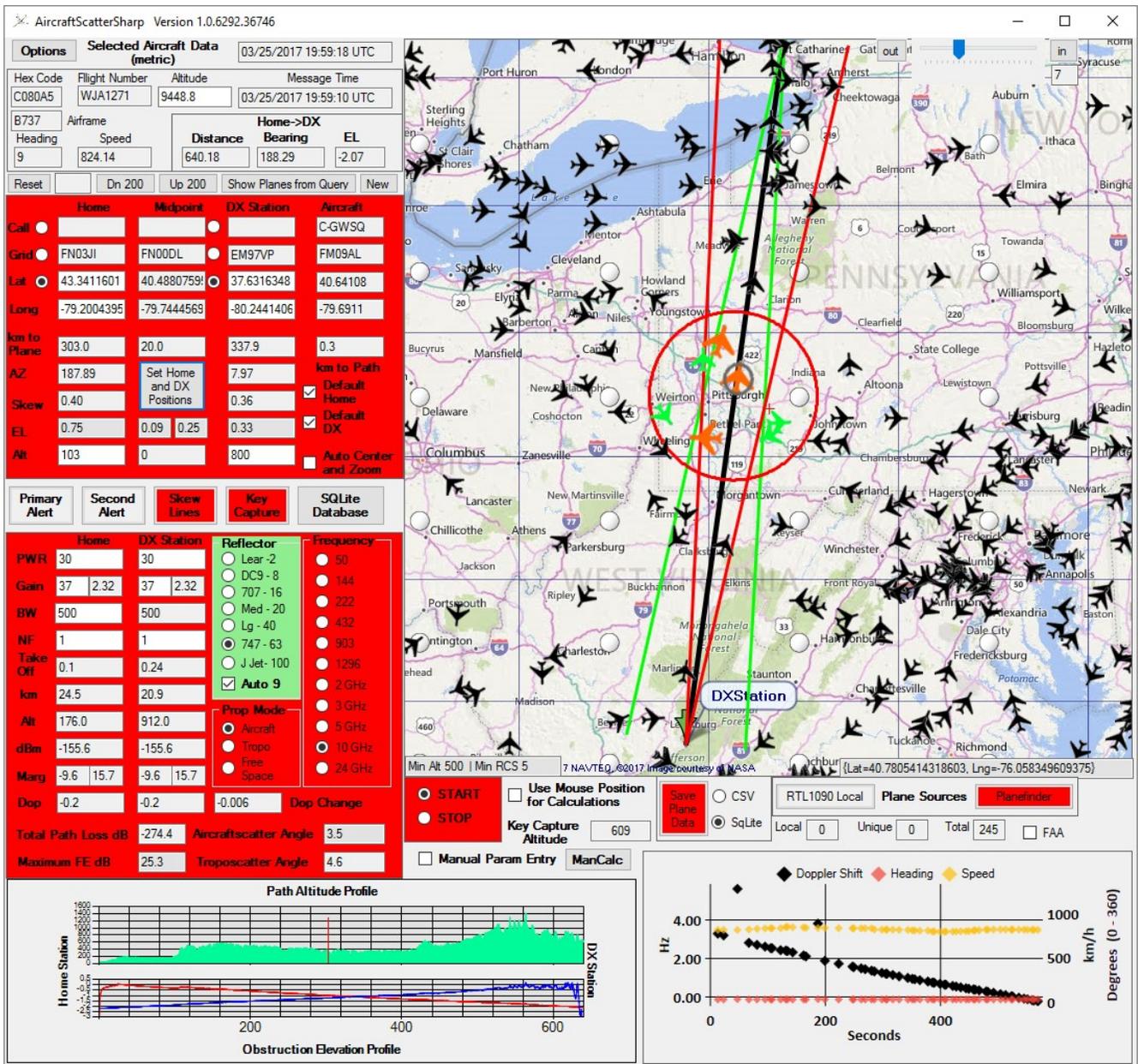
Contrast the situation just described with the image below, which shows a plane flying approximately perpendicular to the inter-station path. In this case the Doppler shift is at the moment only 328 Hz because the aircraft is crossing the inter-station path, but the rate of change of the Doppler shift is -16.48 Hz/second, and you can see from the graph that the Doppler shift had been approximately 12,000 Hz when tracking started. This rate of change means that over a 15 second period the frequency of the received signal will change by 247 Hz. For the previously described plane flying parallel to the inter-station path the frequency change over the same 15 second period would be only 0.09 Hz. In both cases the rate of change of the Doppler shift over time remains constant as long as the aircraft's heading remains unchanged. The great difference in the magnitude of the Doppler shift and its rate of change for planes flying parallel to and along the inter-station path vs those flying perpendicular to that path is one

reason to strongly prefer planes flying along and parallel to the inter-station path for use as scattering objects, especially for the higher frequencies.
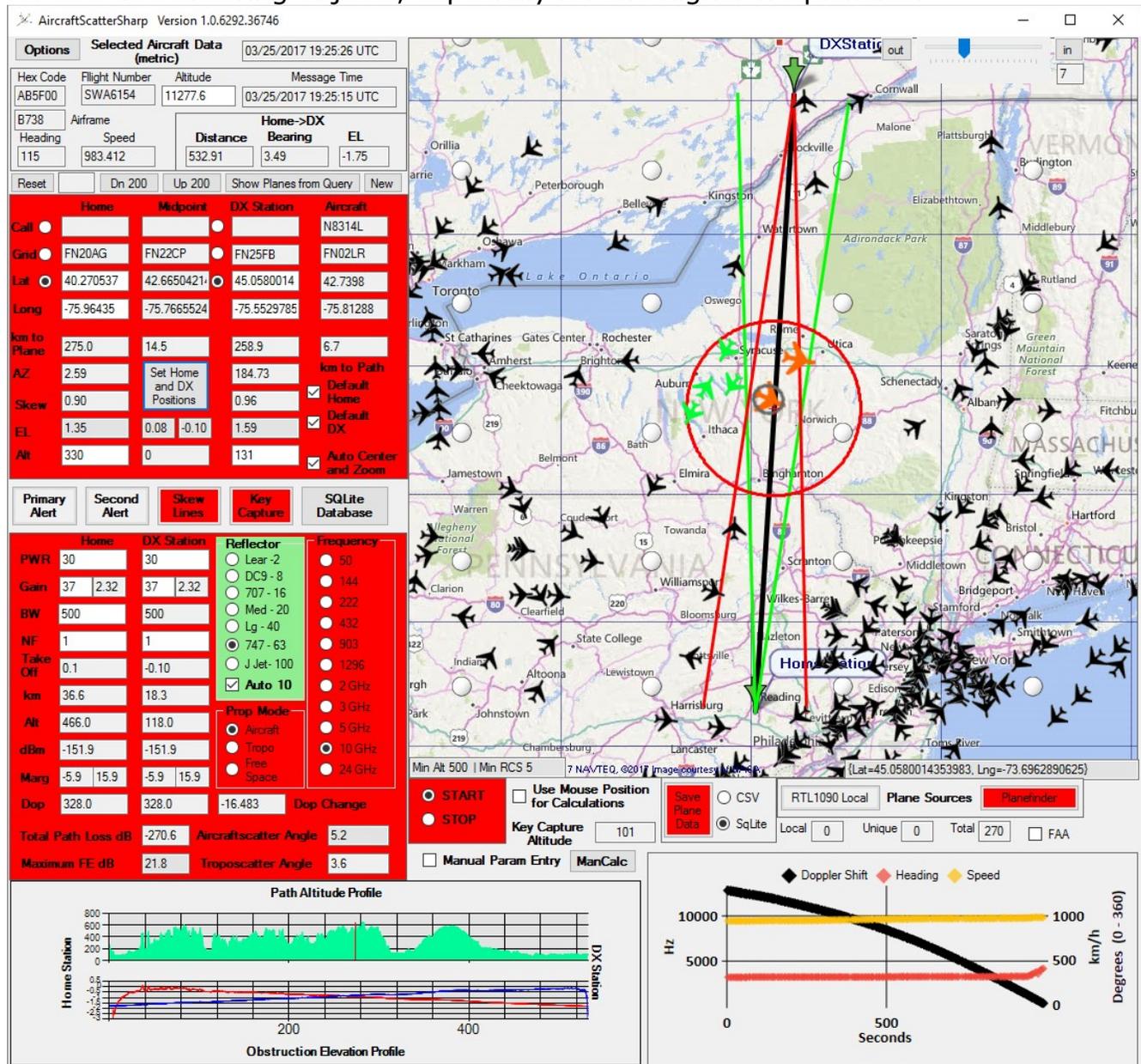
Digital Modes As noted above, the path loss with AS is nearly always greater than 200 dB. Thus AS is truly a weak-signal mode. It should therefore come as no surprise that the digital modes are extremely helpful in making AS contacts, especially on the higher frequencies where the received signal is broken up into very short bursts. A properly chosen digital mode will be one that can both help to pull a very weak signal out of the background noise and also provide sufficiently rapid data transmission so that a complete message can be received during the time available with a very short received signal burst.

The optimum digital mode to use with aircraft scatter will also be one that has sufficiently short T/R cycles so that a complete QSO can be completed in a two-

minute period, which may be all the time that is available to complete a contact (or even more than is available), especially if the operators are forced to use an aircraft traveling perpendicular to the inter-station path.

Additionally, for the higher frequencies it will be necessary to use a mode that is tolerant of substantial Doppler shifts, especially for aircraft that are not flying along and parallel to the inter-station path.

So the important characteristics of the optimum digital mode to use with AS at high frequencies are [1] good weak signal sensitivity, [2] rapid data transmission, [3] short T/R cycles, and [4] good tolerance of large Doppler shifts.

The table below lists the values of these parameters that we need to consider in deciding which of the various WSJT-X modes are best suited to aircraft scatter. I have marked the parameter values that are the most suitable for AS with a yellow background.

Mode	Tone Spacing	BW (Hz)	Keying rate (Baud)	Tx Duration (s)	S/N (dB)
JT4A	4.38	17.5	4.38	47.1	-23
JT9A	1.74	15.6	1.74	49	-27
JT65A	2.69	177.6	2.69	46.8	-25
QRA64A	1.74	111.1	1.74	48.4	-26
ISCAT-A	21.5	905	21.5	1.18	-17*
ISCAT-B	43.1	1809	43.1	0.59	-17*
JT9E	27.78	224	25	3.4	-23
JT9F	55.56	446.2	50	1.7	-22
JT9G	111.11	890.6	100	0.85	-21
JT9H	222.22	1779.5	200	0.43	-20
MSK144		2400	2000	0.07	-2/-8#
MSK144 Sh		2400	2000	0.02	-2&
FT8	6.25	50	6.25	12.64	-20

*achieved with 30 second average   #for 70ms/500ms burst   &20ms burst

The ability of a mode to tolerate changing Doppler shift will be most important on the higher frequencies and when aircraft flying perpendicular to the inter-station path are used for scattering objects. Greater tone spacing should give greater immunity to changing Doppler shift, and so from this standpoint the two ISCAT modes and the fast JT9 modes are superior to the other modes. Conversely, MSK144 will not tolerate Doppler shift and so is excluded from consideration for those situations where significant and changing Doppler shift occurs.

The ability to achieve successful decodes when only short bursts of information are received will also be most important on the higher frequencies. In terms of getting the greatest amount of information across during a short burst, higher Baud rates are better, and so again the ISCAT Modes and the fast JT9 modes rise

to the top of the heap. Transmit duration is highly correlated with Baud rate, and by this parameter the ISCAT and fast JT9 modes are again selected as being good candidates for use with AS. In terms of both Baud rate and Tx duration, JT9F, JT9G, and JT9H appear to be superior to the ISCAT modes.

Those modes with the smallest value (most negative value) for S/N in the chart above (which is the S/N ratio at which correct decodes will occur 50% of the time or more) will have superior weak signal mode performance, and in this regard JT9F, JT9G, and JT9H appear to be superior to the ISCAT modes.

There is often limited time available to complete an AS contact while the aircraft is in the "sweet spot" where FSE is maximized and the aircraft is above the radio horizon for both stations. The slow modes, which include JT65, QRA65, JT4, and the slow forms of JT9 take more than 40 seconds for one transmission period, and this is generally too long for AS work unless the aircraft is running down the center of the direct inter-station path. So these modes are clearly sub-optimal in this regard, although under some circumstances they may be useful.

Rex Moncur ha found ISCAT-A to be the best mode to use with AS on 10 GHz. But on 24 GHz it was not sensitive enough to cope with the increased losses related to water vapor absorption, and so he used JT65-C to for his 462 km and 566 km 24 GHz QSOs. See reference 3 for more on this subject. Rex has not yet tried the new JT9 fast modes for AS.

In practice, ISCAT-A with 15 second periods works well for microwave AS QSOs. On the lower bands where signal peak durations will be longer and Doppler shift smaller, the slow modes such as JT65 can be useful if the plane is available for sufficient time to enable the completion of a contact.

Summary Aircraft Scatter has proven itself to be a very useful tool for extending communications distance on the VHF, UHF, and microwave bands. There are some important guidelines for its use:

1. Try to use aircraft with minimal skew angle (<3-5 degrees), to maximize FSE.
2. Try to use aircraft flying along and parallel to the inter-station path to maximize QSO time, maximize FSE, and minimize Doppler shift and its rate of change
3. Use a program like Aircraft Scatter Sharp to track aircraft in real time so that you know the aircraft's position, heading, and speed, so that you know the Doppler shift and its rate of change, and so that you have some idea of its RCS.
4. Know the beamwidth of your antennas so that you can determine whether or not you need to point away from the direct path between you and your QSO partner and towards the aircraft in order to complete a QSO.
5. Make use of the digital modes to increase your ability to pull weak signals out of the noise and communicate in spite of very short signal bursts and limited QSO time as the aircraft passes through the "sweet spot" where maximum FSE occurs.

6. If you are not sure if something will work, try it and see.
7. The table below can be considered to be a rough guide to which propagation modes might be favored for particular distance and frequency combinations.

MHz km	300 or less	500	700	900
50	T	T / M	M	M
144	T	A	M / A	M
222	T	A	A	$A^{\#}$
432	T	A	A	$A^{\#}$
903	T / A*	A	A	$A^{\#}$
1296 and up	T / A*	A	A	$A^{\#}$

T = TS, A=AS, M = MS.
* TS will be favored over AS for high aircraft elevation angles
 # AS will be useful if the aircraft is above the horizon for both stations

For further information on the program Aircraft Scatter Sharp see the companion article.

--Roger Rehr W3SZ
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