

# SYNTHETIC APERTURE RADAR FREQUENCY SCAN FOR TIME-OF-ECHO COMPRESSION IMAGING MODE

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## ABSTRACT

The paper details a SAR imaging mode named frequency SCan On Receive and Transmit (fSCORT) where, a narrow, frequency-scanning transmit antenna beam is formed illuminating the swath of interest from far to near range. Similarly, the frequency-scanning receive antenna beam collects the return echo signal reflected from the ground. It is shown that the imaging technique trades (sacrifices) range resolution for (improved) signal-to-noise ratio, azimuth resolution, and swath width. It is shown that the (transmit) pulse duty cycle may be significantly increased over what is common for pulsed SAR systems, allowing for a lower peak-to-average transmit power ratio.

The imaging mode is especially suitable for spaceborne SAR systems operating at high carrier frequencies, such as X- or Ka-band where other advanced digital beam-forming techniques may not be feasible due to technology limitations, while, on the other hand, a large system bandwidth may be available.

The paper provides a mathematical model describing fSCORT operation parameters. Closed expressions for the mode performance parameters, such as range resolution, echo window length, etc. are derived.

## 1. INTRODUCTION

The development of synthetic aperture radar (SAR) instruments at higher carrier frequency is motivated, among others, by the relative wavelength scaling, which provides an increased bandwidth and reduced physical dimensions of the RF hardware, for the same coverage. The latter causes a reduced antenna area and a high length-to-height aspect ratio, which is unfavorable, since the resulting design compromise leads to systems of small swath width and low signal-to-noise ratio.

The imaging technique has been described in [1, 2, 3, 4] and utilizes the available bandwidth to form a narrow frequency-scanning antenna beam illuminating the swath of interest from far to near range. The basic concept behind the fSCORT (SCan On Receive and Transmit) imaging mode is straightforward and consists of two aspects related to the antenna's radiation pattern: 1) a frequency dependent antenna main beam 2) scanning the imaged swath from far to near range. The angular direction of the radiation pattern's main lobe of a frequency scanning antenna is a function of the signal's RF frequency. Transmitting a chirp signal will thus generate a narrow transmit beam scanning the swath over time. Consequently the receiving radiation pattern's narrow main lobe is instantaneously pointing towards the echo direction independently of its time-of-arrival. Several options exist for the realization of such an antenna ranging from simple passive arrays utilizing the intrinsic frequency dependency of antennas to active phased array antennas where the frequency dependency is imposed by controlling transmit/receive modules.

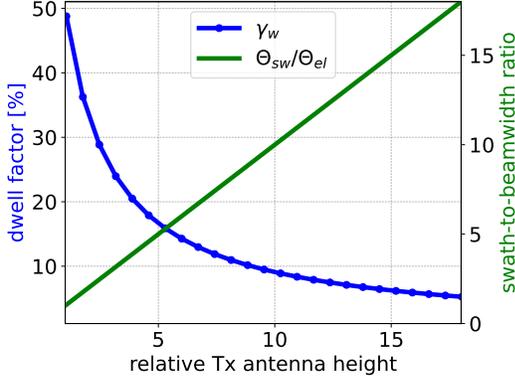
## 2. IMAGING MODE PARAMETERS

### 2.1. Dwell Bandwidth and Dwell Time

The two main parameters are the dwell time and the dwell bandwidth which are defined as the duration during which a point target is illuminated by a single radar transmit pulse and the range of frequencies (bandwidth) seen by the point target during that time, respectively. The dwell bandwidth is given by:

$$B_{dwell} = \frac{B_w}{\frac{\Theta_{sw}}{\Theta_{el}} + 1} \quad (1)$$

where  $\Theta_{sw}$  is the angular swath extent,  $\Theta_{el}$  the antenna beamwidth, and  $B_w$  the signal (chirp) bandwidth.



**Fig. 1:** Dwell bandwidth & dwell time (left ordinate) and the ratio of the angular swath extent to antenna pattern beamwidth (right ordinate) versus the normalized antenna height.

Fig. 1 shows the relative dwell bandwidth,  $B_{dwell}/B_w$  in percent versus the abscissa taken to be the antenna height normalized to the height of a stripmap antenna imaging the same swath. The right ordinate of Fig. 1 represents the swath-to-beamwidth ratio,  $\Theta_{sw}/\Theta_{el}$ .

Similarly, the expression for the dwell time is derived in terms of the transmit pulse duration  $\tau_p$  to be:

$$\tau_{dwell} = \frac{\tau_p}{\frac{\Theta_{sw}}{\Theta_{el}} + 1}. \quad (2)$$

Comparing (2) to (1) shows an identical form of dependency for the dwell time and dwell bandwidth. A reduced dwell bandwidth is advantageous in terms of the SNR, while the opposite is true for the dwell time, since a reduced point target illumination time reduces the average power density and by this causes a reduced SNR.

## 2.2. Echo Time Reversal Condition

The antenna beam scans the swath from far to near range, thus directing the signal at time  $t_1$  to the *far* range and at  $t_1 + \tau_p$  to the *near* range. The scattered echo, w.r.t. the beam center, will arrive at time instance  $t_{far} = t_1 + \tau_{dwell}/2 + 2R_{far}/c_0$  while the echo of the lagging pulse edge will arrive from the near range at time  $t_{near} = t_1 + \tau_p - \tau_{dwell}/2 + 2R_{near}/c_0$ .

The imaging technique allows for an echo time reversal, which occurs when the far range echo arrives before the near range echo. The condition for the minimum

pulse duration to ensure echo time reversal is:

$$t_{far} = t_{near} \Rightarrow \tau_p = \tau_0 = \frac{2}{c_0} (R_{far} - R_{near}) \frac{\Theta_{sc}}{\Theta_{sw}} \quad (3)$$

The ratio of transmit-to-intrinsic pulse duration is relevant, as it allows specifying the fSCORT operation point, defined by:

$$O_p = \frac{\tau_p}{\tau_0} = \frac{\tau_p c_0}{2(R_{far} - R_{near})} \frac{\Theta_{sw}}{\Theta_{sc}} \quad (4)$$

## 3. TIMING PARAMETERS

### 3.1. Range-Time Dependency

For a spherical Earth model there is a one-to-one correspondence between look (off-nadir) angle and slant range. Using the expression for the time varying scan angle

$$\theta_0(t) = \theta_s - \frac{\Theta_{sc}}{\tau_p} \Delta t \quad (5)$$

yields the expression for the range at the beam center as a function of time:

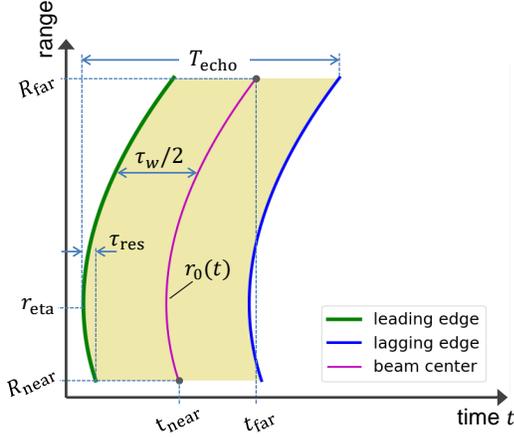
$$r_0(t) = r_O \cos \theta_0(t) - \sqrt{r_E^2 - (r_O \sin \theta_0(t))^2} \quad (6)$$

where  $r_O = r_E + h_{sat}$  is the radius of the satellite orbit, with the Earth radius  $r_E$  and orbit height  $h_{sat}$ , respectively; measured w.r.t. nadir direction

The return echo from range  $r_0(t)$  will be received after a time delay  $2r_0(t)/c_0$  at time:

$$t = t_1 + \Delta t + \frac{2r_0(t)}{c_0} \quad (7)$$

The last two expressions are plotted in Fig. 2 showing the slant range  $r_0(t)$  (bold line) versus the echo arrival time. The shaded region marks the time duration during which a point at range  $r_0(t)$  is within the antenna patterns main beamwidth, which corresponds to the dwell time  $\tau_{dwell}$ . The total echo duration  $T_{echo}$  is the time difference between the time of the last and first return. In Fig. 2 the system operates slightly below inversion point at  $O_p = 0.95$ . Here, the echo compression still occurs, although  $t_{near} < t_{far}$ . Further it is noticed that a residual time  $\tau_{res}$  exists since the minimum arrival time is slightly smaller than  $t_{near}$ .



**Fig. 2:** Range versus time of echo arrival for a SAR operating in the f-fSCORT mode at  $O_p = 0.95$ .

### 3.2. The Echo Window Length

The echo window duration is the time during which the scattered echo signal from the imaged swath arrives at the radar. It is given by:

$$T_{echo} = |t_{near} - t_{far}| + \tau_{dwell} + \tau_{res} \quad (8)$$

where  $t_{far}$  and  $t_{near}$ , defined earlier, mark the echo return times when the beam center moves into and out of the swath, respectively; while the last term is the residual time accounts for the fact that the minimum time of arrival might be smaller than  $t_{near}$  or  $t_{far}$ . Inserting into the above expressions and rearranging terms gives:

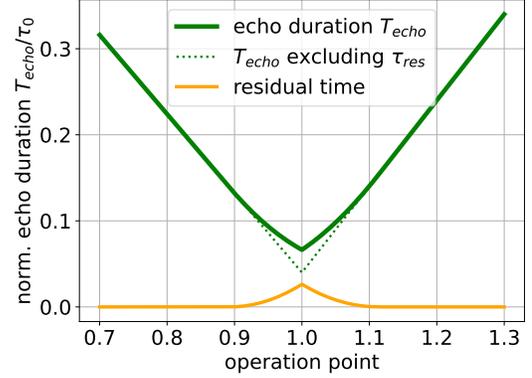
$$T_{echo} = (|(O_p - 1)(\gamma_w - 1)| + \gamma_w O_p) \tau_0 + \tau_{res} \quad (9)$$

To determine  $\tau_{res}$  the echo return time in (7) is differentiated with respect to  $\Delta t$ , the result set to zero and solved for angle  $\theta_{eta}$  pointing to the direction from which the earliest return echo arrives.

Fig. 3 shows the echo window length versus operation point for a fixed intrinsic duration, where the latter is minimum for  $O_p = 1$ . This is intuitively expected, and, given that  $0 < \gamma_w < 1$ , is a general case for fSTEC operation.

### 3.3. Pulse Repetition Frequency

A crucial parameter of SAR is the pulse repetition frequency (PRF),  $f_{PRF} = 1/T_{PRI}$  where  $T_{PRI}$  is the pulse repetition interval, which should be sufficient large to accommodate the transmit pulse duration  $\tau_p$  and

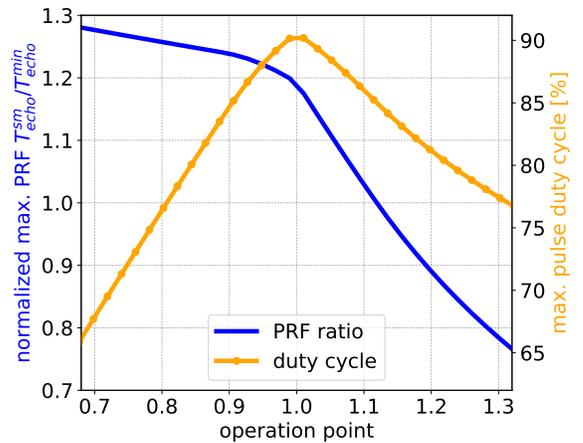


**Fig. 3:** Echo window length normalized to the intrinsic time versus the operation point. Clearly the minimum echo duration is at the reversal point  $O_p = 1$ .

the echo window length  $T_{echo}$ , in addition to a margin (guard time)  $\tau_g$ . The minimum PRI is expressed as:

$$T_{PRI}^{min} = T_{echo} + \tau_p + 2\tau_g \quad (10)$$

Fig. 4 shows the maximum PRF normalized to the stripmap SAR PRF versus the operation point for an example dwell ratio of  $\gamma_w = 10\%$ . The plot shows that near the reversal point the PRF is slightly higher with respect to stripmap operation; this allows a more square-like antenna shape and a better azimuth resolution.



**Fig. 4:** Maximum PRF of an fSCORT SAR relative to the PRF of a stripmap SAR imaging the same swath (left ordinate) and the percentage pulse duty cycle (right ordinate) plotted versus the operation point  $O_p$ .

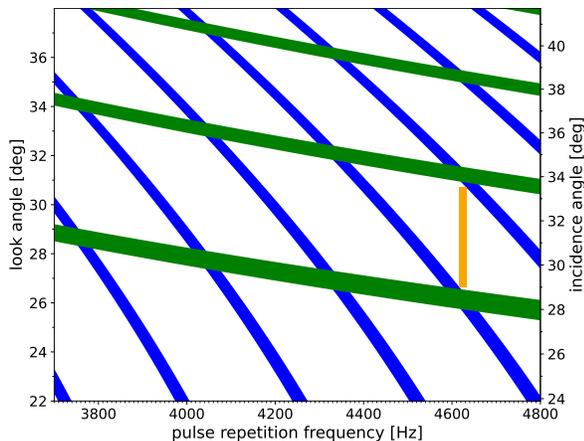
The peak duty cycle at the reversal point exhibits exceptionally high values in the order of 90%. This allows

for low peak-to-average transmit power and is believed to be a major advantage of fSCORT operation as it significantly reduces the complexity of the transmitter unit and allows for large transmit power thus improving the SNR, one of the main challenges of spaceborne Ka-band SAR.

### 3.4. Swath Position Limits

The imaged swath width and position is determined from the timing (diamond) diagram so as to avoid an overlap of the signal echo and the transmit pulse (the imaging gap caused by the transmit pulses is discussed in [5]). It turns out that an identical approach is not applicable to fSCORT SAR, because the echo duration  $T_{echo}$ , the swath width  $\propto (R_{far} - R_{near})$ , and the transmit pulse duration  $\tau_p$  are not independent parameters.

A graphical representation similar to the well known timing diagram is possible provided that the operation point,  $O_p$  is known in order to determine the (start/stop) position of the swath from the timing diagram. The approach considering both the transmit pulse as well as the nadir return blockage is beyond the space limit of this paper and is therefore detailed in [6]. The fSCORT timing diagram for a system operating at a duty cycle of 82% is shown in Fig. 5 and appears familiar



**Fig. 5:** Timing (diamond) diagram for fSCORT system operating at a 82% duty cycle. The transmit pulse blockage (blue strips) and the nadir echo return (green strips) are plotted versus pulse repetition frequency. The imaged swath is indicated by the orange bar.

## 4. CONCLUSION

The paper describes an imaging technique, previously referred to as FSCAN in [1, 2, 4]. The governing mode and instrument parameters of the radar imaging technique are derived in the form of simple closed expressions and the resulting performance is analyzed. It is suggested that fSCORT mode is a suitable choice for SAR systems operating at higher carrier frequencies such as Ka band and above.

## 5. REFERENCES

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