Theoretical Research on New Concepts for the Remote Sensing of Hydrometeors

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ABSTRACT

There is an interest for climatology and meteorology to map hydrometeors, and in particular precipitation, both over the entire globe and across large defined regions. To achieve this goal at the proper spatial and temporal resolution which are required to satisfy the end users needs it has been proposed to use satellite based observations.

This paper presents the results of a theoretical study aiming to the research of new concepts for the remote sensing of hydrometeors with emphasis on precipitation. The concept proposed is a Focused Wide band millimeter wave INTERferometer (WINTER–F) comprising a constellation of two small satellites, flying close to each other. The two satellites, which are phase synchronized by the GNSS (Global Navigation Satellite System) signals, perform near field interferometry by passive (radiometer) and active (radar) means. The study comprises the realization of laboratory experiments to check the validity of the theoretical models.

INTRODUCTION: THE WINTER–F CONCEPT

The Winter–f (mm–Wave wide band INTERferometer – Focused) concept, which was first developed for a passive system, comprises the following main theoretical basis [1]:

– a radiometer can have range resolution much in the same way as a radar does [2],

– range resolution in the one direction is achieved by decorrelation;

– range resolution in another direction is obtained by doppler processing;

When these theoretical basis are applied to a spaceborne passive system for Earth remote sensing the following theoretical results are found:

– the signals from the ground and the continuous atmosphere can be filtered out by selecting a proper spatial frequency (satellite baseline) of observation;

– the signals originated by the hydrometeors (both through scattering and emission) can be observed by the properly chosen satellite baseline;

– the output of the passive system is proportional to the density of hydrometeor particles in the atmosphere.

Thus, the theoretical conclusion is that a radiometer system can be built able to measure directly the density of hydrometeor particles (i.e. rain rate) free of contamination from the background (ground and continuous atmosphere).

The same concept can be applied to an active system (radar) where time gating can be performed. In this case we have a third degree of freedom and the spatial resolution in the third dimension becomes possible.

WINTER–F IMPULSE RESPONSE

Let us compute the response to a point source consisting of an element of volume filled with short dipoles. The current through every short dipole is assumed to represent the processes of emissivity, absorption and scattering which occur in the interaction between matter and radiation.

Consider two receiving antennas at points P_1 and P_2. The signal from every small dipole arrives at point P_1 producing a voltage

$$V_1(t) = \int_{a.s.d.} dV_1(t) \qquad (1)$$

where dV_1 is the voltage produced by every single short dipole and ***a.s.d*** stands for ***all short dipoles***. The signals of the short dipoles arrive at P_2 as well and a similar expression can be written for the voltage at the second antenna.

The antenna voltages constitute the input signals to the receivers and get thus filtered by their frequency response. The impulse response of the Winter–f system is given by the cross correlation of the two receiver outputs

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which assuming coherence between the local oscillators becomes

$$\Gamma_{S_1 S_2}(\tau) = B \left(\frac{\eta L}{2\lambda}\right)^2 \frac{\chi}{r_1 r_2}$$
$$\langle |J|^2 \rangle \, \mathrm{sinc}\left[B(\tau - \Delta r / c) \right] e^{-jk\Delta r} \, dV \quad (2)$$

where $\Gamma_{S_1 S_2}(\tau)$ is the cross correlation evaluated at time τ, B the bandwidth, L the antenna effective length, η the intrincic impedance of vacuum, λ the wavelength, χ an obliquity factor, r_1 and r_2 the distances between the source point and the receivers, $\langle |J|^2 \rangle dV$ the intensity of the source, $\Delta r = r_1 - r_2$ the path difference, c the light speed and k the wavenumber.

RANGE DISCRIMINATION BY DECORRELATION

The impulse response (2) shows that the spatial distribution of the source intensity is weighted by the system filter response according to the sinc function. This fringe washing function accounts for the decorrelation of the signal due to the finite system bandwidth. Thus the system is only sensitive to that volume for which the decorrelation is not excessive, that is, to those points whose path delay is compensated by the system delay within the main lobe of the sinc function

$$\left| \tau - \frac{\Delta r}{c} \right| < \frac{1}{2B} \quad (3)$$

The geometrical volume defined by this equation corresponds to the space between two hyperboloids with foci at the observation points P_1 and P_2 and has been depicted in Figure 1. By changing the system delay τ we can make the sinc function to peak on a different hyperboloidal volume. A range of values of τ correspond to a range of hyperboloidal shells. We realize in this way that we have built a radiometer system which has ranging capability based on near field observations from two points.

SYSTEM RESPONSE TO A DISTRIBUTED SOURCE

When the impulse response (2) is applied over a *uniform* distributed source such as the ground or the gaseous atmosphere it vanishes because $k\Delta r \gg 1$ over the volume of correlation:

$$\Gamma_{S_1 S_2}(\tau) \rightarrow 0 \quad (4)$$

In practice the interferometer would give an output equal to its radiometric sensitivity.

On the contrary, when the impulse response is applied to a *discrete* source such as a distribution of water particles a non zero value is found

$$\Gamma_{S_1 S_2}(r_o) = B \left(\frac{\eta L}{2\lambda}\right)^2 \frac{\chi}{r_1 r_2} \langle |J_p|^2 \rangle \sum_{i=1}^{N} e^{-jk\Delta r_i} \quad (5)$$

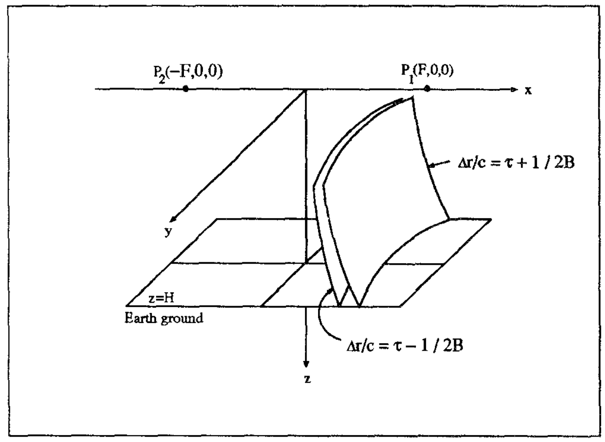

Figure 1: Range discrimination by decorrelation

where the subindex p denotes 'particle' and the summation extends only to the N particles contained inside the resolution volume, for which

$$r_o - \frac{r_c}{2} \leq \Delta r_i \leq r_o + \frac{r_c}{2} \quad (6)$$

$r_c \equiv c/B$ being the correlation length. Assuming a random distribution of particles, the average (over the ensemble of particle distributions) of (5) yields

$$\langle \Gamma_{S_1 S_2}(r_o) \rangle = 0 \quad (7)$$

and its standard deviation

$$\sigma_\Gamma = B \left(\frac{\eta L}{2\lambda}\right)^2 \frac{|\chi|}{r_1 r_2} \sqrt{N} \langle |J_p|^2 \rangle \quad (8)$$

This equation is the response of the Winter–f interferometer to hydrometeor particles and shows that the standard deviation of the cross correlation between the two receivers is proportional to the product of the square root of the number of particles in the resolution volume times the intensity of the particle. The standard deviation of the cross correlation can be measured by root mean square averaging of independent samples.

STUDY ON THE SATELLITE CONSTELLATION

The iso–delta range and iso–delta doppler family lines for a pair of satellites flying close to each other in different configurations have been computed. The optimum view geometry is that providing a perpendicular crossing between the iso–range and iso–doppler lines. One possible scenario was selected where the two satellites fly along the same orbit keeping a spacing of a few kilometers. The local oscillators of the radiometers of the two satellites

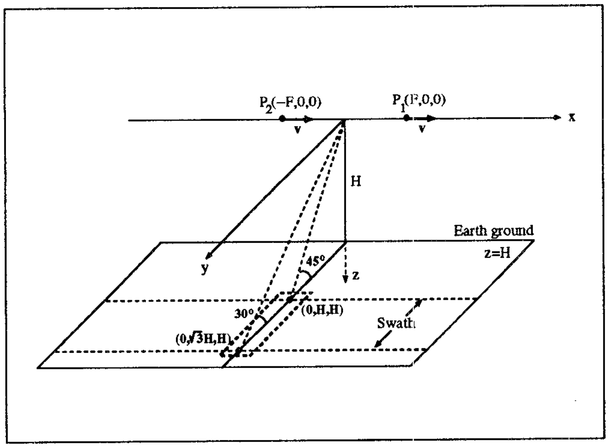

Figure 2: Selected orbital scenario and view geometry

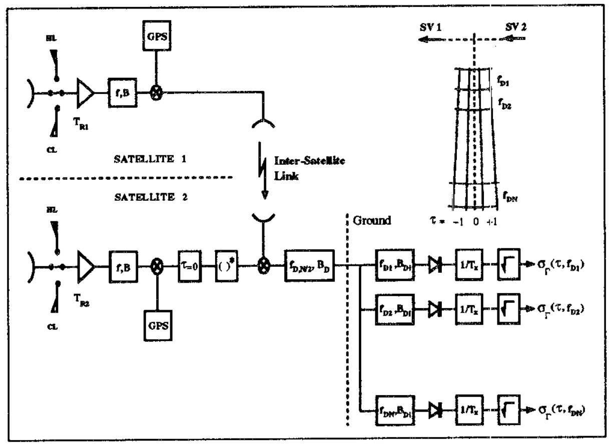

Figure 3: Winter–f block diagram

are derived from the GNSS signals and are thus coherent. The iso–delta range lines are across track while the iso–delta doppler lines are along track. This scenario has been depicted in Figure 2.

RANGE DISCRIMINATION BY DOPPLER

As seen from the system response in (5) the cross correlation of every particle has a different delta doppler shift, defined by

$$\Delta f_i(t) \equiv \frac{1}{\lambda}\frac{d\,\Delta r_i(t)}{dt} \qquad (9)$$

where the sub–index refers to particle i. The further a particle is from the satellites ground track the smaller the doppler is in its cross correlation function.

The cross correlation function is then passed through a bank of doppler sharpening filters to achieve spatial discrimination. The output of every filter corresponds to a different region limited by a pair of iso–delta doppler lines. The width of the doppler filters, and hence, the spatial resolution achievable by doppler, is limited by the transit time and the velocity of the particles.

WINTER–F BLOCK DIAGRAM

The conceptual block diagram of the Winter–f passive interferometer can be derived from the previous theoretical study and is shown in Figure 3. Typically a dual frequency sensor would most likely b mused. The satellites are provided with a radio link to be able to perform the cross correlation on board.

ACTIVE INTERFEROMETRY IN WINTER–F

The same concepts explained on the passive interferometer can be applied to the case when one satellite transmits a pulsed noise–like (or deterministic) signal and the two satellite receive the echo afterwards.

If S_M and S_B indicate the signals received by the transmitting satellite and the second satellite respectively we arrive at the result that the cross correlation $\langle S_M(t)S_B^*(t)\rangle$ is null while the autocorrelations $\langle S_M(t)S_M^*(t)\rangle$ and $\langle S_M(t)S_B^*(t)\rangle$ are proportional to the number of raindrops within the resolution volume.

The fourth order correlation $\langle S_M(t)S_M^*(t)S_B^*(t)S_B(t)\rangle$ is proportional to the product of the two second order autocorrelations, thus giving the number of raindrops within the resolution cell. The properties of the fourth order correlation as an estimator of rain density, both regarding the accuracy of the estimate and the spatial resolution are currently under investigation.

CONCLUSION

The study predicts, within the limitation of the models used, the possibility of a radiometer system with range capability which is sensitive to the hydrometeors but not to the background.

A laboratory experiment of the fundamental concepts is being undertaken to compare the theoretical predictions with the real world behaviour. The usefulness of this effort is worth in view of its potential for a satellite based Rain Detection System.

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