ESTIMATING SOIL MOISTURE PROFILE DYNAMICS FROM NEAR-SURFACE SOIL MOISTURE MEASUREMENTS AND STANDARD METEOROLOGICAL DATA

by

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to

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I hereby certify that the work embodied in this thesis is the result of original research and has not been submitted for a higher degree to any other University or Institution, and to the best of my knowledge this thesis does not contain any material previously published or written by another person, except where due reference is made in the text.

Jeffrey Walker

This work is dedicated

to my wife Wendy,

for her continual

love and support.

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SYNOPSIS

An estimate of the spatial distribution and temporal variation of soil moisture content in the top few metres of the earth's surface is important for numerous environmental studies. Soil moisture content can be determined from: (i) point measurements; (ii) soil moisture models; and (iii) remote sensing. Only a limited area can be monitored with an adequate spatial and temporal resolution using the point measurement technique, while estimates from distributed soil moisture models are generally poor. This is due to an incomplete knowledge of model physics and the large spatial and temporal variation of soil moisture that results from heterogeneity in soil properties, vegetation and precipitation. Remote sensing can be used to collect spatial data over large areas on a routine basis, providing a capability to make frequent and spatially comprehensive measurements of the near-surface soil moisture content. However this technique is limited by an infrequent satellite repeat time and the shallow depth of the soil moisture measurements, consisting of the top few centimetres at most. These upper few centimetres of the soil are the most exposed to the atmosphere, and their soil moisture content varies rapidly in response to rainfall and evaporation.

This thesis overcomes the limitations of the above approaches for determining soil moisture, by linking a physical model of soil moisture movement in both the vertical and horizontal directions, with a data assimilation technique that uses near-surface soil moisture measurements. In this way, the near-surface soil moisture measurements are interpolated in space and time between satellite overpasses, and extrapolated over the soil profile depth. The point measurements of soil moisture profiles are used for calibration of the soil moisture forecasting model, and ongoing evaluation the soil moisture profile estimation from data assimilation.

To address the poor resolution in time of remote sensing data, a water balance approach is used to model soil moisture during the inter-observation period. Using this approach, the soil moisture hydrologic model is forced using estimates of evapotranspiration and precipitation from standard meteorological data. As observations of the near-surface soil moisture content become available, they are incorporated into the soil moisture model using an assimilation technique. This has required the development of a hydrologic model specifically designed to accept remote sensing data as input.

In this thesis, a theoretical model is developed for estimating the satellite observation depth for active microwave observations. Moreover, a procedure is

proposed for inferring the soil moisture profile over the observation depth, from active microwave remote sensing observations.

This thesis has compared the Dirichlet boundary condition, hard-updating and Kalman-filtering assimilation schemes for estimation of the soil moisture profile. Conclusions are reached for the efficiency of these assimilation schemes, the depth over which near-surface soil moisture measurements are required, and the effect of updating interval on soil moisture profile estimation. These questions are addressed initially by a one-dimensional Richards equation soil moisture forecasting model using synthetic data. The study has shown that the Kalman-filter is superior to the hard-updating and Dirichlet boundary condition assimilation schemes. It is has also shown that the observation depth did not have a significant effect on improving the soil moisture profile estimation when using the Kalman-filter assimilation scheme. Moreover, the Kalman-filter was less susceptible to unstable updates if volumetric soil moisture was modelled as the dependent state, rather than matric head.

While suitable for the one-dimensional problem, the Richards equation model was too computationally demanding for the distributed catchment application. Hence, a computationally efficient distributed soil moisture forecasting model for both vertical and lateral redistribution of soil moisture content, based on a conceptualisation of the Buckingham-Darcy equation, was developed. Moreover, the Kalman-filter assimilation scheme was too computationally demanding for forecasting of the model covariance matrix in a spatial application. To overcome this computational burden, a Modified Kalman-filter was developed, which forecast the model covariance matrix using a dynamics simplification approach.

Both the distributed soil moisture forecasting model and the Modified Kalman-filter have been applied to a field application at the “Nerrigundah” experimental catchment. While an application of the one-dimensional version of this simplified soil moisture model has evaluated the vertical redistribution component, the catchment application has evaluated the lateral redistribution component. Moreover, the usefulness of near-surface soil moisture measurements for updating of soil moisture models to improve the prediction of soil moisture content over the soil profile has been illustrated, showing that an improved estimate of the soil moisture profile was achieved.

LIST OF ACRONYMS AND ABBREVIATIONS

ABDOMEN1D	Approximate Buckingham-Darcy equatiOn for Moisture EstimatioN in 1 Dimension
ABDOMEN3D	Approximate Buckingham-Darcy equatiOn for Moisture EstimatioN in 3 Dimensions
AHD	Australian Height Datum
AMI	Active Microwave Instrument
AMG	Australian Map Grid
AMSR	Advanced Microwave Scanning Radiometer
API	Antecedent Precipitation Index
AS	Australian Standard
DEM	Digital Elevation Model
DGPS	Differential Global Positioning System
EMAC'94	European Multi-sensor Airborne Campaign 1994
EMI	ElectroMagnetic Induction
EMSL	European Microwave Signature Laboratory
ERS	European Remote Sensing
ESTAR	Electronically Scanned Thinned Array Radiometer
FWM	Full Wave Model
GCM	Global Climate Model
GOM	Geometrical Optics Model
GPS	Global Positioning System
hh	transmitted and received waves are horizontally polarised
hv	transmitted wave is horizontally polarised and received wave is vertically polarised
IEM	Integral Equation Model
JERS	Japanese Earth Resources Satellite
KM	Kirchhoff Model
MIMR	Multi-frequency Imaging Microwave Radiometer
MSS	Multi Spectral Scanner
NASA	National Aeronautical and Space Administration

NDVI	Normalised Difference Vegetation Index
NMM	Neutron Moisture Meter
PBMR	Push-Broom Microwave Radiometer
POM	Physical Optics Model
PPM	Phase Perturbation Model
PROXSIM1D	PROfile eXplicit SIMulation in 1 Dimension
RADAR	RAdio Detection And Ranging
rms	root mean square
SAR	Synthetic Aperture Radar
SIF	Soil Indication Functions
SPM	Small Perturbation Model
SPLaSHWaTr	Simulation Program for Land-Surface Heat and Water Transport
SPOT	Systeme Pour l'Observation de la Terre
SVAT	Soil Vegetation Atmosphere Transfer
SWATRE	Soil Water Actual TRanspiration Extended
TDAS	Terrain Data Acquisition System
TDR	Time Domain Reflectometry
TM	Thematic Mapper
USDAHL	United States Department of Agriculture Hydrograph Laboratory
vh	transmitted wave is vertically polarised and received wave is horizontally polarised
vv	transmitted and received waves are vertically polarised

LIST OF SYMBOLS

A	–	vegetation structure parameter related to plant geometry
A	degrees	aspect angle
A_l	cm	wave amplitude for horizontal polarisation in layer l
A_{l+1}	cm	wave amplitude for horizontal polarisation in layer l+1
$\mathbf{A}^n$		matrix relating the system states at time n+1 to the system states at time n
$\underline{\mathbf{A}}$		state augmented **A** matrix
$\overline{\mathbf{A}}$		autoregressive smoothed **A** matrix
a	–	empirical regression coefficient
a	–	amplitude attenuation factor
a_1	–	amplitude attenuation factor of incident layer
a_2	–	amplitude attenuation factor of transmission layer
a_{nir}	–	reflectance at near infra-red wavelength
a_{pq}		empirical coefficient for transmission at polarisation p and reception at polarisation q
a_{vh}		empirical coefficient for vertically polarised transmission and horizontally polarised reception
a_{vis}		reflectance at visible wavelength
a_{vv}		empirical coefficient for vertically polarised transmission and vertically polarised reception
$\mathbf{B}$		transformation matrix
B_l	cm	wave amplitude for horizontal polarisation in layer l
B_{l+1}	cm	wave amplitude for horizontal polarisation in layer l+1
b		empirical regression coefficient
b		vegetation parameter
b	–	Clapp and Hornberger soil texture parameter
b_{pq}		empirical coefficient for transmission at polarisation p and reception at polarisation q
b_{vh}		empirical coefficient for vertically polarised transmission and horizontally polarised reception
b_{vv}		empirical coefficient for vertically polarised

		transmission and vertically polarised reception
C	g g^{-1}	clay mass fraction
C_d	cal cm^{-3} °C^{-1}	volumetric heat capacity of the dry soil
C_E	–	moisture transfer coefficient
C_i	cal cm^{-3} °C^{-1}	volumetric heat capacity of the *i*th soil constituent
C_l		wave amplitude for vertical polarisation in layer *l*
C_{l+1}		wave amplitude for vertical polarisation in layer *l*+1
C_T	cal cm^{-3} °C^{-1}	volumetric heat capacity of the bulk soil medium
C_{T_i}	cal cm^{-3} °C^{-1}	volumetric heat capacity of the bulk soil medium in layer *i*
C_2	cal cm^{-3} °C^{-1}	volumetric heat capacity of air
C_3	cal cm^{-3} °C^{-1}	volumetric heat capacity of quartz
C_4	cal cm^{-3} °C^{-1}	volumetric heat capacity of other minerals
C_5	cal cm^{-3} °C^{-1}	volumetric heat capacity of organic matter
$C_{T_2}^n$	cal cm^{-3} °C^{-1}	volumetric heat capacity of the bulk soil medium at node 2, time step *n*
$C_{T_j}^n$	cal cm^{-3} °C^{-1}	volumetric heat capacity of the bulk soil medium at node *j*, time step *n*
$C_{T_{N-1}}^n$	cal cm^{-3} °C^{-1}	volumetric heat capacity of the bulk soil medium at node *N*–1, time step *n*
C_ψ	cm^{-1}	soil capillary capacity, $C_\psi = \partial\theta/\partial\psi$
C_{ψ_1}	cm^{-1}	soil capillary capacity $\partial\theta/\partial\psi$ at node 1
C_{ψ_N}	cm^{-1}	soil capillary capacity $\partial\theta/\partial\psi$ at node *N*
$C_{\psi_2}^n$	cm^{-1}	soil capillary capacity $\partial\theta/\partial\psi$ at node 2, time step *n*
$C_{\psi_j}^n$	cm^{-1}	soil capillary capacity $\partial\theta/\partial\psi$ at node *j*, time step *n*
$C_{\psi_{N-1}}^n$	cm^{-1}	soil capillary capacity $\partial\theta/\partial\psi$ at node *N*–1, time step *n*
c	cm s^{-1}	propagation velocity of an electromagnetic wave
c	–	Brooks and Corey soil texture parameter
c_a	cal g^{-1} °C^{-1}	specific heat capacity of moist air, 0.242 cal g^{-1} °C^{-1}
c_l	cal g^{-1} °C^{-1}	specific heat capacity of liquid water, 1.0 cal g^{-1} °C^{-1}
c_o	cm s^{-1}	propagation velocity of an electromagnetic wave

		in a vacuum, 2.997925×10^{10} cm s^{-1}
c_p	cal g^{-1} °C^{-1}	specific heat capacity of water vapour at constant pressure, 0.449 cal g^{-1} °C^{-1}
D	cm	total soil depth
D_{atm}	cm^{-2} s^{-1}	molecular diffusion coefficient of water vapour in air
D_l	cm	wave amplitude for vertical polarisation in layer *l*
D_{l+1}	cm	wave amplitude for vertical polarisation in layer *l*+1
D_T	cm^2 s^{-1} °C^{-1}	thermal moisture diffusivity, $D_T = D_{Tl} + D_{Tv}$
D_{Tl}	cm^2 s^{-1} °C^{-1}	thermal liquid diffusivity
D_{Tv}	cm^2 s^{-1} °C^{-1}	thermal vapour diffusivity
D_ψ	cm s^{-1}	isothermal moisture diffusivity, $D_\psi = D_{\psi l} + D_{\psi v}$
$D_{\psi l}$	cm s^{-1}	isothermal liquid hydraulic conductivity, $D_{\psi l} = K$
$D_{\psi v}$	cm s^{-1}	isothermal vapour conductivity
$D^n_{\psi l_1}$	cm s^{-1}	isothermal liquid hydraulic conductivity of node 1, time step *n*
$D^n_{\psi l_{1\frac{1}{2}}}$	cm s^{-1}	average isothermal liquid hydraulic conductivity of nodes 1 and 2, time step *n*
$D^n_{\psi l_2}$	cm s^{-1}	isothermal liquid hydraulic conductivity of node 2, time step *n*
$D^n_{\psi l_3}$	cm s^{-1}	isothermal liquid hydraulic conductivity of node 3, time step *n*
$D^n_{\psi l_{j-2}}$	cm s^{-1}	isothermal liquid hydraulic conductivity of node *j*–2, time step *n*
$D^n_{\psi l_{j-1}}$	cm s^{-1}	isothermal liquid hydraulic conductivity of node *j*–1, time step *n*
$D^n_{\psi l_{j-\frac{1}{2}}}$	cm s^{-1}	average isothermal liquid hydraulic conductivity of nodes *j* and *j* –1, time step *n*
$D^n_{\psi l_j}$	cm s^{-1}	isothermal liquid hydraulic conductivity of node *j*, time step *n*
$D^n_{\psi l_{j+\frac{1}{2}}}$	cm s^{-1}	average isothermal liquid hydraulic conductivity of nodes *j* and *j*+1, time step *n*
$D^n_{\psi l_{j+1}}$	cm s^{-1}	isothermal liquid hydraulic conductivity of node *j*+1, time step *n*
$D^n_{\psi l_{j+2}}$	cm s^{-1}	isothermal liquid hydraulic conductivity of node *j*+2, time step *n*
$D^n_{\psi l_{N-2}}$	cm s^{-1}	isothermal liquid hydraulic conductivity of node *N*–2, time step *n*

$D^n_{\psi l_{N-1}}$	cm s^{-1}	isothermal liquid hydraulic conductivity of node N–1, time step n
$D^n_{\psi l_{N-½}}$	cm s^{-1}	average isothermal liquid hydraulic conductivity of nodes N and N –1, time step n
$D^n_{\psi l_N}$	cm s^{-1}	isothermal liquid hydraulic conductivity of node N, time step n
DX	cm	lateral distance between layer grid points
DZ	cm	perpendicular distance between layer grid points
d_l	cm	depth of soil to interface between layer l and layer l+1, positive upwards
$d_{l\text{-}1}$	cm	depth of soil to interface between layer l–1 and layer l, positive upwards
d_{l+1}	cm	depth of soil to interface between layer l+1 and layer l+2, positive upwards
d_m	cm	representative soil particle size
d_n	cm	depth of soil to layer n, positive upwards
d_o	cm	zero plane displacement of the wind profile
d_{veg}	cm	vegetation height
d_z	cm	soil layer thickness
$\mathbf{E}_i$		phasor form of the incident electromagnetic wave
$\mathbf{E}_r$		phasor form of the reflected electromagnetic wave
$\mathbf{E}_t$		phasor form of the transmitted electromagnetic wave
E		expectation
E_i	cm	incident wave amplitude
E_r	cm	reflected wave amplitude
$E_r^{\prime}$	cm	reflected wave attenuated amplitude
E_R	cm	returned wave amplitude
E_s	cm	surface scattered wave amplitude
E_t	cm	transmitted wave amplitude
$E_t^{\prime}$	cm	transmitted wave attenuated amplitude
E_v	cm	volume scattered wave amplitude
ET_a	cm s^{-1}	actual evapotranspiration
ET_p	cm s^{-1}	potential evapotranspiration
e	kPa	partial water vapour pressure
$\mathrm{e_a}$	kPa	saturation partial water vapour pressure in air
$\mathrm{e_d}$	kPa	dew point partial water vapour pressure in air
$\mathrm{e_S}$	kPa	saturation partial water vapour pressure in soil at

		the surface
e	–	smooth surface emissivity
e_h	–	smooth surface emissivity at horizontal polarisation
e_p	–	smooth surface emissivity at polarisation p
e_R	–	rough surface emissivity
e_{R_p}	–	rough surface emissivity at polarisation p
e_v	–	smooth surface emissivity at vertical polarisation
F_{hh}		complementary field coefficient for horizontally polarised transmission and horizontally polarised reception
F_{pq}		complementary field coefficient when transmission is at polarisation p and reception is at polarisation q
F_{vv}		complementary field coefficient for vertically polarised transmission and vertically polarised reception
f	Hz	frequency, $f = c/\lambda$
fc	–	vegetation fractional cover
f_{hh}		Kirchhoff coefficient for horizontally polarised transmission and horizontally polarised reception
f_{p_i}		fractional absorption of layer i at polarisation p
f_{pq}		Kirchhoff coefficient when transmission is at polarisation p and reception is at polarisation q
f_T	Hz	transition frequency
f_{vv}		Kirchhoff coefficient for vertically polarised transmission and vertically polarised reception
$GRAD_{j+1/2,k,l}$	–	average gradient parameter for grid elements j,k,l and $j+1,k,l$
$GRAD_{j,k+1/2,l}$	–	average gradient parameter for grid elements j,k,l and $j,k+1,l$
g	cm s^{-2}	acceleration due to gravity, 981 cm s^{-2}
g_2	–	shape factor of the 2nd soil constituent being air
g_i	–	shape factor of the ith soil constituent
$\mathbf{H}$		matrix relating the observation vector $\mathbf{Z}$ to the system state vector $\mathbf{X}$
$\mathbf{H}^{n+1}$		$\mathbf{H}$ matrix at time $n+1$
$\underline{\mathbf{H}}$		state augmented $\mathbf{H}$ matrix
h	–	effective roughness factor
h_c	cm	crop height

$\mathbf{I}$	–	identity matrix
Im( )	–	imaginary part of ( )
i	–	imaginary number, •–1
$J_0(\,)$		Bessel function of the first kind of order 0
$J_{-v}(\,)$	–	Bessel function of the second kind of order v with the imaginary argument
K	cm s^{-1}	unsaturated hydraulic conductivity of soil
$K_{j,k,l}$	cm s^{-1}	unsaturated hydraulic conductivity of soil for grid element j,k,l
$K_{j+1/2,k,l}$	cm s^{-1}	average unsaturated hydraulic conductivity of soil for grid elements j,k,l and $j+1,k,l$
$K_{j+1,k,l}$	cm s^{-1}	unsaturated hydraulic conductivity of soil for grid element $j+1,k,l$
$K_{j,k+1/2,l}$	cm s^{-1}	average unsaturated hydraulic conductivity of soil for grid elements j,k,l and $j,k+1,l$
$K_{j,k+1,l}$	cm s^{-1}	unsaturated hydraulic conductivity of soil for grid element $j,k+1,l$
K_s	cm s^{-1}	saturated hydraulic conductivity of soil
$\mathbf{K}^{n+1}$		Kalman-filter gain matrix at time $n+1$
k	–	von Karmen constant, 0.41
k	cm^{-1}	wave number, $k = 2\pi/\lambda = 2\pi f \bullet (\mu\varepsilon)$
k_1	–	ratio of the average temperature gradient in the soil liquid water to the average temperature gradient of the bulk medium
k_2	–	ratio of the average temperature gradient in the soil air to the average temperature gradient of the bulk medium
k_3	–	ratio of the average temperature gradient in the soil quartz to the average temperature gradient of the bulk medium
k_4	–	ratio of the average temperature gradient in the soil minerals to the average temperature gradient of the bulk medium
k_5	–	ratio of the average temperature gradient in the soil organic matter to the average temperature gradient of the bulk medium
k_i	–	ratio of the average temperature gradient in the ith soil constituent to the average temperature gradient of the bulk medium
k_1	cm^{-1}	wave number in incident layer
k_{x1}	cm^{-1}	x component of wave number in incident layer,

		$k_{x1} = k_1 \sin\vartheta$
k_{z1}	cm^{-1}	z component of wave number in incident layer, $k_{z1} = k_1 \cos\vartheta$
k_2	cm^{-1}	wave number in transmission layer
k_{x2}	cm^{-1}	x component of wave number in transmission layer, $k_{x2} = k_2 \sin\vartheta$
k_{z2}	cm^{-1}	z component of wave number in transmission layer, $k_{z2} = k_2 \cos\vartheta$
k_l	cm^{-1}	wave number in layer l, $k_l = 2\pi f \bullet (\mu_l \varepsilon_l)$
k_o	cm^{-1}	free space wave number, $k_o = 2\pi/\lambda_o$
k_{o_T}	cm^{-1}	free space wave number at the transition frequency
k_v	–	propagation constant depending on the dielectric properties of the vegetation layer
k_x	cm^{-1}	x component of wave number, $k_x = k \sin\vartheta$
k_{xo}	cm^{-1}	x component of free space wave number, $k_{xo} = k_o \sin\vartheta$
k_z	cm^{-1}	z component of wave number, $k_z = k \cos\vartheta$
k_{zl}	cm^{-1}	z component of wave number in layer l, $k_{zl} = 2\pi f \bullet (\mu_l \varepsilon_l) \cos\vartheta$
$k_{z(l+1)}$	cm^{-1}	z component of wave number in layer $l+1$
k_{zl}'	cm^{-1}	real part of z component of wave number in layer l
k_{zl}''	cm^{-1}	imaginary part of z component of wave number in layer l
k_{zo}	cm^{-1}	z component of free space wave number, $k_{zo} = k_o \cos\vartheta$
k_{zt}''	cm^{-1}	imaginary part of z component of wave number in region t
L	cm	length of hillslope
L	cm	length of transmission line
L	$\mathrm{cal\ g}^{-1}$	latent heat of vaporisation
L_{ref}	$\mathrm{cal\ g}^{-1}$	latent heat of vaporisation at the reference temperature T_{ref}, 591.6 $\mathrm{cal\ g}^{-1}$ at 10 °C
LAI	–	leaf area index
LDF	–	lateral distribution factor
l	cm	surface correlation length
M_o	–	soil moisture availability
$MGRAD$	cm, $\mathrm{cm\ cm}^{-1}$	maximum gradient parameter

$MGRAD_{j,k,l}$	cm, cm cm^{-1}	maximum gradient parameter for grid element *j*,*k*,*l*
$MGRAD_{j+1,k,l}$	cm, cm cm^{-1}	maximum gradient parameter for grid element *j*+1,*k*,*l*
$MGRAD_{j,k+1,l}$	cm, cm cm^{-1}	maximum gradient parameter for grid element *j*,*k*+1,*l*
m	cm^{-1}	transition rate factor
m	–	van Genuchten soil texture parameter
m_w	cm	Clapp and Hornberger parameter
NDVI	–	normalised difference vegetation index
$\mathrm{NDVI}_{\max}$	–	maximum normalised difference vegetation index
$\mathrm{NDVI}_{\min}$	–	minimum normalised difference vegetation index
N	–	number of layers
n	–	refractive index
n	–	van Genuchten soil texture parameter
n_w	–	Clapp and Hornberger parameter
P	cm	cumulative precipitation
P	cal cm^{-2} $°C^{-1}$ $s^{-1/2}$	soil thermal inertia
P_{atm}	kPa	atmospheric pressure
Q	–	polarisation mixing factor
Q	cm s^{-1}	volumetric flux of liquid water, +ve downwards
Q_{ss}	cm^2 s^{-1}	sub-surface discharge
Q_V	cm s^{-1}	volumetric flux of liquid water in the vertical direction, +ve downwards
$Q_{V\,j-1,k,l}$	cm s^{-1}	volumetric flux of liquid water in the vertical direction for grid element *j* −1,*k*,*l*, +ve downwards
$Q_{V\,j,k,l}$	cm s^{-1}	volumetric flux of liquid water in the vertical direction for grid element *j*,*k*,*l*, +ve downwards
Q_L	cm s^{-1}	volumetric flux of liquid water in the lateral direction, +ve downwards
$Q_{L\,j,k,l-1}$	cm s^{-1}	volumetric flux of liquid water in the lateral direction for grid element *j*,*k*,*l*–1, +ve downwards
$Q_{L\,j,k,l}$	cm s^{-1}	volumetric flux of liquid water in the lateral direction for grid element *j*,*k*,*l*, +ve downwards
$\mathbf{Q}$		covariance matrix of the system noise
$\mathbf{Q}^n$		covariance matrix of the system noise at time

		step *n*
$\mathbf{Q}_\mathrm{x}$		covariance matrix of the system noise of the system states
$\mathbf{Q}_\alpha$		covariance matrix of the system noise of the system parameters
$\underline{\mathbf{Q}}$		covariance matrix of the system noise of the state augmented system
Q_{bot}^{T}	cal cm^{-2} s^{-1}	soil heat flux at bottom of soil column, +ve upwards
Q_{top}^{T}	cal cm^{-2} s^{-1}	soil heat flux at top of soil column, +ve upwards
Q_{bot}^{ψ}	cm s^{-1}	volume soil moisture flux at bottom of soil column, +ve upwards
Q_{top}^{ψ}	cm s^{-1}	volume soil moisture flux at top of soil column, +ve upwards
q_S	–	specific humidity in the soil at the surface
q_T	–	specific humidity in the air at height z_T
q_{in}	g cm^{-2} s^{-1}	mass flux into elemental area, +ve upwards
q_{h}	cal cm^{-2} s^{-1}	soil heat flux, +ve upwards
q_{h_i}	g cm^{-2} s^{-1}	soil heat flux entering the bottom of the soil layer *i*
$\mathrm{q}_{h_{i-1}}$	g cm^{-2} s^{-1}	soil heat flux leaving the top of the soil layer *i*
q_{l}	g cm^{-2} s^{-1}	liquid mass flux, +ve upwards
$\mathrm{q}_{l_1}^{n}$	g cm^{-2} s^{-1}	liquid mass flux at node 1, time step *n*
$\mathrm{q}_{l_2}^{n}$	g cm^{-2} s^{-1}	liquid mass flux at node 2, time step *n*
$\mathrm{q}_{l_3}^{n}$	g cm^{-2} s^{-1}	liquid mass flux at node 3, time step *n*
$\mathrm{q}_{l_{j-1}}^{n}$	g cm^{-2} s^{-1}	liquid mass flux at node j–1, time step *n*
$\mathrm{q}_{l_j}^{n}$	g cm^{-2} s^{-1}	liquid mass flux at node j, time step *n*
$\mathrm{q}_{l_{j+1}}^{n}$	g cm^{-2} s^{-1}	liquid mass flux at node j+1, time step *n*
$\mathrm{q}_{l_{N-2}}^{n}$	g cm^{-2} s^{-1}	liquid mass flux at node N–2, time step *n*
$\mathrm{q}_{l_{N-1}}^{n}$	g cm^{-2} s^{-1}	liquid mass flux at node N–1, time step *n*
$\mathrm{q}_{l_N}^{n}$	g cm^{-2} s^{-1}	liquid mass flux at node N, time step *n*
q_{m}	g cm^{-2} s^{-1}	total mass flux, $\mathrm{q}_m = \mathrm{q}_l + \mathrm{q}_v$
q_{out}	g cm^{-2} s^{-1}	mass flux out of elemental area, +ve upwards
q_{v}	g cm^{-2} s^{-1}	vapour mass flux
R	cm s^{-1}	rainfall rate
R_0	–	reflection coefficient at nadir
R_d	erg g^{-1} °C^{-1}	specific gas constant of dry air,

		2.8704×10^6 erg g^{-1} °C^{-1}
R_h	–	reflection coefficient for horizontal polarisation
R_{net}	cal cm^{-2} s^{-1}	net radiation flux at the soil surface
R_p	–	reflection coefficient for polarisation p
R_T	–	reflection coefficient at the transition frequency
R_v	–	reflection coefficient for vertical polarisation
R_V	erg g^{-1} °C^{-1}	gas constant of water vapour, 4.615×10^6 erg g^{-1} °C^{-1}
$R_{h(l+1)l}$	–	reflection coefficient for horizontal polarisation between layer l+1 and layer l
$R_{v(l+1)l}$	–	reflection coefficient for vertical polarisation between layer l+1 and layer l
R_ϑ	–	reflection coefficient at incidence angle ϑ
RH_{air}	–	relative humidity in air at the reference height z_T
RH_S	–	relative humidity in the soil at the soil surface
RH_{soil}	–	relative humidity in the soil
$\mathrm{r_a}$	s cm^{-1}	aerodynamic resistance
$\mathrm{r_c}$	s cm^{-1}	crop resistance
S	degrees	pixel slope
S	g g^{-1}	sand mass fraction
S_h	cal cm^{-3}	soil heat storage
S_R		roughness parameter
S_θ	g cm^{-3}	soil moisture storage
SI	–	soil stress index
$SLOPE$	cm cm^{-1}	surface slope in maximum downslope direction
S_w	–	water saturation, $S_w = \theta/\phi$
$S_{0\psi}$	–	specific storativity
$S_{w_j}^n$	–	water saturation of node j, time step n
$S_{w_2}^n$	–	water saturation of node 2, time step n
$S_{w_{N-1}}^n$	–	water saturation of node N–1, time step n
$S_{0\psi_j}^n$	–	specific storativity of node j, time step n
$S_{0\psi_2}^n$	–	specific storativity of node 2, time step n
$S_{0\psi_{N-1}}^n$	–	specific storativity of node N–1, time step n
s	–	$2k_o/m$
T	degrees	flight track
T	–	reflectivity transition function
T	°C	soil temperature
T_j	°C	soil temperature at node j

T_1	°C	soil temperature at node 1
T_2	°C	soil temperature at node 2
T_{N-1}	°C	soil temperature at node N–1
T_N	°C	soil temperature at node N
T_1^n	°C	soil temperature at node 1, time step n
T_2^n	°C	soil temperature at node 2, time step n
T_3^n	°C	soil temperature at node 3, time step n
T_1^{n+1}	°C	soil temperature at node 1, time step n+1
T_2^{n+1}	°C	soil temperature at node 2, time step n+1
T_{air}	°C	air temperature at reference height z_T
T_{atm}	K	atmospheric radiometric temperature
T_b	K	brightness temperature
$T_{b\,p}$	K	brightness temperature at polarisation p
T_{b_h}	K	brightness temperature at horizontal polarisation
T_{b_v}	K	brightness temperature at vertical polarisation
T_{eff}	K	effective soil temperature
T_h	–	transmission coefficient for horizontal polarisation
T_i^n	°C	soil temperature of ith soil layer, time step n
T_i^{n+1}	°C	soil temperature of ith soil layer, time step n+1
T_{j-1}^n	°C	soil temperature at node j–1, time step n
T_j^n	°C	soil temperature at node j, time step n
T_{j+1}^n	°C	soil temperature at node j+1, time step n
T_j^{n-1}	°C	soil temperature at node j, time step n–1
T_j^{n+1}	°C	soil temperature at node j, time step n+1
T_l	K	soil temperature in layer l
T_{N-2}^n	°C	soil temperature at node N–2, time step n
T_{N-1}^n	°C	soil temperature at node N–1, time step n
T_N^n	°C	soil temperature at node N, time step n
T_{N-1}^{n+1}	°C	soil temperature at node N–1, time step n+1
T_N^{n+1}	°C	soil temperature at node N, time step n+1
T_{ref}	°C	reference temperature
T_S	°C	surface soil temperature
T_{sky}	K	sky radiometric temperature
T_{soil}	K	soil temperature
T_{surf}	K	surface temperature

T_t	K	soil temperature in layer t
T_v	–	transmission coefficient for vertical polarisation
T_{veg}	K	vegetation temperature
T_∞	K	deep soil temperature
t	s	travel time
t	s	time
t_d	s	rainfall duration
t^n	s	simulation time at time step n
t^{n-1}	s	simulation time at time step $n-1$
t^{n+1}	s	simulation time at time step $n+1$
t_r	s	time at commencement of recession limb of sub-surface hydrograph
t_s	s	time taken to reach steady state
U	cm s^{-1}	wind speed at reference height z_U
$\mathbf{U}$		vector of forcing
$\mathbf{U}^n$		vector of forcing at time step n
$\underline{\mathbf{U}}$		state augmented vector of forcing
VDF	–	vertical distribution factor
v	cm s^{-1}	propagation speed of electromagnetic wave
$\mathbf{v}$		vector of observation error
W		roughness spectrum
W	cal g^{-1}	differential heat of wetting
W	–	Clapp and Hornberger saturation ratio
W_d	g	weight of dry soil
W_i	–	Clapp and Hornberger saturation ratio at air entry saturation
W^n		roughness spectrum related to the nth power of the correlation function by the Fourier transformation
W_w	g	weight of water in moist soil
$\mathbf{w}^n$		vector of model error at time n
X	cm	distance in the lateral direction
X_1		element 1 of the system state vector
X_j		element j of the system state vector
X_N		element N of the system state vector
$\mathbf{X}$		system state vector
$\hat{\mathbf{X}}$		best estimate of the system state vector
$\hat{\mathbf{X}}^{0/0}$		initial estimate of the system state vector
$\hat{\mathbf{X}}^{n/n}$		estimate of the system state vector at time n
$\hat{\mathbf{X}}^{n+1/n}$		forecast estimate of the system state vector at time $n+1$ given the system state vector estimate

		at time *n*
$\hat{\mathbf{X}}^{n+1/n+1}$		updated estimate of the system state vector at time *n*+1 given the forecast system state vector estimate at time *n*+1
$\underline{\mathbf{X}}$		state augmented system state vector
$\mathbf{Y}$		transformed system state vector
Z	cm	distance in the vertical direction
Z	degrees	zenith angle
$\mathbf{Z}$		vector of observations
$\mathbf{Z}^n$		vector of observations at time *n*+1
z	cm	elevation in soil, +ve upwards from soil surface
z_1	cm	elevation in soil of node 1
z_2	cm	elevation in soil of node 2
z_3	cm	elevation in soil of node 3
z_i	cm	elevation in soil at base of layer *i*
z_{I-1}	cm	elevation in soil at top of layer *i*
z_{j-1}	cm	elevation in soil of node *j*–1
$z_{j-1/2}$	cm	elevation in soil of node *j*–1/2
z_j	cm	elevation in soil of node *j*
$z_{j+1/2}$	cm	elevation in soil of node *j*+1/2
z_{j+1}	cm	elevation in soil of node *j*+1
z_{N-2}	cm	elevation in soil of node *N*–2
z_{N-1}	cm	elevation in soil of node *N*–1
z_N	cm	elevation in soil of node *N*
z_{om}	cm	momentum roughness length
z_{ov}	cm	heat and water vapour roughness length
z_T	cm	height of temperature and relative humidity measurements
z_U	cm	height of wind speed measurements
α		attenuation constant
α	cm^{-1}	coefficient of compressibility of the soil solid matrix
α		single scattering albedo of vegetation
α	–	auto-regressive smoothing value
α_1		soil parameter 1
α_i		*i*th soil parameter
α_m		*m*th soil parameter
α_{pq}		approximation to I_{pq} for transmission at polarisation *p* and reception at polarisation *q*
α_{hh}		approximation to I_{hh} for horizontally polarised

		transmission and horizontally polarised reception
α_{vv}		approximation to I_{vv} for vertically polarised transmission and vertically polarised reception
β		phase constant
β	cm^{-1}	coefficient of compressibility for water
β	g cm^{-3} °C^{-1}	$\partial\rho_o/\partial T = 1.05 \times 10^6$ g cm^{-3} °C^{-1} at 20 °C
β'	–	empirically determined soil type constant for real component of the dielectric constant
β''	–	empirically determined soil type constant for imaginary component of the dielectric constant
Γ	–	reflectivity
$\Gamma(\ )$		Gamma function
Γ_0	–	reflectivity at nadir
Γ_h	–	reflectivity for horizontal polarisation
$\Gamma_{i,j}$	–	i,jth element of the matrix Γ for estimating correlations
Γ_p	–	reflectivity for polarisation p
Γ_v	–	reflectivity for vertical polarisation
Γ_{veg}	–	two-way attenuation by vegetation
γ	–	surface rms slope, $\gamma = \sigma/l$
γ	°C^{-1}	temperature coefficient of water surface tension, -2.09×10^{-3} °C^{-1} at 20°C
γ	kPa °C^{-1}	psychometric constant
Δ	kPa °C^{-1}	slope of vapour pressure curve
Δf	Hz	frequency change
$(\Delta t)^n$	s	time step size for time step n
$(\Delta t)^{n+1}$	s	time step size for time step n+1
δ_p	cm	penetration depth
$\in$	–	ratio of molecular weight of water vapour to molecular weight of dry air
ε	farad m^{-1}	complex dielectric constant, $\varepsilon = \varepsilon' + i\varepsilon''$
ε'	farad m^{-1}	real part of dielectric constant ε
ε''	farad m^{-1}	imaginary part of dielectric constant ε
ε_{fw}'	–	real part of relative dielectric constant of free water
ε_{fw}''	–	imaginary part of relative dielectric constant of free water
ε_l	farad m^{-1}	complex dielectric constant ε for layer l
ε_{l+1}	farad m^{-1}	complex dielectric constant ε for layer l+1

ε_l''	farad m^{-1}	imaginary component of complex dielectric constant ε for layer l
ε_{leaf}	farad m^{-1}	leaf dielectric constant
ε_o	farad m^{-1}	complex dielectric constant of free space, 8.85×10^{-12} farad m^{-1}
ε_r	–	complex relative dielectric constant, $\varepsilon_r = \varepsilon / \varepsilon_o = \varepsilon_r' + i\varepsilon_r''$
$\varepsilon_{r_{air}}$	–	relative dielectric constant of air, 1
ε_{r_∞}	–	complex infinity depth relative dielectric constant value
ε_s	–	relative dielectric constant of the soil solids
ε_T^n	°C	maximum change in soil temperature at time step n
$\hat{\varepsilon}_T$	°C	target change in soil temperature
ε''_t	farad m^{-1}	imaginary part of dielectric constant ε for region t
ε_{veg}	–	relative vegetation dielectric constant
ε''_{veg}	–	imaginary part of the relative vegetation dielectric constant
ε_{wo}	–	static relative dielectric constant of water
$\varepsilon_{w\infty}$	–	high frequency limit of ε_{fw}''
$\hat{\varepsilon}_\theta$	v v^{-1}	target relative change in volumetric soil moisture
ε_θ^n	v v^{-1}	maximum relative change in volumetric soil moisture at time step n
ε_ψ^n	–	maximum relative change in soil matric potential at time step n
$\hat{\varepsilon}_\psi$	–	target relative change in soil matric potential
η	–	van Genuchten soil texture parameter
η_o	Ω	intrinsic impedence of free space, 376.7 Ω
η_1	Ω	intrinsic impedence of incident layer
η_2	Ω	intrinsic impedence of transmission layer
Θ	–	van Genuchten saturation ratio
ϑ	degrees	angle of incidence
ϑ_i	degrees	angle of incidence
ϑ_s	degrees	soil transmission angle
ϑ_1	degrees	angle of incidence
ϑ_2	degrees	transmission angle
θ	v v^{-1}	volumetric soil moisture fraction

θ_{fc}	v v^{-1}	volumetric soil moisture fraction at field capacity
θ_i	v v^{-1}	volumetric soil moisture fraction of layer i
$\theta_{j,k,l}$	v v^{-1}	volumetric soil moisture fraction of grid element j,k,l
$\theta_{j+1,k,l}$	v v^{-1}	volumetric soil moisture fraction of grid element $j+1,k,l$
$\theta_{j+1/2,k,l}$	v v^{-1}	average volumetric soil moisture fraction of grid elements j,k,l and $j+1,k,l$
$\theta_{j,k+1,l}$	v v^{-1}	volumetric soil moisture fraction of grid element $j,k+1,l$
$\theta_{j,k+1/2,l}$	v v^{-1}	average volumetric soil moisture fraction of grid elements j,k,l and $j,k+1,l$
$\theta^{n}_{j,k,l}$	v v^{-1}	volumetric soil moisture fraction of grid element j,k,l, time step n
$\theta^{n-1}_{j,k,l}$	v v^{-1}	volumetric soil moisture fraction of grid element j,k,l, time step $n–1$
$\theta^{n+1}_{j,k,l}$	v v^{-1}	volumetric soil moisture fraction of grid element j,k,l, time step $n+1$
θ_{l}	v v^{-1}	liquid component of volumetric soil moisture fraction
θ_{l_1}	v v^{-1}	liquid component of volumetric soil moisture fraction at node 1
θ_{l_2}	v v^{-1}	liquid component of volumetric soil moisture fraction at node 2
θ_{lj}	v v^{-1}	liquid component of volumetric soil moisture fraction at node j
θ_{l_N}	v v^{-1}	liquid component of volumetric soil moisture fraction at node N
$\theta^{n}_{l_2}$	v v^{-1}	liquid component of volumetric soil moisture fraction at node 2, time step n
$\theta^{n-1}_{l_2}$	v v^{-1}	liquid component of volumetric soil moisture fraction at node 2, time step $n–1$
$\theta^{n}_{l_j}$	v v^{-1}	liquid component of volumetric soil moisture fraction at node j, time step n
$\theta^{n-1}_{l_j}$	v v^{-1}	liquid component of volumetric soil moisture fraction at node j, time step $n–1$
$\theta^{n}_{l_{N-1}}$	v v^{-1}	liquid component of volumetric soil moisture fraction at node $N–1$, time step n
$\theta^{n-1}_{l_{N-1}}$	v v^{-1}	liquid component of volumetric soil moisture fraction at node $N–1$, time step $n–1$

θ_{m_i}	v v^{-1}	soil mineral matter content volume fraction of layer *i*
θ_{o_i}	v v^{-1}	soil organic matter content volume fraction of layer *i*
θ_r	v v^{-1}	residual soil moisture
$\theta_{r_{j,k,l}}$	v v^{-1}	residual soil moisture for grid element j,k,l
$\theta_{r_{j+1,k,l}}$	v v^{-1}	residual soil moisture for grid element $j+1,k,l$
$\theta_{r_{j,k+1,l}}$	v v^{-1}	residual soil moisture for grid element $j,k+1,l$
θ_v	v v^{-1}	vapour component of volumetric soil moisture fraction
θ_{veg}	kg m^{-2}	vegetation moisture
θ_{wp}	v v^{-1}	volumetric moisture fraction at field capacity
θ_1	v v^{-1}	volumetric fraction of liquid water
θ_2	v v^{-1}	volumetric fraction of air
θ_3	v v^{-1}	volumetric fraction of quartz
θ_4	v v^{-1}	volumetric fraction of other minerals
θ_5	v v^{-1}	volumetric fraction of organic matter
λ	cm	wavelength, $\lambda = c/f$
λ	cal cm^{-1} s^{-1} $°\text{C}^{-1}$	apparent thermal conductivity of bulk soil medium
λ_1	cal cm^{-1} s^{-1} $°\text{C}^{-1}$	thermal conductivity of liquid water
λ_2	cal cm^{-1} s^{-1} $°\text{C}^{-1}$	apparent thermal conductivity of air-filled pores, $\lambda_2 = \lambda_a + \lambda_{vap}$
λ_3	cal cm^{-1} s^{-1} $°\text{C}^{-1}$	thermal conductivity of quartz
λ_4	cal cm^{-1} s^{-1} $°\text{C}^{-1}$	thermal conductivity of other minerals
λ_5	cal cm^{-1} s^{-1} $°\text{C}^{-1}$	thermal conductivity of organic matter
λ_a	cal cm^{-1} s^{-1} $°\text{C}^{-1}$	thermal conductivity of dry air alone
λ_i	cal cm^{-1} s^{-1} $°\text{C}^{-1}$	thermal conductivity of *i*th soil constituent in bulk soil medium
λ_{vap}	cal cm^{-1} s^{-1} $°\text{C}^{-1}$	apparent thermal conductivity of an air-filled pore due to vapour diffusion
λ_o	cm	free-space wavelength
λ_j	cal cm^{-1} s^{-1} $°\text{C}^{-1}$	apparent thermal conductivity of bulk soil medium at node *j*
λ_{j-1}	cal cm^{-1} s^{-1} $°\text{C}^{-1}$	apparent thermal conductivity of bulk soil medium at node *j*–1
$\lambda_{j-1/2}$	cal cm^{-1} s^{-1} $°\text{C}^{-1}$	average apparent thermal conductivity of bulk soil medium for nodes *j* and *j*–1

$\lambda_{j+\frac{1}{2}}$	cal cm^{-1} s^{-1} °C^{-1}	average apparent thermal conductivity of bulk soil medium for nodes *j* and *j*+1
λ_{j+1}	cal cm^{-1} s^{-1} °C^{-1}	apparent thermal conductivity of bulk soil medium at node *j*+1
λ_1^n	cal cm^{-1} s^{-1} °C^{-1}	apparent thermal conductivity of bulk soil medium at node 1, time step *n*
$\lambda_{1\frac{1}{2}}^n$	cal cm^{-1} s^{-1} °C^{-1}	average apparent thermal conductivity of bulk soil medium at nodes 1 and 2, time step *n*
λ_2^n	cal cm^{-1} s^{-1} °C^{-1}	apparent thermal conductivity of bulk soil medium at node 2, time step *n*
λ_3^n	cal cm^{-1} s^{-1} °C^{-1}	apparent thermal conductivity of bulk soil medium at node 3, time step *n*
λ_j^n	cal cm^{-1} s^{-1} °C^{-1}	apparent thermal conductivity of bulk soil medium at node *j*, time step *n*
λ_{j-1}^n	cal cm^{-1} s^{-1} °C^{-1}	apparent thermal conductivity of bulk soil medium at node *j*–1, time step *n*
$\lambda_{j-\frac{1}{2}}^n$	cal cm^{-1} s^{-1} °C^{-1}	average apparent thermal conductivity of bulk soil medium for nodes *j* and *j*–1, time step *n*
$\lambda_{j+\frac{1}{2}}^n$	cal cm^{-1} s^{-1} °C^{-1}	average apparent thermal conductivity of bulk soil medium for nodes *j* and *j*+1, time step *n*
λ_{j+1}^n	cal cm^{-1} s^{-1} °C^{-1}	apparent thermal conductivity of bulk soil medium at node *j*+1, time step *n*
λ_{N-2}^n	cal cm^{-1} s^{-1} °C^{-1}	apparent thermal conductivity of bulk soil medium at node *N*–2, time step *n*
λ_{N-1}^n	cal cm^{-1} s^{-1} °C^{-1}	apparent thermal conductivity of bulk soil medium at node *N*–1, time step *n*
$\lambda_{N-\frac{1}{2}}^n$	cal cm^{-1} s^{-1} °C^{-1}	average apparent thermal conductivity of bulk soil medium for nodes *N*–1 and *N*, time step *n*
λ_N^n	cal cm^{-1} s^{-1} °C^{-1}	apparent thermal conductivity of bulk soil medium at node *N*, time step *n*
μ	g cm^{-1} s^{-1}	fluid viscosity
μ	henry m^{-1}	magnetic permeability
μ_l	henry m^{-1}	magnetic permeability of layer *l*
μ_{l+1}	henry m^{-1}	magnetic permeability of layer *l*+1
μ_o	henry m^{-1}	magnetic permeability of free space, $4\pi \times 10^{-7}$ henry m^{-1}
μ_r	–	relative magnetic permeability, $\mu_r = \mu/\mu_o$
μ_{X_i}		mean of *i*th system state variable
$\mu_{X'_i}$		transformed mean of *i*th system state variable
ν	–	empirically determined constant

ξ	–	tortuosity factor for diffusion of gases in soils, ≈ 0.67
$\rho(\xi)$	–	single parameter surface autocorrelation function
$\rho(\xi,\zeta)$	–	two parameter surface autocorrelation function
ρ	g cm^{-3}	fluid density
ρ_{air}	g cm^{-3}	air density
ρ_b	g cm^{-3}	soil bulk density
ρ_l	g cm^{-3}	density of liquid water
ρ_o	g cm^{-3}	density of saturated water vapour
ρ_{om}	g cm^{-3}	density of organic matter, 1.3 g cm^{-3}
ρ_s	g cm^{-3}	soil specific density, 2.65 g cm^{-3}
ρ_v	g cm^{-3}	density of water vapour
ρ_w	g cm^{-3}	density of water
$\rho_{X_i X_j}$	–	correlation between the *i*th and *j*th system state variables
$\rho_{X'_i X'_j}$	–	correlation between the transformed *i*th and transformed *j*th system state variables
$\rho_{X'_i X_j}$	–	correlation between the transformed *i*th and untransformed *j*th system state variables
$\Sigma_{\mathbf{X}}$		covariance matrix of system states
$\Sigma_{\mathbf{X}}^{0/0}$		initial covariance matrix of system states
$\Sigma_{\mathbf{X}}^{n/n}$		estimated covariance matrix of system states at time *n*
$\Sigma_{\mathbf{X}}^{n+1/n}$		forecast covariance matrix of system states at time *n*+1 given the covariance matrix at time *n*
$\Sigma_{\mathbf{X}}^{n+1/n+1}$		updated covariance matrix of system states at time *n*+1
$\Sigma_{\mathbf{Y}}$		transformed covariance matrix of system states
σ	cm	rms roughness height
σ_{eff}	s m^{-1}	effective conductivity
σ_{X_i}		standard deviation of *i*th system state variable
σ_{Xj}		standard deviation of *j*th system state variable
$\sigma_{X'_i}$		standard deviation of *i*th transformed system state variable
$\sigma_{X'_j}$		standard deviation of *j*th transformed system state variable
σ^o	–	backscattering coefficient
$\sigma^o{}_{bare}$	–	bare soil backscattering coefficient
$\sigma^o{}_d$	–	direct backscattering coefficient from the

		vegetation layer
σ^{o}_{dB}	dB	backscattering coefficient in decibels
σ^{o}_{dr}	–	direct reflected backscattering coefficient from the vegetation layer
σ^{o}_{ground}	–	backscattering coefficient from soil covered with a vegetation layer
σ^{o}_{hh}	–	backscattering coefficient for horizontally polarised transmission and horizontally polarised reception
$\sigma^{o}_{hh/vv_{dB}}$	dB	ratio of *hh* to *vv* polarisation backscattering coefficients in dB
σ^{o}_{hv}	–	backscattering coefficient for horizontally polarised transmission and vertically polarised reception
σ^{o}_{pp}	–	backscattering coefficient when transmission and reception are at polarisation *p*
σ^{o}_{pq}	–	backscattering coefficient when transmission is at polarisation *p* and reception is at polarisation *q*
σ^{o}_{r}	–	reflected backscattering from the vegetation layer
σ^{o}_{total}	–	total backscattering from a soil-vegetation layer
σ^{o}_{veg}	–	backscattering from the vegetation layer
σ^{o}_{vv}	–	backscattering coefficient for vertically polarised transmission and vertically polarised reception
τ		atmospheric transmission
τ	Np	optical depth
τ_{w}	s	relaxation time for water
Υ	–	transmissivity
Υ_{veg}	–	transmissivity of vegetation layer
Φ_{1}^{n}		system state forecasting matrix at time step *n* given the system state estimate at time step *n*
Φ_{1}^{n+1}		system state forecasting matrix at time step *n*+1 given the system state estimate at time step *n*+1
$\overline{\Phi}_{1}$		auto-regressive smoothed system state forecasting matrix
$\overline{\Phi}_{1}^{n}$		auto-regressive smoothed system state forecasting matrix at time step *n* given the system state estimate at time step *n*
$\overline{\Phi}_{1}^{n+1}$		auto-regressive smoothed system state forecasting matrix at time step *n*+1 given the

		system state estimate at time step n+1
Φ_2^n		system state forecasting matrix at time step n given the system state estimate at time step n
Φ_2^{n+1}		system state forecasting matrix at time step n+1 given the system state estimate at time step n+1
$\overline{\Phi}_2$		auto-regressive smoothed system state forecasting matrix
$\overline{\Phi}_2^n$		auto-regressive smoothed system state forecasting matrix at time step n given the system state estimate at time step n
$\overline{\Phi}_2^{n+1}$		auto-regressive smoothed system state forecasting matrix at time step n+1 given the system state estimate at time step n+1
ϕ	radians	phase change of the electromagnetic wave
ϕ	v v^{-1}	soil porosity
ϕ_e	v v^{-1}	effective soil porosity, $\phi_e = \phi - \theta_{fc}$
$\phi_{j,k,l}$	v v^{-1}	soil porosity of grid element j,k,l
$\phi_{j+1,k,l}$	v v^{-1}	soil porosity of grid element $j+1,k,l$
$\phi_{j,k+1,l}$	v v^{-1}	soil porosity of grid element $j,k+1,l$
φ	–	Brooks and Corey pore size distribution index
ψ	cm	soil matric potential
ψ_b	cm	bubbling soil matric potential
ψ_d	cm	soil matric potential at the observation depth
ψ_i	cm	soil matric potential at air entry
ψ_s	cm	saturated soil matric potential
ψ_j	cm	soil matric potential at node j
ψ_{j-1}	cm	soil matric potential at node j–1
ψ_{j+1}	cm	soil matric potential at node j+1
ψ_N	cm	soil matric potential at node N
ψ_{N-1}	cm	soil matric potential at node N–1
ψ_{N-2}	cm	soil matric potential at node N–2
ψ_1	cm	saturated soil matric potential at node 1
ψ_2	cm	saturated soil matric potential at node 2
ψ_{j-1}^n	cm	soil matric potential at node j–1, time step n
ψ_j^n	cm	soil matric potential at node j, time step n
ψ_{j+1}^n	cm	soil matric potential at node j+1, time step n
ψ_N^n	cm	soil matric potential at node N, time step n

ψ_{N-1}^{n}	cm	soil matric potential at node *N*–1, time step *n*
ψ_{j}^{n-1}	cm	soil matric potential at node *j*, time step *n*–1
ψ_{j}^{n+1}	cm	soil matric potential at node *j*, time step *n*+1
ψ_{N-1}^{n+1}	cm	soil matric potential at node *N*-1, time step *n*+1
ψ_{N}^{n+1}	cm	soil matric potential at node *N*, time step *n*+1
ψ_{1}^{n}	cm	soil matric potential at node 1, time step *n*
ψ_{2}^{n}	cm	soil matric potential at node 2, time step *n*
ψ_{3}^{n}	cm	soil matric potential at node 3, time step *n*
ψ_{1}^{n+1}	cm	soil matric potential at node 1, time step *n*+1
ψ_{2}^{n+1}	cm	soil matric potential at node 2, time step *n*+1
Ω^{n}		vector of forcing at time step *n*
Ω^{n+1}		vector of forcing at time step *n*+1
$\partial\sigma_{dB}^{o}$	dB	backscattering sensitivity
∂		partial derivative operator
∇		gradient operator

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