SOFTWARE–TYPE WAVE–PARTICLE INTERACTION ANALYZER (S–WPIA) BY RPWI FOR JUICE: SCIENCE OBJECTIVES AND IMPLEMENTATION

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Abstract

We present science objectives of the Software–type Wave–Particle Interaction Analyzer (S–WPIA), which will be realized as a software function of the Low-Frequency receiver (LF) running on the DPU of RPWI (Radio and Plasma Waves Investigation) for the ESA JUICE mission. S–WPIA conducts onboard computations of physical quantities indicating the energy exchange between plasma waves and energetic ions. Onboard inter–instruments communications are necessary to realize S–WPIA, which will be implemented by efforts of RPWI, PEP (Particle Environment Package) and J–MAG (JUICE Magnetometer). By providing the direct evidence of ion energization processes by plasma waves around Jovian satellites, S–WPIA increases the scientific output of JUICE while keeping its impact on the telemetry data size to a minimum; S–WPIA outputs 0.2 kB at the smallest from 440 kB waveform and particle raw data.

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1 Introduction

A Wave–Particle Interaction Analyzer (WPIA) has been proposed by Fukuhara et al. [2009] to measure the energy transfer process between energetic particles and plasma waves. Software–type WPIA (S–WPIA) was first implemented in the ERG satellite of JAXA to measure interactions between relativistic electrons and whistler–mode chorus in Earth's inner magnetosphere [Miyoshi et al., 2012; Katoh et al., 2013; 2014; Hikishima et al., 2014; Kasahara et al., 2016]. Interactions of chorus and relativistic electrons are a fascinating research topic in the Jovian magnetosphere as well [e.g., Katoh et al., 2011], but the required time resolution in synchronizing instruments related to S–WPIA cannot be achieved without a dedicated system as we implemented it in the ERG satellite. Since the requirement on the time resolution is relaxed for ion–scale interactions, as the next step, we plan to apply S–WPIA to ion–scale wave–particle interactions occurring in the Jovian magnetosphere. S–WPIA will be realized as a software function of the Low-Frequency receiver (LF) running on the DPU of RPWI (Radio and Plasma Waves Investigation; PI: J.–E. Wahlund, IRF–Uppsala, Sweden) for the ESA JUICE mission, where LF measures 6 components of wave electromagnetic field from DC to 20 kHz [Wahlund et al., 2013]. The prime target of S-WPIA on JUICE are ion cyclotron waves (∼1 Hz) and related wave–particle interactions occurring in the region close to Ganymede and other Jovian satellites. In S–WPIA of RPWI for JUICE, we focus on the interactions between energetic ions (a few to tens of keV) and ion cyclotron waves (typically less than 1 Hz). S–WPIA uses wave electromagnetic field and ion velocity vectors provided by RPWI sensors and PEP (Particle Environment Package; PI: Stas Barabash, IRF–Kiruna, Sweden), respectively, with referring three–components of the background magnetic field detected by J–MAG (JUICE Magnetometer; PI: M. Dougherty, ICL, UK). For the particle data, S–WPIA uses particle counts detected by JDC (Jovian plasma Dynamics and Composition) of PEP in the energy range from 1 eV/q to 25 keV/q.

As shown in Figure 1, S–WPIA measures a relative phase angle between the velocity vector $\boldsymbol{v}_i$ of the i-th particle of charge q_i and the wave electric field vector at the timing of the particle's detection ($\boldsymbol{E}(t_i)$) and computes an inner product of $W(t_i) = q_i\boldsymbol{E}(t_i)\cdot\boldsymbol{v}_i$, where $W(t_i)$ corresponds to the gain (positive) or the loss (negative) of the kinetic energy of the i-th energetic particle;

$$\frac{d}{dt}\left(\frac{1}{2}m|\boldsymbol{v}|^2\right) = m\boldsymbol{v}\cdot\frac{d\boldsymbol{v}}{dt} = m\boldsymbol{v}\cdot\left\{\frac{q}{m}\left(\boldsymbol{E}+\boldsymbol{v}\times\boldsymbol{B}\right)\right\} = q\boldsymbol{E}\cdot\boldsymbol{v}. \tag{1}$$

We accumulate W for detected particles to obtain the net amount of the energy exchange, $W_{\text{int}} = \sum_i W(t_i)$, and we expect a statistically significant W_{int} for the case of the measurement at the site of efficient wave–particle interactions. According to Katoh et al. [2013], the net variation of the kinetic energy of charged particles $\Delta W(\boldsymbol{r},t)$ during a time interval Δt is given by

$$\Delta W(\boldsymbol{r},t) = \int_t^{t+\Delta t}\iiint q\boldsymbol{E}(\boldsymbol{r},t')\cdot\boldsymbol{v}f(\boldsymbol{r},\boldsymbol{v},t')d\boldsymbol{v}dt', \tag{2}$$

where f is the phase space density of charged particles. Since the measurement of f is performed for discrete times, we rewrite $\Delta W(\boldsymbol{r},t)$ as a summation of $W(t_i) = q\boldsymbol{E}(t_i)\cdot\boldsymbol{v}_i$

measured over the time interval Δt, given by

$$\Delta W(\boldsymbol{r}, t) = \sum_{t \leq t_i \leq t+\Delta t}^{N} q\boldsymbol{E}(t_i) \cdot \boldsymbol{v}_i, \tag{3}$$

where N represents the number of particles detected during the time interval Δt, t_i is the detection timing of the i-th particle, $\boldsymbol{E}(t_i)$ is the wave electric field vector at t_i, and $\boldsymbol{v}_i$ is the velocity vector of the i-th particle. Since $W(t_i)$ is the gain or the loss of the kinetic energy of the i-th particle, we obtain the net amount of the energy exchange in the region of interest by accumulating W for detected particles (W_{int}). The summation over the velocity in Equation (2) is carried out in the kinetic energy range covered by the PEP/JDC. Therefore, the energy exchange obtained by the S–WPIA is limited in the observed energy range. Since we use the finite number of particles in the computation of W_{int}, there must be fluctuation over time. The fluctuation originates from thermal fluctuation of the distribution of energetic electrons as well as the fluctuation of both wave electric field amplitude and relative phase angle between wave and velocity vectors. For the evaluation of the statistical significance of the obtained W_{int} compared to the fluctuation, we use the standard deviation σ_w by computing

$$\sigma_W = \sqrt{\sum_{i=1}^{N} (q\boldsymbol{E}(t_i) \cdot \boldsymbol{v}_i)^2 - \frac{1}{N}\left(\sum_{i=1}^{N} q\boldsymbol{E}(t_i) \cdot \boldsymbol{v}_i\right)^2}, \tag{4}$$

where the first and second terms on the right-hand side correspond to the width and the center of the distribution of $q\boldsymbol{E}(t_i) \cdot \boldsymbol{v}_i$, respectively. We can identify the efficient energy exchange between waves and particles when W_{int} is sufficiently larger than σ_W obtained by the S–WPIA. In other words, we need to collect enough particles for the computation of W_{int} so that the obtained W_{int} exceeds σ_W and satisfies the required statistical significance; assuming a Gaussian distribution, 1.64 σ_W for a statistical significance of 90% and 1.96 σ_W for 95%. Recently Shoji et al. [2017] succeeded in showing that the WPIA is capable for the direct measurement of the formation of an ion hole through interactions of electromagnetic ion cyclotron waves and energetic ions in Earth's inner magnetosphere. S–WPIA can also measure the pitch angle scattering of energetic ions by ion cyclotron waves by computing $F_{\theta i} = q_i(\boldsymbol{E}(t_i) + \boldsymbol{v}_i \times \boldsymbol{B}) \cdot \boldsymbol{e}_\theta$ to obtain $g = \sum_i F_{\theta i}$, where $\boldsymbol{e}_\theta$ is a unit vector in the direction of increasing pitch angle [Kitahara and Katoh, 2016]. In this paper, we discuss details of the implementation of S–WPIA of RPWI and inter–instruments communications on board JUICE.

2 Data packets of S–WPIA

We discuss the required resolutions of physical quantities to realize S–WPIA. It is essential for S–WPIA to synchronize instruments in a time resolution better than the time scale of wave–particle interactions. For waves of frequency around 1 Hz, which corresponds to the typical cyclotron frequency of oxygen ions in the Ganymede's polar magnetosphere [cf. Kivelson et al., 1997], a time resolution better than 100 ms should be realized so as

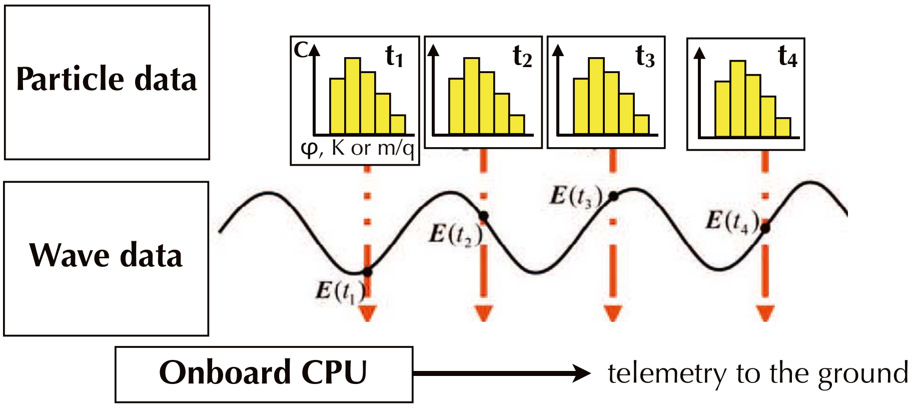

Figure 1: Schematic of the time sequence of the plasma wave and particle measurements required to realize S–WPIA. The number of counts C as a function of azimuth (ϕ) etc. are stored with a time–tag showing the timing of the measurement. The time–tag will be used to identify the relative phase angle between the velocity vectors of detected particles and the wave electromagnetic field vectors.

to measure the relative phase angle between wave electromagnetic and velocity vectors better than ∼40 degrees. We assume that the particle data consists of the number of counts C as a function of azimuth (ϕ), elevation (α), energy (K), and mass–per–charge (m/q) steps with a time–tag showing the timing of the measurement of each step. We define that the particle data is provided as a matrix $C(K, \phi, \alpha, m/q)$, which is taken for every elevation step of 250 ms. Since the energy step is swept during 250 ms, the detection timing of particle counts of a specific energy range can be identified with a time resolution better than 100 ms; for the case of 32 energy steps, C of one energy step is the number of particle counts collected during ∼8 ms. Although the time interval of each K, ϕ, α, m/q step is enough shorter than the wave phase rotation of ion cyclotron waves, we cannot measure particles which are not in the field of view of the particle detector. We need to assume the ergodic hypothesis and that the same type of wave–particle interactions occurs during the accumulation of a full ion distribution function. We are not able to apply the S–WPIA in the case that this assumption cannot be utilized, for example a rapid change of wave spectra or velocity distribution function of ions occurs in a time scale less than the integration time of the S–WPIA.

2.1 Definition of data–unit of S–WPIA

S–WPIA uses $C(K, \phi, \alpha, m/q)$ and waveform simultaneously observed in the region of interest. We define an 8 s observation as “1 data–unit” of S–WPIA. S–WPIA requires that at least 1 data–unit of wave and particle data (obtained during 8 s) should be stored so as to realize onboard computation of S–WPIA. The length of 1 data-unit is defined from 1024 pt. of the waveform data sampled at 128 Hz. Since S–WPIA uses the dataset stored in the onboard memory, the computation is not necessarily real–time but can be done later. The timing of the computation can be flexibly determined depending on the capability of the DPU.

2.2 Output of S–WPIA

The output of S–WPIA consists of three quantities; W_{int}, N, and σ, where N is the number of particle counts used in the computation of W_{int}, and σ is the standard deviation of the computed W_{int}. These three quantities can be obtained for every data–unit and for every mass–per–charge (m/q) step as a function of the kinetic energy (K), pitch angle (θ), and relative phase angle between wave magnetic field and particle velocity vectors (ζ); $W_{\mathrm{int}}(K,\theta,\zeta)$, $N(K,\theta,\zeta)$, and $\sigma(K,\theta,\zeta)$.

The sequence of the onboard S–WPIA computation for 1 data–unit is described as follows.

1. If necessary, calibration of the 8 s waveform (in particular, wave phase calibration in order to realize the accuracy enough to detect the sign of W correctly) and particle raw data (compensation of the g–factor difference for azimuth and/or elevation bins) by referring results of the ground pre-flight test of instruments
2. Computation of the instantaneous wave electromagnetic field vector ($\boldsymbol{E}_W$ and $\boldsymbol{B}_W$) from 3 components of waveform and the detection timing of $C(K,\phi,\alpha,m/q)$
3. Computation of the relative phase angle between wave field and particle velocity vectors, using the estimated instantaneous wave electromagnetic field vector and the field–of–view of azimuth and elevation angle of each bin of the particle raw data
4. Computation of the pitch angle θ corresponding to each bins of $C(K,\phi,\alpha,m/q)$ by referring ϕ, α, and the background magnetic field vector
5. Computation of W_i for each bin of $C(K,\phi,\alpha,m/q)$ and then integration of W_i to obtain $W_{\mathrm{int}}(K,\theta,\zeta,m/q)$ or $W_{\mathrm{int}}(K,\theta,m/q)$ or $W_{\mathrm{int}}(K,m/q)$ (σ and N are computed as well.)

As long as the measurement is carried out in a region where the same type of interactions are occurring, each data–unit does not need to be measured sequentially in time. As the nominal data amount of S–WPIA, 10 data–units will be used for one telemetry data block to be transferred to the ground. The number of data–units can be determined flexibly, depending on the memory size of the DPU and/or the capability of the computation. The computation of the stored data should not necessarily be real–time. S–WPIA refers to time–tags, which are embedded on the wave, particle, and field data in the computation. We note that the interval of each data–unit determines the spatial coverage (or spatial resolution) of S–WPIA, as we discuss later in the 'observation plan' section.

The data size to be transferred to the ground can be reduced by integrating the S–WPIA output of $W_{\mathrm{int}}(K,\theta,\zeta)$, $N(K,\theta,\zeta)$, and $\sigma(K,\theta,\zeta)$ for θ and/or ζ to obtain $W_{\mathrm{int}}(K,\theta)$, $\sigma(K,\theta)$, and $\sigma(K,\theta)$ or $W_{\mathrm{int}}(K)$, $N(K)$, and $\sigma(K)$, as given by Table 1. If we assume 32 ch for K, 18 ch for θ, 8 ch for ζ, and 2 bytes for each data, the telemetry data size of S–WPIA output matrices can be estimated to be 27 kB for 1 m/q step. If we integrate the matrices for ζ, the output becomes $W_{\mathrm{int}}(K,\theta)$, $N(K,\theta)$, and $\sigma(K,\theta)$, resulting in the total data size of 3.5 kB. If we integrate the matrices for both θ and ζ, the matrices becomes

$W_{\mathrm{int}}(K)$, $N(K)$, and $\sigma(K)$, and then the data size becomes 0.2 kB. The data size can be reduced up to 6 bytes by integrating $W_{\mathrm{int}}(K)$, $N(K)$, and $\sigma(K)$ for K, if necessary. If we transfer the whole data used in the 10 data–unit of S–WPIA by selective downlink, the data size is estimated to be 440 kB.

Table 1: Example of the telemetry data size of S–WPIA output

Output	Telemetry data size of 1 data–unit for 1 m/q step
$W_{\mathrm{int}}(K,\theta,\zeta)$, $N(K,\theta,\zeta)$, and $\sigma(K,\theta,\zeta)$	27 kB
$W_{\mathrm{int}}(K,\theta)$, $N(K,\theta)$, and $\sigma(K,\theta)$	3.5 kB
$W_{\mathrm{int}}(K)$, $N(K)$, and $\sigma(K)$	0.2 kB
Selective downlink	
Waveform (2 bytes × 128 pt. × 6 ch × 8 s)	12 kB
Particle raw data (2 bytes × 32 steps for K, 16 steps for ϕ, 8 steps for α during 2 s)	32 kB

2.3 Inter–instruments communication

The data packets necessary for the onboard S–WPIA computation is transferred among related instruments measuring plasma waves, particles, and the background magnetic field through the onboard network. The synchronization of the observation can be realized by a scheduled operation. The software function of S–WPIA is running on the wave instrument, and the data packets are stored in the onboard memory of the wave instrument (Figure 2). The inter–instruments communication is realized when "the particle instrument puts the data packets to the wave instrument". The data transfer will be initiated by the particle instrument by pushing the data toward the wave instrument. The buffer area dedicated to this data transfer will be prepared in the wave instrument. A software function of S–WPIA running on the wave instrument stores the data packets transferred from the particle instrument as well as waveform and the background magnetic field data.

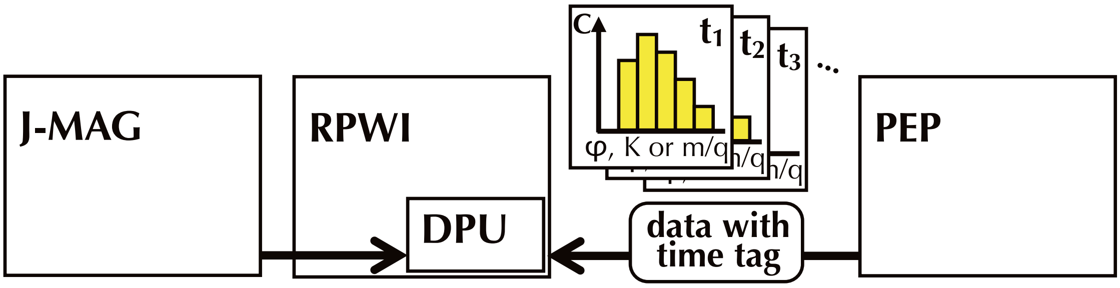

Figure 2: Schematic of the inter–instruments communication among RPWI, PEP, and J–MAG.

3 Observation plan

The prime target of S–WPIA are ion cyclotron waves (∼1 Hz) and related wave–particle interactions occurring in the region close to Ganymede and other Jovian satellites. In particular, according to the results of Galileo spacecraft observations, we expect significant wave–particle interactions in the polar and the equatorial region of Ganymede's magnetosphere [Gurnett et al., 1996; Volwerk et al., 2013], regions around Galilean moons (Europa and Callisto) [Russell, 2005; Volwerk et al., 2010], and the equatorial region of the Jovian magnetosphere [Thorne and Moses, 1983; Russell et al., 2000].

S–WPIA uses 10 data–units of wave and particle data, where 1 data–unit is the data continuously obtained by RPWI, PEP, and J–MAG during 8 s. Each data–unit is not necessarily continuous but should be measured in the location where a similar type of wave–particle interaction occurs. Therefore we should collect 10 data–units (total of 80 s of data) in the same region of interest.

The number of data–units required is determined by the count rate from the particle instrument in each energy/pitch angle bin. Enough particle counts are needed to obtain a statistical significant result. If a 1% modulation in the velocity phase space distribution of ions is needed, we need to collect 10000 counts. For the case of 100–1000 counts/s for each bin, we would need to collect particles during 10–100 s. While we assume 10 data–units (total of 80 s of data) is adequate for the expected count rates, we can revise the nominal number of data–units if necessary.

The sampling of data at the wave and particle instruments should be synchronized. S–WPIA uses the time–tag embedded in the wave, particle, and the background magnetic field data for the analysis. If the required time resolution of the time–tag (better than 100 ms) is satisfied, the time–tags embedded in the data packets are not necessarily identical to each other, because S–WPIA can adjust the time difference by interpolating the waveform.

The synchronization should be realized by a scheduled operation of the observation. For an example, if we focus on Ganymede's polar magnetosphere at an altitude of less than 2000 km from Ganymede, where the spacecraft travels for 10 min in the polar region, we can consider the following observation plan so as to collect 10 data–units in the region of interest:

(I) 80 s continuous measurement; we collect 1 set of 10 data–units during 80 s

(II) 1 data–unit every 1 min; we collect 1 set of 10 data–units during 10 min

(III) 10 data–units at 10 different locations every orbit; we collect 10 sets of 10 data–units during 10 orbits of a flyby

(IV) 1 data–unit every orbit; we collect 1 set of 10 data–units during 10 orbits

In Plan–(I), we need to store 80 s data in the memory of the DPU of LF/RPWI, and then we do S–WPIA analysis on the stored data. The required memory size can be roughly estimated to 1.56 MB, which is ten times larger than that required in other plans. The output of S–WPIA by 1 set of 10 data–units is estimated to be 0.2–27 kB for 1 m/q step, so 0.8–108 kB in total for 4 steps of m/q. If we focus on phenomena occurring in a small spatial scale region and have to use continuous data in order to resolve fine structure ($\sim$160 km, corresponding to the spacecraft motion with 2 km/s during 80 s), we choose Plan–(I). On the other hand, since we have to wait for a certain time interval to finish the sequence (roughly a few minutes, required for data transfer and S–WPIA analysis of all 10 data–units) to obtain the next, we have to accept the lack of temporal continuity of each set of 10 data–units.

Plan–(II) is the basic plan. We need to store 8 s data in the memory, and then we do S–WPIA analysis on the stored data. The required memory size can be 140.1 kB for the wave and particle data as well as the memory size for the output of S–WPIA (0.2–27 kB for 1 m/q step, so 0.8–108 kB in total for 4 steps of m/q for every 1 set of 10 data–units). Compared to Plan–(I), the lack of temporal continuity of each data–unit lowers the spatial resolution of S–WPIA output ($\sim$1200 km, corresponding to the spacecraft motion of 2 km/s during 10 min), but on the other hand we can measure the averaged activities of interactions in the region of interest and its temporal variation for every orbit, by the use of the relatively large spatial coverage of the S–WPIA output. The sequence of the analysis (data transfer and the S–WPIA analysis) should be finished within 1 min so as to realize Plan–(II). In case of restrictions of data transfer or computation time preventing us to finish the sequence during 1 min, it would be possible to use longer duty cycle (e.g., 2 min). The computation time of the S–WPIA analysis should be optimized by testing on the onboard CPU.

Plan–(III) is an operation plan during a Galilean moon flyby. We collect 10 data–units measured at 10 different locations in the region of interest for every orbit, and we obtain 10 sets of 10 data–units. The location of the operation can be scheduled by referring to the orbit of the spacecraft (e.g., every 1 degree of latitude in the polar or equatorial region). Compared to Plans–(I) and (II), the time resolution of the S–WPIA output becomes low (corresponding to 10 orbits) but we can resolve the spatial distribution of the averaged activities of interactions.

In Plan–(IV), corresponding to our minimum requirement, we collect 1 data–unit measured at the same location in Ganymede's magnetosphere for every orbit, and we obtain 1 set of 10 data–units. The location of the operation should be carefully selected by referring to the orbit of the spacecraft.

4 Summary

In the present study, we discussed the science objectives and implementation of S–WPIA, which will be realized as a software function of the LF running on the DPU of RPWI for the ESA JUICE mission. S–WPIA conducts onboard computations of physical quantities indicating the energy exchange between plasma waves and energetic ions. Onboard inter–instruments communications are necessary to realize S–WPIA, which will be implemented by efforts of RPWI, PEP and J–MAG. The in-flight S–WPIA computation significantly reduces the data volume to be downlinked to ground. By providing the direct evidence of ion energization processes by plasma waves around Jovian satellites, S–WPIA contributes scientific output to JUICE while keeping its impact on the telemetry data size to a minimum.

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