Early Science with ALMA

Draft of Interim Report - September 3, 2002

1. Introduction

In June 2002, the ASAC was requested by the ACC to define the early science which could be started before the full completion of the ALMA baseline project. The charge is as follows:

The ASAC is requested to make an assessment of ALMA early science. What kinds of scientific data (including the balance between spectroscopic and continuum data) are likely to be most desired as ALMA begins operations? Based on this probable interest, what are the commissioning and operational implications for the array's baseline capabilities, frequency coverage and operating modes?

A working group was constituted with the following members: Pierre Cox, Stephane Guilloteau, Diego Mardones, Hiroshi Matsuo, Ken Tatematsu, Ewine van Dishoeck, Malcolm Walmsley, David Wilner, Christine Wilson, and Al Wootten. This is a progress report summarising the discussions and outlining some of the issues related to the Early Science with ALMA.

2. Definition, Requirements and Goals of Early Science

The main purpose of this document is to explore realistic goals for the early phases of ALMA scientific operations, before ALMA is sufficiently complete, where the term "sufficiently complete" should be defined, since no input definition has been given yet (see § 6).

Early Science is *not* Commissioning (§ 3). Early Science will involve the community, therefore implying that it will go through a phase of Call for Proposals, although perhaps in some restricted form, and that the programmes will be selected according to criteria to be defined.

The goals of Early Science are manifold and we recommend that they include:

- Early Science must demonstrate the *unique capabilities* and the scientific potential of ALMA by providing unique scientific results
- Early Science should foster a *rapid scientific return* from ALMA, for a wide range of topics, from solar system physics (including the sun) to the high redshift universe
- Early Science must show these capabilities to *all astronomers*, not only experts in millimeter/submillimeter astronomy, in order to involve scientists from a large community in a *prompt and efficient use of ALMA* and to familiarize the community with these new techniques
- Early Science must produce *compelling images*, which is not only the best way to convince the community, in particular the optical astronomers, but will also catch the public's interest
- Early Science must be used to provide *feedback* to ALMA on *operations* from the User Community.

3. Science Verification during Commissioning

The goals of Science Verification in the Commissioning are different from those of Early Science and are as follows:

- Science Verification must demonstrate the *basic* ALMA capabilities
- Science Verification must test systematically the expected *operating modes* of ALMA
- Science Verification must have a *verifiable output*, which should be made available to the community as the basis for advertising Early Science capabilities (in the Call for Proposals)
- Results from the Science Verification could serve public relations purposes early on, as well as inviting Early Science proposals. Scientific topics could include first high quality images of Centaurus A, 30 Doradus, η Carina, or spectral line results, e.g., confirming the presence of glycine toward Sgr B2.

Science Verification during Commissioning is therefore closely linked with the ALMA operations and will only involve experts, i.e. people who are close to the instrument and the operations. However, Commissioning can be a phased activity overlapping with Early Science. When more ALMA capabilities become available, they first go through a phase of Commissioning, before being offered for Early Science.

4. Unique Capabilities of ALMA in Early Science

Prior to the start of operations of the full ALMA array, i.e. 64 antennas (at the end of 2011), ALMA will provide the community with capabilities exceeding those of current or planned millimeter/submillimeter arrays. Early Science will utilize the ALMA capabilities which have been demonstrated during Science Commissioning. Those capabilities include:

- **Sensitivity**

  From the first year of operation onwards the sensitivity of ALMA will exceed that of all existing or planned array in all 4 Priority Bands (see Figs. 1 & 2 and Tables 1-5). During the first year, the continuum sensitivity will be a factor 2-3 better (Fig. 1) due to the wide bandwidths, with only a slight improvement in spectral line sensitivity (Fig. 2). During the following years, as the number of antennas increases, the gain in both continuum and line sensitivities improves by a factor ≈ 2, approaching 50% of the ultimate sensitivity after the third year of operation (32 antennas). We note that besides offering the best continuum sensitivity, wide bandwidth will also be a major advantage for any spectral line survey

- **Long Baselines**

  By 2007, ALMA will be equipped up to 4 km baselines, i.e. much longer than any array so far, and on a superior site. This will enable to achieve unprecedented spatial resolution at millimeter and submillimeter wavelengths. Using long baselines requires that phase correction techniques are operational and that bringing those into operation should be planned for early on in the project

- **Frequency Coverage**

The frequency coverage offered by ALMA and the site characteristics of Chajnantor will allow astronomers to observe not only at millimeter wavelengths (1 and 3 mm) but also at high frequencies, i.e. using Bands 7 & 9 at 345 and 675 GHz, and explore the submillimeter domain at unprecedented spatial resolution and sensitivity (especially in the continuum). It should be noted that, even with 6 antennas, ALMA will have 3 times better continuum and line sensitivity at 345 and 675 GHz than the eSMA (Figs. 1 & 2). However, since it is technically more challenging to bring the array on-line at the highest frequencies, the set of initial bands to be offered for Early Science may not include Band 9

- **Polarization**

  Although polarization measurements will build on the discoveries made by pioneering efforts on other arrays, polarization will certainly not be fully exploited when ALMA can start operations around 2007. Polarization is a crucial aspect of the ALMA capabilities, and its scientific verification should be planned early on

- **Southern Sky Sources**

  The access to the southern Sky opens up the possibility to observe unique sources which are only (or best) visible in the southern hemisphere, such as the Galactic Center, the Magellanic Clouds, Centaurus A, some of the major star formation regions in the Southern sky, in particular the Carina Nebula (including the massive star η Car), the debris disk β Pictoris, and transient objects (comets). However, we note that repeating the same sort of science that arrays in the Northern hemisphere will have been doing on Northern sources should be avoided as much as possible in Early Science

- **Image Quality**

  As soon as the number of antennas will exceed 12, the imaging quality will be better and the imaging speed will surpass by a large amount that of other instruments. However, the imaging quality may depend on the nature of the field being imaged

- **Calibration Accuracy**

  Accurate calibration is a goal of the ALMA project. The better site will help, but there is no guarantee.

5. What should be avoided in Early Science

In Early Science at least two things should be avoided. First, there is no need in trying to obtain a result in, e.g., 3 months during the first year, while it could be obtained in a only a day once ALMA is completed. It is important to remember that with 6 antennas, ALMA will be 100 times slower than when fully completed. This implies that any experiment in the Early Science phase should not exceed 1 week of observing time. In particular, very extensive surveys should not be conducted. Second, imposing requirements which cannot be met should be avoided. In any case, during Early Science, priority should be given to science which makes the best use of ALMA's unique capabilities.

6. Steps and Duration of Early Science

Early Science starts as soon as 6 to 8 (or perhaps even more) antennas have been commissioned in Q3 2007. The reasons for starting with at least 6 antennas are: (i) ALMA with less than 6 antennas is not competitive scientifically in sensitivity and UV coverage compared with other facilities available in 2007; (ii) commissioning is a delicate problem and a learning curve is required; (iii) science commissioning requires 6 antennas to be operational to ensure most modes have been tested; and (iv) commissioning of additional antennas and/or receiver bands requires sub-array capabilities.

We recommend that commissioning of new telescopes and/or receivers is done in a separate sub-array and is not shared with Early Science. Thus, a minimum of 8 commissioned antennas (6 in main array for Early Science, 2 + new to be commissioned antenna in sub-array) will be necessary. In addition, 1 antenna equipped for total power observations should be available from the start. Once new antennas and/or receiver bands have been commissioned, they should be added to the science array as soon as possible, and in the case of the antennas in groups of 4, 6 or 8 antennas (rather than one by one). Early Science phases can be applied separately to different frequency bands.

We recommend that Early Science observing does not start with less than 2 receiver bands. For commissioning, the availability of Band 3 receivers is essential. As noted above, the largest gains in sensitivity and spatial resolution are obtained at the highest frequencies, but Band 9 will be technically challenging to commission in the first year. Experience at other observatories has shown that Band 7 should not be more difficult to commission than Band 6. Band 9 should be tested and commissioned early-on, at least on a sub-array to characterize the antennas and site at the highest frequencies. The final choice of initial bands to be implemented must involve a trade-off between scientific, technical and programmatic arguments.

A natural end-point of Early Science is when 32 antennas have been commissioned, expected around late 2009. The reasons are: i) with 32 antennas the sensitivity is half of the final one (Fig. 1 & 2); ii) the imaging quality is close to final.

7. Recommendations

Based on the discussions summarized in the previous sections, the ASAC makes the following recommendations concerning the ALMA Early Science:

1. Early Science observing should start with not less than 6 antennas and 1 antenna in total power mode
2. Early Science observing should include both continuum and line observations from the start
3. Early Science observing should start with not less than 2 receiver bands
4. Phase correction should be available at the start of Early Science observations
5. The array for Early Science should be separated from the telescope's array for commissioning through sub-array capabilities
6. Additional telescopes and/or receivers bands should be brought into the science array as soon as they have been commissioned.

8. ALMA Sensitivity

The following presents a quantitative comparison of the sensitivity expected with ALMA with 6, 12, 32 and 64 antennas for the four Bands of the baseline project compared with existing and future facilities. The results are presented in the form of tables (Tables 1 to 5) and figures (Fig. 1 & 2). They illustrate the evolution of the capabilities of the ALMA array prior to the end of 2011, when ALMA will become fully operational.

We adopted a 5 hr on-source integration time to represent a typical track in Early Science and assumed that high-frequency 650 GHz observations are only done during good weather ($\tau_{225} \approx 0.05$). For line brightness sensitivities, all values have been scaled to the same synthesized beam, rather than using specific beams for each (existing) array according to the available/planned configurations. Two baselines, 150 m and 1 km, have been taken as representative of low and high angular resolution Early Science observations.

None of the existing or planned arrays has baselines as large as 4 km, so ALMA is unique in this area. The ALMA sensitivities for 4 km are given below in the Table 4 & 5.

The sensitivities have been calculated under the following assumptions:

- **General**
  - Use standard radiometric formulae for point source continuum sensitivity (e.g., Butler & Wootten, ALMA memo 276, October 1999)
  - Calculate line brightness sensitivity in K for baseline B in km and line width $\delta\nu_{\rm line}$ in Hz from continuum sensitivity in mJy according to:
    $\delta S_{\rm line} = (\delta\nu_{\rm cont}/\delta\nu_{\rm line}) \times \delta S_{\rm cont}$ (mJy)
    $\delta T_{\rm line} = 0.32\, B_{\rm km}^2 \times \delta S_{\rm line}$
- **ALMA**

  Use input values from Butler & Wootten, ALMA memo 276, except $T_{\rm sys}$ from Guilloteau, ALMA memo 393, May 2002, Fig. 1. Specifically:
  - 110 GHz: $T_{\rm sys}$ = 81 K
  - 230 GHz: $T_{\rm sys}$ = 153 K
  - 345 GHz: $T_{\rm sys}$ = 222 K
  - 675 GHz: $T_{\rm sys}$ = 1200 K

  Note that these values are up to a factor of 2 higher than those of Butler & Wootten (1999), especially at 110 and 230 GHz.
- **PdB**

  Sentivities taken from the Plateau de Bure interferometer Web page, assuming $T_{\rm sys}$ = 150 K at 3 mm and $T_{\rm sys}$ = 330 K at 1 mm
- **PdB+**

  Sensitivities are calculated assuming the same $T_{\rm sys}$ as for the PdB, but for dual-polarisation wide-band receivers. At 345 GHz, $T_{\rm sys}$ = 320 K
- **OVRO**

  Sensitivities from G. Blake (private communication) assuming average values of $T_{\rm sys}$, i.e. $T_{\rm sys}$ = 350 K at 3 mm and $T_{\rm sys}$ = 450 K at 1 mm

- **BIMA**

  Sensitivities taken from L. Mundy (private communication), assuming T_{sys} = 300 K at 3 mm and T_{sys} = 500 K at 1 mm

- **CARMA**

  Sensitivities from Tony Beasley July 2002 as provided with NSF proposal

- **NMA and Rainbow**

  Sentivities taken from Nobeyama Web page. It is not clear if the NMA and Rainbow arrays will still operate after 2007. In the tables, Rainbow is labeled as RB

- **SMA**

  Use sensitivities from Wilner (private communication) with:

  230 GHz: T_{sys} = 164 K

  345 GHz: T_{sys} = 413 K

  675 GHz: T_{sys} = 3650 K

- **eSMA**

  eSMA=SMA + JCMT + CSO. Sensitivities have been calculated by, e.g., Moriarty-Schieven (1996), JCMT upgrade proposal. Roughly, the improvement is a factor of 2 compared with SMA.

Table 1: Point source continuum sensitivity (mJy) - 5 hr, 1 σ

Freq.	PdB	PdB$^+$	OVRO	BIMA	CARMA	NMA	RB	SMA	eSMA		ALMA	
GHz										6	12	64
110	0.3	0.06	0.6	1.1	0.04	0.7	0.5	-	-	0.028	0.013	0.0024
230	0.9	0.14	1.6	2.5	0.10	6.3	3.2	0.4	0.2	0.056	0.027	0.0049
345	-	-	-	-	0.70	-	-	0.9	0.46	0.088	0.042	0.0076
675	-	-	-	-	-	-	-	8.5	4.9	0.69	0.33	0.060

Table 2: Line sensitivity (K) for $1\,\mathrm{km\,s^{-1}}$ line width, 5 hr 1 σ, 150 meter baseline

Freq.	θ	PdB	PdB$^+$	OVRO	BIMA	CARMA	NMA	RB	SMA	eSMA		ALMA	
GHz	$''$										6	12	64
110	4.5	0.11	0.07	0.35	0.24	0.04	0.40	0.28	-	-	0.03	0.014	0.003
230	2.1	0.27	0.11	0.48	0.62	0.06	2.31	1.6	0.15	0.07	0.04	0.020	0.004
345	1.4	-	-	-	-	-	-	-	0.27	0.14	0.05	0.025	0.005
675	0.7	-	-	-	-	-	-	-	1.8	1.1	0.3	0.14	0.03

Table 3: Line sensitivity (K) for $1\,\mathrm{km\,s^{-1}}$ line width, 5 hr $1\,\sigma$, 1 kilometer baseline

Freq.	θ	PdB	PdB$^+$	OVRO	BIMA	CARMA	NMA	RB	SMA	eSMA	ALMA		
GHz	$''$										6	12	64
110	0.67	7.1	-	16.8	13.9	1.8	-	-	-	-	1.3	0.64	0.12
230	0.32	0.27	-	21.2	34.6	3.3	-	-	6.9	3.3	1.7	0.85	0.16
345	0.22	-	-	-	-	-	-	-	12.0	6.1	2.1	1.15	0.20
675	0.11	-	-	-	-	-	-	-	46.7	46.7	12.3	6.1	1.15

Table 4: Line sensitivity (K) for $1\,\mathrm{km\,s^{-1}}$ line width, 5 hr $1\,\sigma$, 4 kilometer baseline

Freq.	θ	PdB	PdB$^+$	OVRO	BIMA	CARMA	NMA	RB	SMA	eSMA	ALMA		
GHz	$''$										6	12	64
110	0.17	-	-	-	-	-	-	-	-	-	21.4	10.2	1.8
230	0.08	-	-	-	-	-	-	-	-	-	29.5	14.1	2.5
345	0.05	-	-	-	-	-	-	-	-	-	37.4	17.9	3.2
675	0.03	-	-	-	-	-	-	-	-	-	211.0	10.1	18.2

Table 5: Continuum sensitivity (K), 5 hr $1\,\sigma$, 4 kilometer baseline and 8 GHz Bandwidth

Freq.	θ	PdB	PdB$^+$	OVRO	BIMA	CARMA	NMA	RB	SMA	eSMA	ALMA		
GHz	$''$										6	12	64
110	0.17	-	-	-	-	-	-	-	-	-	0.14	0.07	0.013
230	0.08	-	-	-	-	-	-	-	-	-	0.29	0.14	0.025
345	0.05	-	-	-	-	-	-	-	-	-	0.45	0.21	0.039
675	0.03	-	-	-	-	-	-	-	-	-	3.5	1.7	0.31

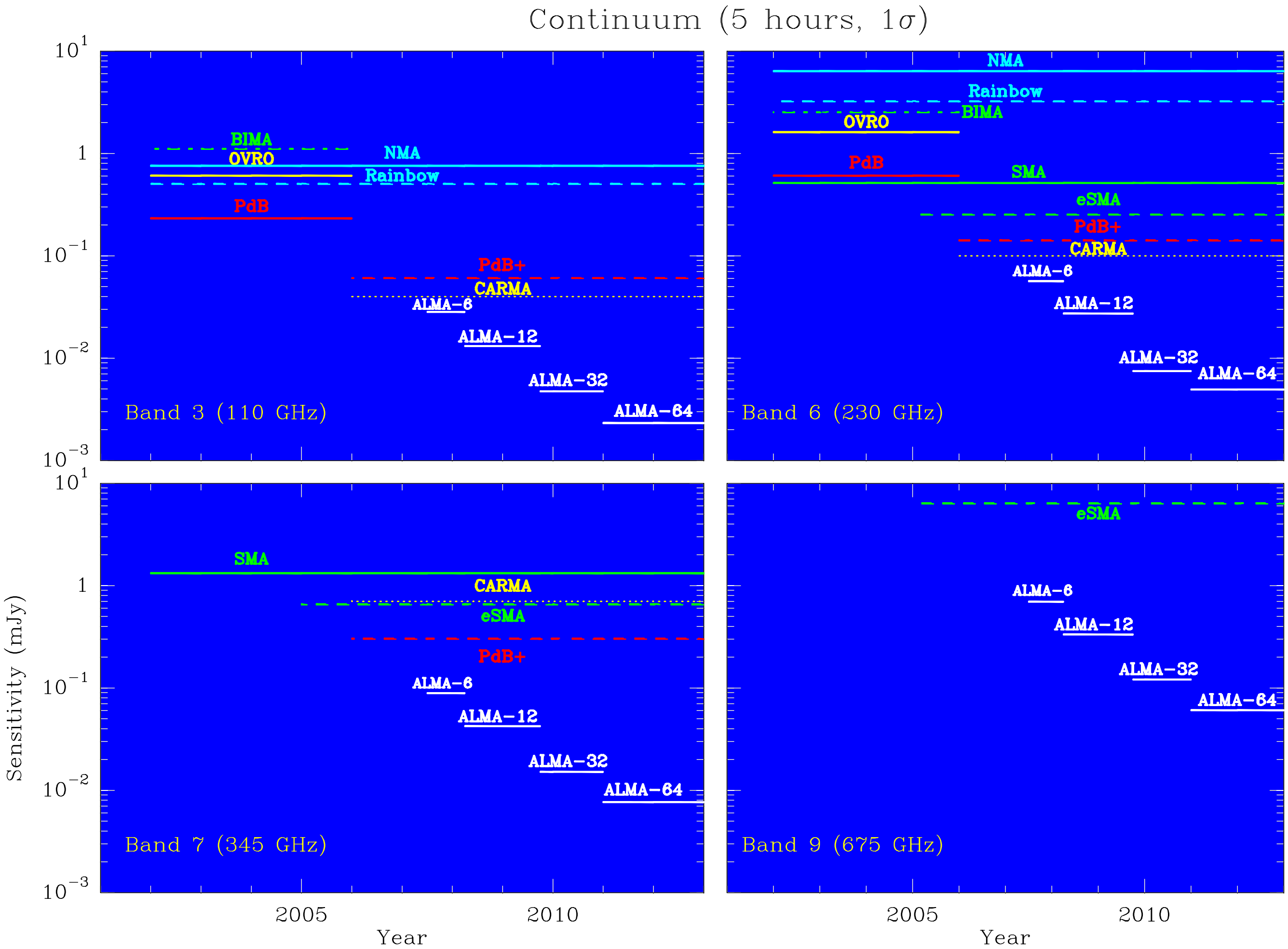

Fig. 1.— Sensitivity in the continuum (1 σ, 5 hours) for ALMA with 6, 12, 32 and 64 antennas in the four priority 1 Bands compared to the sensitivities of the present and planned millimeter/submillimeter arrays. See text for details.

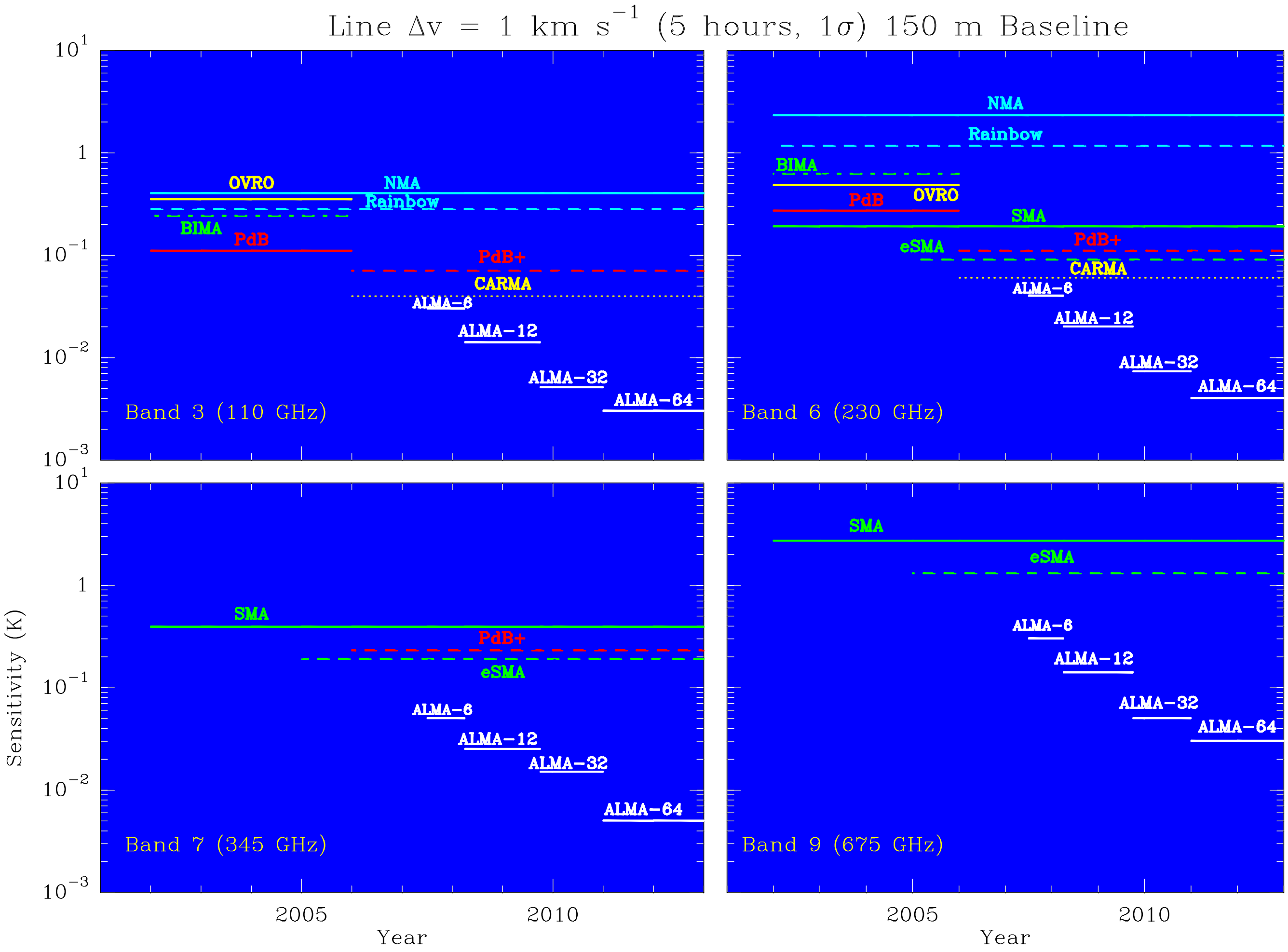

Fig. 2.— Sensitivity for line emission of width $1\,\mathrm{km\,s^{-1}}$ ($1\ \sigma$, 5 hours) for ALMA with 6, 12, 32 and 64 antennas in the four priority 1 Bands compared to the sensitivities of the present and planned millimeter/submillimeter arrays. See text for details.